STUDIES IN THE INTERCHANGE OF HEAT BETWEEN THE BOVINE AND ITS ENVIRONMENT

A Thesis submitted to the University of Glasgow for the Degree of Doctor of Philosophy in the Faculty of Science

by

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CONTAINS PULLOUTS

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Statement of Originality.

The physiological work described in the Thesis was carried out as part of a Climatological project directed by Dr. J.D.Findlay, and the work on animals in which I played a major part was carried out under his Vivisection licence. The physiological measurements formed part of a prearranged programme in the planning of which I played a large part. I claim originality in the analysis and presentation of the data, the Discussions on it, the interpretation of the results and the conclusions reached. Technical assistance was used in taking many of the readings, and exclusively in caring for the animals. A small part of the routine calculations was performed by a technical assistant.

As stated in the Thesis the original commercially-built chamber did not function and the subsequent new designs of the control systems were made by me. The system of controlling absolute humidity by wet and dry bulb thermometers; the use of thermistors and magnetic amplifiers to provide an accurate and stable control system, and the feedback circuits associated with the control of boiler current are my original work. The air temperature control system combining a simple on-off action with a special electronic Variac controller to give automatic adjustment of backing heat are original. In the final assembly and testing of these controllers I acknowledge the assistance of Mr. W. Nisbet, an Assistant Experimental Officer at the Institute. The necessity for using the temperature measuring system described in Chapter 9 was put forward by me and most of the work described in that chapter(in particular the assessment and prevention of the errors, the reference junction and its power supplies, the matching of thermocouples and the design of the switches) was my own original work. The design of the polythene covered rectal thermometer is due to Mr.W.Nisbet who also at my request measured the e.m.f. of the Kalium cells. The work on using a non-linear thermister in a linear thermometer is original. The design and developement of the Cardiotachometer capable of working on the bovine under adverse signal:noise conditions is original. In this no claim is made, of course, for the originality of such wellknown circuits as the Phantastron, cathode follower, Twin T network etc., but since in some cases the original references are not available these have not been given. It is thought that the accurate timing and trigger circuits are new developements.

W. R. Beadle

11 May 1953.

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Part I

The Effects of Thermal Environments from 20°C. to 40°C. at High and Low Humidities on the Physiological Reactions of Young Calves

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PART I

The Effects of Thermal Environments from 20°C. to 40°C. at High and Low Humidities on the Physiological Reactions of Young Calves.

Chapter 1

General Introduction

In countries of the temperate regions of the world cattle have for long been subjected to selective breeding, and a number of different breeds have been evolved, each highly adapted to its own function and environment. Amohgst the most specialised breeds are the dairy cattle, which have been developed to produce high yields and good quality milk in their normal environment. The high milk yield of some of these dairy cattle, as compared with that of the undeveloped tropical cattle, has caused farmers and breeders in tropical countries to import them on a large scale. As soon as these animals enter the warmer environment, however, their milk yield falls, and later their pure and cross-bred progeny degenerate, often to a level lower than that of the native cattle they are meant to replace. At least part of this decline is caused by the climate, although some of it is undoubtedly caused by such factors as management, nutrition and disease. Regan & Richardson (1938) among others have investigated the effect of temperature alone on the milk production of Jersey cows and have demonstrated a fall in milk yield from 29 lb./day at an environmental temperature of 5°C. to 17 lb./day at 35°C.

Many workers have entered this field of animal climatology. A valuable review of the subject up to the beginning of 1949 has been published by Findlay (1950), and an important contribution to the physiol-

ogical background of the subject has been made by Brody (1948).

Two different types of direct approach to the problem have been made:

(1) Results have been collected in the field where the animals are naturally subject to the prevailing weather conditions. This method makes possible the examination of large numbers of animals, but it is not always possible to separate the effects of the different factors of the environment, nor to compare results from one district with those from another. For example, in the field temperature and humidity usually vary in such a way that in any one place the effects of temperature completely mask the effects of humidity; and the diurnal changes in temperature, with cold nights and temperature rising during the mornings to high levels in the afternoon, cause effects due to temperature to be inextricably mixed with those due to time of day.

(2) A few experiments have been carried out in buildings equipped with special air-conditioning and heating equipment, and to which the general term "psychrometric chamber" can be applied. These buildings can hold but a comparatively small number of animals at any one time and the collection of a large number of results is therefore a lengthy process. It is however possible in these psychrometric chambers to isolate completely one or other of several environmental conditions and so study in detail the effect of one

particular variable. Much more intensive study of individual animals is possible in the psychrometric chamber, and this is indeed desirable since in large-scale work causative associations tend to become hidden in the overall estimation of the reactions of a large population of animals. A quotation from Witz (1936) ".....in each species each individual has its own particular method of heat regulation", is doubtless an overstatement but its general implications are of great importance.

The construction of a psychrometric chamber at the Hannah Dairy Research Institute was begun in 1947. Many difficulties were encountered in constructing and equipping it for use in fundamental studies of heat regulation in cattle. However, during the course of these preparations it was possible to use the chamber to investigate some of the reactions of calves to their thermal environment, reactions which had not previously been investigated, or for which the published results were inconclusive.

No systematic study of the skin temperature of cattle, and only isolated experiments in the field on scrotal temperature had been made. Heart rates had been studied, but it was believed that the presence of the observer might have disturbed the animals and that the large variations which were observed might have been considerably reduced by using a method by which the observer could be remote from the experimental animal. Respiration rate had received much attention, but a

disconcerting relationship had appeared in the literature from which it seemed that respiration rate followed the van't Hoff-Arrhenius equation with respect to environmental temperature rather than the temperature of the reacting system. The effect of body temperature on respiration rate was uncertain. The sweating ability of cattle had been investigated (e.g. by Regan & Richardson,1938), but results were inconclusive, and the relative importance of heat-loss by evaporation of water from the skin was not known. The effects of humidity had been examined in a psychrometric chamber at an environmental temperature of 41°C. (Rieck & Lee, 1948), but apart from a few inconclusive field experiments, at no other temperature. No thorough investigations had been made of the effect on an animal of time of exposure to a particular environment, nor had an assessment been made of the time necessary for an animal to reach approximate thermal equilibrium with its environment.

In this thesis a description is given of the experiments which were made to provide further knowledge of those factors and to answer as many as possible of the questions they raise.

The Psychrometric Chamber

In 1946 plans were made at the Hannah Dairy Research Institute to convert two adjoining loose-boxes on the Institute's farm into a Psychrometric Chamber and an Observation Room, with the object of studying the thermal regulation of cattle. A much larger chamber was already being constructed at the University

of Missouri; this has been described by McCalmont (1946). At the beginning of 1947 conversion of the loose-boxes, and the installation of control equipment was started by a firm of heating and ventilating engineers. In the spring of 1948 the contractors handed over the psychrometric chamber for its initial tests.

These tests showed that the chamber was useless in the state in which the contractors had left it; three major faults were present:

(1) The temperature control system enabled only two limited ranges of temperature to be maintained over the total required range of 15 to 45°C., and these ranges changed with external air temperature. Even within these ranges the chamber temperature could not be controlled to within 2°C.

(2) Control of humidity was impossible.

(3) When the chamber was maintained at constant temperature (with respect to time) the floor temperature was very much lower than the air temperature in the middle of the chamber, and a large vertical temperature gradient existed.

The insufficient range of control (item 1) was discovered first and a number of unsuccessful attempts were made by the contractors to correct it. During this time the other two items were discovered and experiments by the author showed that a stream of warm air over the floor would maintain it at the required temperature and reduce the vertical temperature gradient to negligible proportions. Separate floor heating at

that time was impracticable. Finally it was left to the contractors to instal the additional floor ducting whilst the author redesigned and installed the temperature and humidity control systems. These control systems (in their final form) are fully described in Part II, Chapter 8 of this thesis.

Plate 1 is a photograph of the psychrometric chamber, which accommodates only one animal at a time. Its internal dimensions are 11'6" long, 6'8" wide, and 7'6" high. Owing to the ducting along the floor at the sides, access to the animal is rather restricted and it is undesirable to use adult cows in the chamber. The walls are lined with cork 6 in. thick, the cork being covered with one half inch of plaster painted with a moisture-proof paint. The part of the floor on which the animal stands is covered with 4 in. of compressed cork; the surrounds are of cement. Behind the animal is a shallow concrete well for the collection of faeces and urine. During an experiment the animal is held in position by the adjustable framework of tubular steel, seen in the centre of Plate 1, which can be adjusted to hold any size of farm animal. There are two doors to the chamber. The larger one, through which the animal enters the chamber is in the rear, the photograph having been taken in this doorway. It is a heavily insulated door such as is used in large refrigerators, and opens directly on to the farm road, with no intervening air-lock. The second door, smaller but equally well-insulated, leads to the observation

room, and is just off the extreme right foreground of the photograph.

Fig.1 shows the system by which heated and humidified air is supplied to the chamber. The fan blows air at the rate of approximately 300 cu.ft./min. over a bank of heaters, and through a compartment into which steam may be injected. The conditioned air is led into the psychrometric chamber through the system of ducts which is seen in detail on the right hand side of Plate 1. A damper controls the division of air between the lower and upper ducts. The lower duct carries air to heat the floor and the upper duct provides the main air supply to the chamber. The four circular appendages to the upper duct are air diffusers which thoroughly mix the high velocity air stream inside the duct with the air in the chamber, so that at a distance of only a few inches from the diffusers the air velocity is no greater than 20 ft./min., and is less than this near the animal. The outlet duct can be seen running along the floor on the left of the photograph, rising to the top of the far wall and leaving the chamber at its top right-hand corner. Thence it passes into the observation room. The measuring elements for the temperature and humidity controllers are situated in the duct just where it emerges from the wall. Provision is made for partially dehumidifying the air if required, diversion from the main stream being possible with the aid of a series of dampers. This dehumidification is effective only at comparatively high

humidities. The air may then be recirculated or allowed to escape, the degree of recirculation being adjustable by a damper in a compartment which is common to the fresh air, exhaust and fan ducts.

To maintain the chamber at 40°C. while continually supplying fresh air when the outside temperature is 0°C., approximately 10 kW. of heat must be supplied to the air. To raise the temperature of the chamber from a low value to 40°C. in a short time much more heat is necessary, mostly because of the high thermal capacity of the walls and floor. A nominal total of 16.5 kW. is available in the electric heater bank, being supplied by one 6 kW. heater, one 3 kW heater, a continuously variable 0 - 6 kW. heater, and two smaller heaters of 500 W. and 1 kW. respectively. The larger heaters supply the main heating load for the chamber, and either of the smaller ones may be controlled by the thermostat to hold the temperature of the chamber within fine limits. The 0 - 6 kW. heater is automatically adjusted in steps of 100 to 200 W. to provide any change in backing heat rendered necessary by changes in the temperature of the outside air, in the voltage of the power lines, or by a change in the thermal demand of the chamber. For some time an adjustable bimetal thermostat was used as the temperature-sensitive element in the dry-bulb temperature control system but this proved to be unsatisfactory and was replaced by a thermistor/magnetic amplifier system. Air temperature control to within $\pm$ o.2°C. over long

periods is now possible in the room over a range from the external ambient temperature to 45°C. On setting the air temperature to a different value it reaches equilibrium within less than 10 min. between any two points within the range. The wall temperatures take much longer to reach equilibrium, their time constant being 3 to 4 hr. Because of heat losses through the walls their average temperature differs from the chamber air temperature by about 1°C. for each 15 to 20°C. difference between the temperature of the chamber air and that of the external air.

The humidity of the chamber is controlled by a wet-bulb thermometer in the outlet duct. The signal from a wetted thermistor after amplification maintains the water in an electrode boiler at such a level that the rate of generation of steam is sufficient to hold the chamber at the required humidity, or change it to it. The system has been carefully desighed to prevent oscillation and can maintain the absolute humidity at any value between the humidity of the external air and 55 mg/l., which corresponds to saturation at 42°C. Accuracy of control is to within $\pm$ 0.2°C. wet bulb temperature, which is in general much less than 1 mg/l. change in absolute humidity.

Experimental Procedure

Four male calves were individually subjected to a number of different environmental temperatures at different humidities. The standard environmental temperatures used were 20, 25, 30, 35 and 40°C. The

absolute humidity was kept at 15 mg/l. at 20°C., and on different occasions either the absolute humidity was held at 17 mg/l. ('low humidity' conditions) or the saturation deficit was held constant at 6 mg/l. ('high humidity' conditions) at the other environmental temperatures. The different value at 20°C. was chosen because 17 mg/l. is just about saturation value at this temperature; and since the humidity could not be reduced below the prevailing external value, only a very limited choice was available. Table 1 shows the interrelationships of these different environmental humidities.

Two different periods of exposure to a given condition were adopted. In the 'short term' experiments the chamber, initially at 20°C., was held at each standard temperature for 1 hr before being raised to the next highest temperature, humidity being maintained 'low' or 'high' throughout the day. This type of condition was adopted as a formalised quasi-tropical day. In the 'long term' experiments the animal was exposed for approximately 6 hr. to one particular standard temperature at either 'high' or 'low' humidity on each day. Longer periods of exposure were impracticable at this stage of the work for three reasons:

(a) The chamber was not suitable for leaving an animal unattended overnight.

(b) The animal was not allowed to lie down during an experiment and would become tired after standing for more than 6 hr.

(c) Feeding and drinking would almost certainly modify the physiological responses of the animal, and it was not considered desirable to leave the animal for too long without water.

When not in the chamber the animals were housed in a loose-box maintained at a temperature of about 18°C. During the weeks when a calf was on experiment it was fed a standard ration of ½ lb. dried grass, 1½ lb. balanced concentrates and 3 lb. hay at 7.30 a.m. When an experiment was to be performed the calf was put in the chamber at approximately 10 a.m. The chamber had already reached equilibrium under the initial environmental condition for that day, except when the humidity was to be high at the environmental temperature of 40°C. Then the humidity was not raised until the thermocouples, stethograph and cardiograph electrodes had been attached to the animal.

During the period of exposure the animal was held by means of a metal structure placed around it and to which the animal was haltered. This allowed the animal some freedom of movement, but would not allow it to lie down or change its orientation within the chamber. Plate 2 shows a calf in the chamber.

Much of the first hour in the chamber was taken up by fixing the thermocouples and other apparatus to the calf. The period of exposure generally lasted until 4 p.m. or just after, but if the calf's rectal temperature rose above 42°C. before the full time elapsed the experiment was stopped. At the end of the exposure period the calf was removed from the chamber to the loose-box and fed and watered. No feeding or drinking was permitted during the time the animal was in the chamber.

Tables 2, 3, 4 and 5 give the details of the calves used and show to what environmental conditions each was exposed.

In each experiment, respiration rate, heart rate, rectal temperature, skin temperature at eleven different locations, and scrotal surface temperature were measured, as well as the air temperature of the chamber, the temperature of its walls, floor and ceiling, and its humidity. Readings of all of these were made at five minute intervals throughout the day, except during part of the first (and very occasionally the second) hour, whilst the measuring apparatus was being attached to the animal. The skin of each calf was examined for signs of sweating two or three times during the course of each day's experimental period.

All the readings were taken in the observation room. This was done for three reasons:

(a) In order that the presence of the observer might not disturb the animal.

(b) So many readings were taken 'simultaneously' that it was necessary to centralise all indicators and to make the readings self-recording as far as possible.

(c) At the higher temperatures and humidities in the chamber the observer's efficiency is greatly depressed.

The methods used in measuring each response are described in the particular chapter to which each refers. Details of the apparatus specially developed for any of the methods are given in Part II of the thesis.

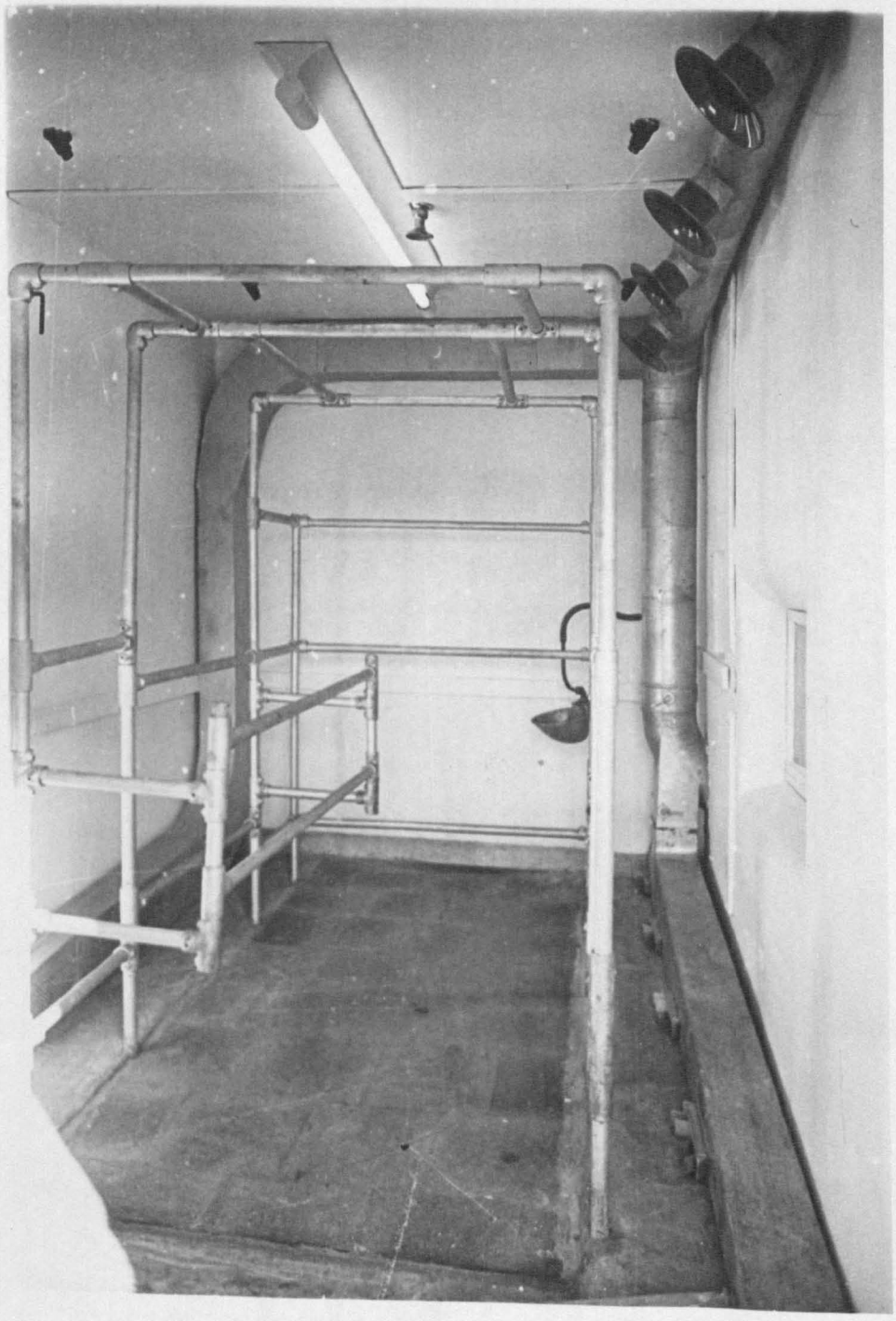


Plate 1. The Psychrometric Chamber

(A description is given on p.4)

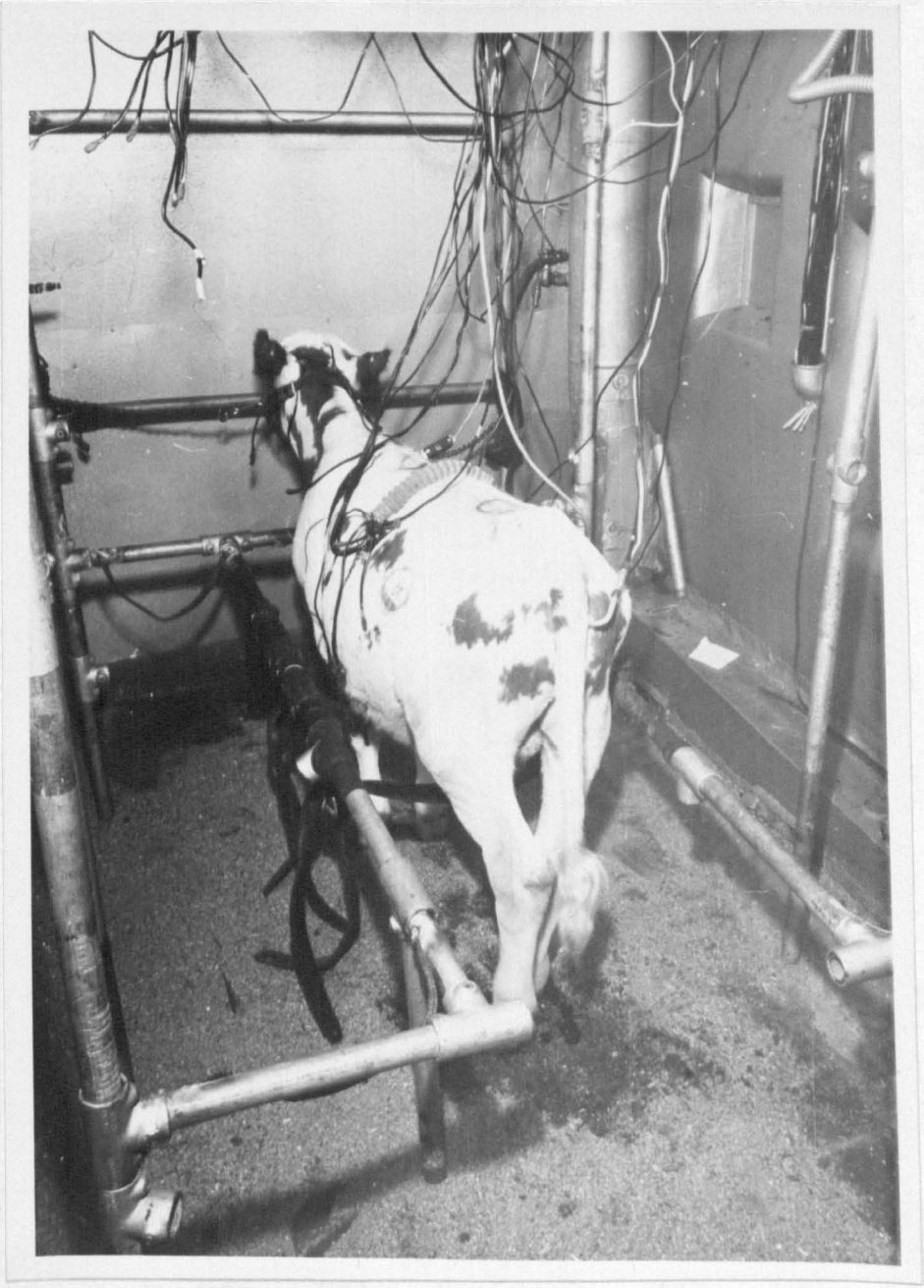


Plate 2. A calf in position in the psychrometric chamber with thermocouples, cardiograph belt and stethograph attached. The rectal thermometer has been slightly withdrawn to show detail.

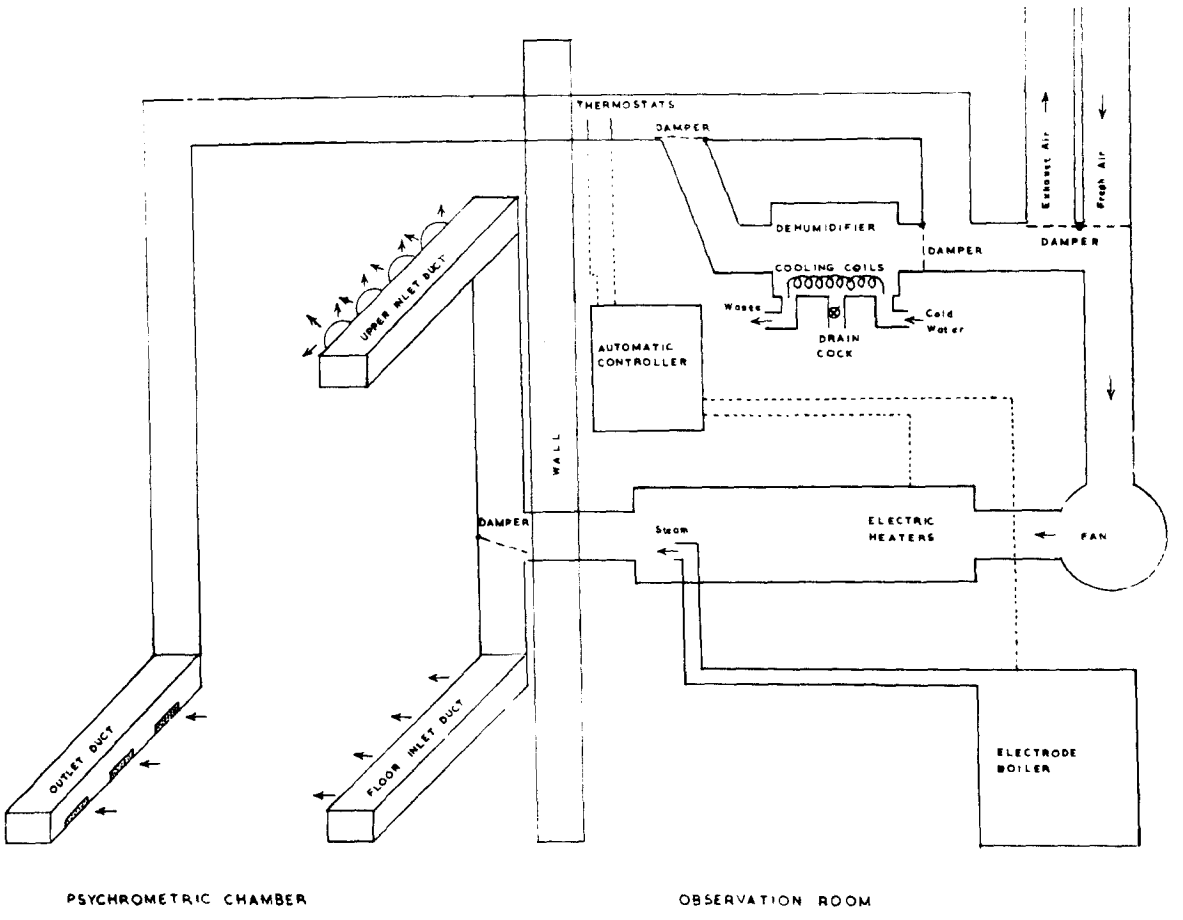


Figure 1. Schematic diagram of the air-conditioning equipment for the psychrometric chamber.

Table 1. The standard environmental humidities employed, together with their equivalent values on other humidity scales

Factor held "constant"	Humidity scale	Environmental temperature (°C.)				
		20	25	30	35	40
Absolute humidity	Absolute humidity (mg/l.)	15	17	17	17	17
	Saturation deficit (mg/l.)	2	6	13	23	34
	Relative humidity (%)	88	74	56	43	33
	Wet bulb temperature (°C.)	18.6	21.4	23.0	24.6	26.2
Saturation deficit	Saturation deficit (mg/l.)	2	6	6	6	6
	Absolute humidity (mg/l.)	15	17	24	34	45
	Relative humidity (%)	88	74	80	85	88
	Wet bulb temperature (°C.)	18.6	21.4	27.2	32.8	38.1

Table 2. Schedule of experiments on calf AC/2

Breed: Ayrshire

Approximate date of birth 3rd Jan. 1950
Weight at beginning of experiment 120 kg.
Weight at end of experiment 140 kg.

Experiment No.	Date	Environmental temperature (°C.)	Humidity
	1950		
1	17 June		
2	22		
3	23		
4	26		
5	27		Mixed
6	28		
7	3 July		
8	10		
9	12 July	20 - 40	
10	13		Low
11	18		
12	19 July		
13	20		High
14	21		

Table 3. Schedule of experiments on calf AC/3

Breed : Ayrshire

Approximate date of birth 14th April 1950
Weight at beginning of experiment 120 kg.
Weight at end of experiment 170 kg.

Experiment No.	Date	Environmental temperature (°C.)	Humidity
1	25 August 1950	20 - 40	Low
2	28 August		
3	29 August		
4	30 August		
6	27 September		
7	28 September		
8	29 September		
9	10 October	12 - 30	-
10	11 October		
11	12 October	20 - 40	High
12	13 October		
13	18 October		
14	19 October		
15	20 October		
16	23 October	20	Low
17	24 October	20	
18	25 October	25	
19	26 October	25	
20	27 October	30	
21	30 October	30	
22	31 October	30	
23	1 November	30	High
24	2 November	35	Low
25	3 November	35	High
26	8 November	40	Low
27	9 November	40	Low
28	10 November	40	High
29	16 November	40	High
30	28 November	12 - 30	-

Experiments Nos. 9, 10, 30 were special experiments in which the environmental temperature was slowly and steadily raised during the period of exposure.

Table 4. Schedule of experiments on calf HC/1

Breed : Highland

Approximate date of birth 12th April 1950
Weight at beginning of experiments 100 kg.
Weight at end of experiments 120 kg.

Experiment No.	Date	Environmental temperature (°C.)	Humidity
	1950		
1	4 December	20	Low
2	7 December	20	Low
3	18 December	25	Low
4	19 December	30	Low
5	20 December	35	Low
6	21 December	40	Low
	1951		
7	8 January	20	High
8	9 January	25	High
9	10 January	30	High
10	11 January	35	High
11	12 January	40	High

Table 5. Schedule of experiments on calf AC/4

Breed : Ayrshire
Approximate date of birth 14th August 1950
Weight at beginning of experiments 110 kg.
Weight at end of experiments 150 kg.

Experiment No.	Date	Environmental temperature (°C.)	Humidity
	1951		
1	12 March	20	Low
2	13	20	
3	14	20	
4	15	25	
5	16	25	
6	19	30	
8	21	30	
9	22	30	
10	28	30	
11	29	35	
12	30	35	
14	3 April	40	
15	6	40	
16	9	25	
17	10	25	
18	11 April	30	High
19	12	30	
20	16	35	
21	17	35	
22	24	40	
23	25	40	
24	27 April	20	Low
25	1 May	20 - 40	
26	2	20 - 40	
27	3 May	20 - 40	High
28	4	20 - 40	
29	7	40	
30	8 May	40	Low
31	9	35	Low
32	10	35	High

Chapter 2

The Effect of Thermal Environment on the Respiration Rate of Calves

Introduction

It is well known that the respiration rates of cattle increase greatly with increasing environmental temperature, thus increasing the evaporative losses from the respiratory tract. It has been shown by a number of workers (e.g. Kleiber & Regan, 1935) that the respiration rate approximately doubles for a 10°C. increase in environmental temperature. In the present work a new investigation has been made of this relationship.

Seath & Miller (1946) in a statistical examination of field data could find no significant changes in respiration rate caused by changes in the relative humidity of the environment, but Rieck & Lee (1948) working in a psychrometric chamber showed that changes in humidity at an environmental temperature of 41°C. produced large changes in the respiration rates of Jersey cows and calves. The present work has extended this information to include the effects of humidity at other environmental temperatures.

Field workers have remarked on the great variability of the respiration rate of cattle in similar thermal environments. These variations are of great practical importance. Firstly, the variations between animals may be due to differences between their ther-

moregulatory mechanisms. If these differences are large, selection of individual animals for specific purposes is possible. Secondly, variations occurring in one animal on different occasions under apparently identical conditions make more difficult the assessment of the characteristic behaviour of that animal, and necessitate the making of a large number of observations to determine the exact magnitude of the effect. Thus the length of any experiment or test performed on an animal depends on the expected variations of the quantity measured. Further, the demonstration of the existence of variations is a necessary precedent to the examination of their causes. The present work therefore includes an investigation into the existence and possible magnitude of such variations in the respiration rate.

Methods and Apparatus

A stethograph was fastened round the animal in a position directly over the last thoracic vertebra (see Plate 2). This transmitted flank respiratory movement to a tambour whose movement was recorded on the paper of a kymograph moving at a speed of approximately 25 cm/min. A standard 50 cycle A.C. motor-driven impulse timer was used to provide 5 or 10 second time marks on the trace. It was initially confirmed that the record obtained actually was that of the respirations by comparing the count obtained from the tracings with those obtained simultaneously by (a) counting the flank movements, (b) feeling with the hand the air

expired at the animal's nostrils and (c) counting the facial movements of the animal during panting. Plate 3 shows examples of the type of record obtained, the top trace on each recording being the time marker, and the bottom one the respirations.

The kymograph was run for approximately 1½ min. at nominally 5 min. intervals throughout the course of the experiment. The records were later counted with reference to the time marker. Wherever possible two separate half-minute periods on each recording were counted and the sum of these taken as representative of the respiration rate during the preceding 5 min.

Results

In the short term experiments each calf spent rather more than an hour at a temperature of 20°C. and a humidity of 15 mg/l. at the beginning of its period of exposure. The holding room from which the animal had been taken was at 18°C. and therefore the animal experienced very little change in its thermal environment when changing its quarters. The mean respiration rates over the last half hour at 20°C. for each of 3 calves, for each day of the short term experiments and at a corresponding time in the 20°C. long term experiments are given in Table 6. It will be seen that the variations, both between animals and for the same animal on different days, were very pronounced. The differences between the results for the different days appeared to be random in order of date. It is clear that large variations occur naturally at this temper-

ature, but the cause is not at present known.

Table 7 summarizes the results obtained for the average respiration rates of three calves at the standard temperatures and humidities in the short term experiments. It shows that for all three animals both temperature and humidity had a large effect on respiration rate. As already stated, the 'high' humidity and 'low' humidity conditions at 20°C. were identical (p.16), and this was so also for 25°C. It would therefore be expected that the measured respiration rates of a calf would be approximately the same under each pair of conditions at these temperatures, but in fact every animal exhibited a higher respiration rate at 'high' humidity than at 'low' humidity at all temperatures. The differences, however, between each pair of means for calves AC/3 and AC/4 were not significant at 20 and 25°C., but those for AC/2 were. This illustrates the great care which must be taken in interpreting the data from these short term experiments and indicates that they are not suitable for showing effects due to humidity.

Table 8 summarizes the results obtained from the long term experiments on calves AC/3, AC/4 and HC/1. The results of all replications under similar conditions have been combined to present a mean respiration rate for each animal for each condition for each hour of exposure. As in the short term experiments, increasing temperature had a pronounced effect on the respiration rate, and this was very different for each calf. For the two animals AC/3 and HC/1 an increase in humidity

at environmental temperatures of 35° and 40°C. was accompanied by an increase in respiration rate, but calf AC/4 was apparently unaffected by humidity. The table clearly shows the influence of a third factor which was not apparent in the results for the short term experiments, namely the time of exposure. This also was very different for each of the three calves, the respiration rate of AC/4 tending to rise to a plateau during the second or third hour; that of AC/3 rising to a maximum about the third hour and then falling except at 35°C. high humidity when it attained a plateau at 2 hours; and that of HC/1 rising to a maximum and subsequently falling at the lower temperatures, the time of the commencement of the fall being deferred at intermediate temperatures, and then at the highest temperatures continuing to rise throughout the day.

The effect of time of exposure, and the differences between the animals are more apparent in Fig.2, in which all readings of the respiration rate taken at the normal 5 min. intervals are plotted against the time of exposure, for the environmental condition of 30°C. at low humidity; all replications, where these were performed, being included in the graphs. The curve for experiment 6 and AC/4 was completely anomolous, the animal having been constipated for a few days, refusing its food and showing abnormal rectal temperature and heart rate. The plateau attained by AC/4, the fall in respiration rate of AC/3 near the middle of the day, and the steady rise in respiration rate of HC/1 are all

plainly visible. The degree of replication, when the curves were smoothed, was good, although there was a large amount of scatter between consecutive points taken at 5 minute intervals. There were also variations over much longer periods, a steady rise and fall over a period greater than 30 min. being observable in some regions of the curves. Even within the individual kymograph recordings of respiration rate, large variations occurred. Plate 3 gives examples of these. Each tracing was continuous, but the different tracings were taken from different experiments. It was found that the mean respiration rate over 1/4 min. to 1 min. about each of the obviously different portions of each tracing were 15 & 46, 32 & 58, and 53 & 26/min. respectively. The tracings obtained for variations at higher respiration rates were unsuitable for photographic reproduction owing to the close spacing of the cycles but a few numerical examples of such 'instantaneous' variations are 80 & 42, 60 & 108, 104 & 136, 232 & 180 and 164 & 204. There was a tendency for the respiration rate to be less erratic at the higher frequencies, but these changes existed in plenty over the whole range of respiration rates encountered.

A series of analyses of variance has been made in a number of individual experiments taken at random from all the long term experiments on the three animals, and these are presented in Table 9. In all but one the variances due to the scatter of readings within the hours are seen to be much less than those due to the hourly variations, which demonstrates that the number

of measurements made was sufficient to detect the hourly variations and that these existed; and that little information concerning the overall variation during the day was lost by grouping the 5 min. readings into hourly means.

These hourly means, together with their standard errors, are presented in Tables 10, 11 and 12, replications for each environmental condition being given where these were performed. It may be seen that the degree of replication obtained under all conditions was similar to that demonstrated in Fig.2 for an environment of 30°C. at low humidity.

The reactions of the calves to an environmental temperature of 40°C. at high humidity are not clearly illustrated in these tables, since the humidity was not raised until a variable time after the calf's entry into the chamber, in order that apparatus could be attached to the animal. Fig.3 shows the animals' respiration rate in this environment. To show more clearly the effect of humidity the corresponding curves for 40°C. at low humidity are also shown in these graphs. The higher humidity caused an increase in the respiration rate of two of the calves, but about 1 hr. after the humidity had been raised, the respiration rate of AC/4 started falling, and the fall contihued until the calf was removed from the chamber. Such a fall occurring before the end of the second hour in the chamber was not apparent for any other environmental condition to which this animal was exposed, which suggests that AC/4 had reached some particularly critical condition in this environment.

It is instructive to examine the intervals of time between the three high-humidity experiments Nos. AC/4/22, 23 and 29. In spite of the fact that twelve days devoted to experiments under other environmental conditions elapsed between experiments 23 and 29, the repeatability of the observations was good.

An analysis of variance of the hourly means of the respiration rate of AC/4 in Table 11 is given in Table 13. Only the figures for environments of 20, 25, 30, 35°C. at low humidity and 30 and 35°C. at high humidity, from the second to the sixth hour of exposure have been included in this analysis, and experiments nos. 6 and 17 have been omitted; experiment no.6 being an anomolous experiment as discussed earlier, and no. 17 being incomplete with regard to the measurement of other physiological reactions. Insufficient replications were performed in the experiments on AC/3 and HC/1 to warrant any attempt at mathematical analysis of the results for these animals. The analysis confirms that the respiration rate of AC/4 rose with environmental temperature, and shows that these experiments did not provide any evidence for departure from linearity in the curve relating respiration rate with environmental temperature up to 35°C. It confirms that humidity did not measurably affect this animal, but that time of exposure did, and that at any rate from the second hour the respiration rate changed non-linearly with time. It further shows that no interaction was apparent between the effects of time and temperature or humidity, i.e. that the general shape of the curves for AC/4 in Fig.2

is typical of the other temperatures and humidities included in the analysis.

Since the reactions of the three animals in the long term experiments were so different from each other, yet showed in many instances very good replications for each individual, Table 14 is given which contrasts the main features of their behaviour.

Panting was observed in all animals almost universally at environmental temperatures of 35 and 40°C. at high humidity, frequently at 40°C. at low humidity and occasionally at 30 and 35°C. at low humidity.

Discussion

Many workers (Kleiber & Regan, 1935; Regan & Richardson, 1938; Blaxter & Price, 1945) have attempted to fit their results to a van't Hoff-Arrhenius equation, and some have reported success in this, the general claim being that a temperature coefficient of Q_{10}= 2 approximately has been found. Brody (1945) has discussed the van't Hoff relationship and its apparent applicability to respiration rate and environmental temperature. Following Kleiber & Regan (1935) the logarithms of the respiration rates of the calves used in the present experiments have been plotted against the reciprocal of the absolute temperature of the environment to give Fig.4. This has been done for various times of exposure. With such axes any curve fitting the van't Hoff-Arrhenius equation is a straight line, and Kleiber & Regan demonstrated that their data fell very close to a straight line whose slope was equivalent to a Q_{10} value of very nearly 2. In trying to fit the

present data into such a relationship various complicating factors arise. The principal of these is the effect of time of exposure on the respiration rate of the animals. This makes it very difficult to allocate a particular value of respiration rate to an animal in a given environment. Secondly, the variation between animals in respiratory behaviour was so great that it is obvious from Fig.4 that even if it were possible to draw straight lines through the points on the graph, the slopes of these straight lines would be very different for different animals, and even for the same animal at different times of exposure.

The results obtained in the present experiments show the existence of very marked variations in respiration rate over a number of different periods, ranging from 'instantaneous' to a general overall variation during the day. Since the heat lost by respiration over any period is dependent partly on the total number of respirations within that period, it is important to select a sufficiently large sample to obtain an accurate estimate of the mean value for that period. The analyses of variance in Table 9 indicate that this has been done in the present experiments. Fewer measurements would have masked the effect of time of exposure and led to a lack of confidence in the repeatability of the results in the different replications, and greater uncertainty in detecting the effects of humidity. Thus by adopting this system of making measurements every 5 min., the number of necessary replications may be made reasonably

small (but not less than three), so keeping the time required for the whole series of experiments to a minimum.

The influence of time of exposure to a given thermal environment on respiration rate imposes a difficulty in experimental procedure which cannot readily be overcome. The short term experiments produced values for the respiration rates at the higher temperatures considerably below those in the long term experiments. This would be expected, since in the short term experiments the animals had certainly not had time to approach equilibrium with their environment. In the long term experiments, particularly those on HC/1 at the higher temperatures it is doubtful whether the animals had attained equilibrium even after exposure for 6 hr. On the other hand, in experiments of the type performed by Brody (e.g. Kibler, Brody & Worstell, 1949) in which the animals were subjected to the given environment for a week or more at a time, definite evidence of acclimatization was found. Further work is needed to clarify this point, but it is clear that if a calf is in a constant environment for less than 6 hr. the full effect of the environment on the animal is not likely to be determined.

In planning the present experiments it had been tacitly assumed that it would be possible to obtain a mean respiration rate for each environment for each animal. This was found to be impossible owing to the great influence of the time of exposure. Had such figures been obtainable, a further step would have been

to use them as a basis of comparison of the equivalence of environments whereby a certain change in humidity could be said to have the same effect as a certain change of temperature. This may be done to a very limited degree with the present data, Table 8 showing that for the two calves AC/3 and HC/1 which were affected by humidity, an increase in absolute humidity from 17 mg/l. to 34 mg/l. at 35°C. produced a change in respiration rate about twice as large as that produced by a change in temperature from 35°C. to 40°C. at an absolute humidity of 17 mg/l. Thus in this region a rise in temperature of 5°C. was approximately equivalent to a change in absolute humidity of 8 mg/l.

Bonsma (1940) and Gaalaas (1945) working under practical conditions in the tropics, with calves and cows respectively, have noted the great differences between individual animals, but this individual variation has not in the past been emphasised by laboratory workers. Such differences are all too obvious in the present work, and complicate any conclusions that might be drawn on the effect of humidity on the calves, for example. It would be expected that a large increase in humidity, such as may be imposed on the animals at 35 and 40°C., would cause an increase in respiration rate, as has been demonstrated by Rieck & Lee (1948) and also in the present series of experiments for two of the calves but not for the third. It is probable that an increase in humidity at these temperatures produces an increase in respiration rate provided the animal has not already

reached its maximum rate under less severe conditions. This maximum rate lay between 200 and 250 respirations/min. for the calves used in the present work.

It is desirable to use the results of these experiments to attempt to place the animals in order of heat tolerance, so that a comparison may be made with such an order provided by the measurements of the other physiological reactions which have been studied in the present work. Although the respiration rate of the calf AC/3 was comparatively high at 20°C. it rose much less than that of the other calves at higher environmental temperatures, and appeared to reach a limiting value above 220 respirations/min. only under conditions of extreme stress; also it decreased with time of exposure at all temperatures at low humidity. One has no hesitation therefore in placing AC/3 first in order of heat tolerance. Of the other two animals Table 8 shows that at and above 30°C. AC/4 had the highest respiration rate, but attained its daily maximum at an early hour whilst HC/1 exhibited a steady rise over a long period. It is therefore possible that although AC/4 was making greater use of respiration as a heat loss mechanism, thermoregulation in HC/1 was less efficient and responded to the stimulus evoked by the environmental temperature only when its heat balance was more greatly disturbed. The animals may therefore tentatively be placed in the order AC/3, AC/4, HC/1.

Summary and Conclusions

1. The respiration rates of four bull calves were measured under various controlled environmental temperatures and humidities and for different times of exposure to each thermal environment, involving a total of approximately 3500 measurements of respiration rate.

2. A comparison of the results obtained in 'long term' and in 'short term' experiments showed that as far as respiration rates were concerned a considerable period at each environmental temperature was required if the animal was to reach equilibrium with its environment. Any saving of time which might accompany the use of short term experiments would be greatly offset by the loss of accuracy in attaining a reliable result.

3. The respiratory behaviour varied considerably from calf to calf.

4. Under standardized conditions at an environmental temperature of 20°C. the mean respiration rates over 30 min. of three calves varied from 12 to 84/min.

5. The respiration rates of all four calves rose with increasing environmental temperature. At 20°C. the respiration rates of the three calves used in the long term experiments were 26 - 36, 52 - 70, and 78 - 108/min. respectively, rising to above 200/min. at 40°C.

6. The maximum rate of change of respiration rate with environmental temperature occurred between 25 and 35°C.

7. It was found impossible to fit any of the data from these experiments to a van't Hoff-Arrhenius equation in which the independent variable was environmental temperature.

8. An increase in humidity affected each calf differently. It caused a pronounced increase in the respiration rate of two of the calves at 35 and 40°C. but the other calf was scarcely affected at 35°C. and even exhibited a fall in respiration rate at the higher humidity at 40°C.

9. During individual experiments large variations in the respiration rate were found to occur, ranging from an increase or decrease of up to 100% within a few seconds, to a regular and reproducible overall variation during the day. It is suggested that measurements at 5 min. intervals are necessary to investigate fully a calf's respiratory behaviour, and that by so doing the overall duration of a series of experiments may be minimized. For the first two calves, the effect on the respiration rate of an increase in temperature of 5°C. was equivalent to the effect of an increase in absolute humidity of approximately 8 mg/l. at 35°C.

10. Time of exposure to any environment influenced respiration rate markedly, although the effect varied from calf to calf. Thus at 30°C. the respiration rate of one calf reached a plateau after exposure for 2 hr.; that of another rose to a maximum after 3 hr. and continued to fall to the end of the period of exposure; whilst that of the third continued to rise steadily

throughout the 6 hr. period.

11. Owing to the influence of time of exposure it was impossible to obtain from these experiments any mean respiration rate for a particular environment for any of the calves.

12. Panting was observed in all the animals, occasionally at 30°C. and almost continuously at the highest humidities at 35 and 40°C.

13. The large differences in respiratory behaviour between the calves point to either a large degree of difference in their heat tolerance (in which case they would be placed in the order AC/3, AC/4, HC/1 of decreasing heat tolerance), or else to varying degrees of importance of the respiratory functions as a heat loss mechanism. This is a subject which needs careful investigation before any attempt is made to utilize respiration rate as the basis of a heat tolerance test for individual calves.

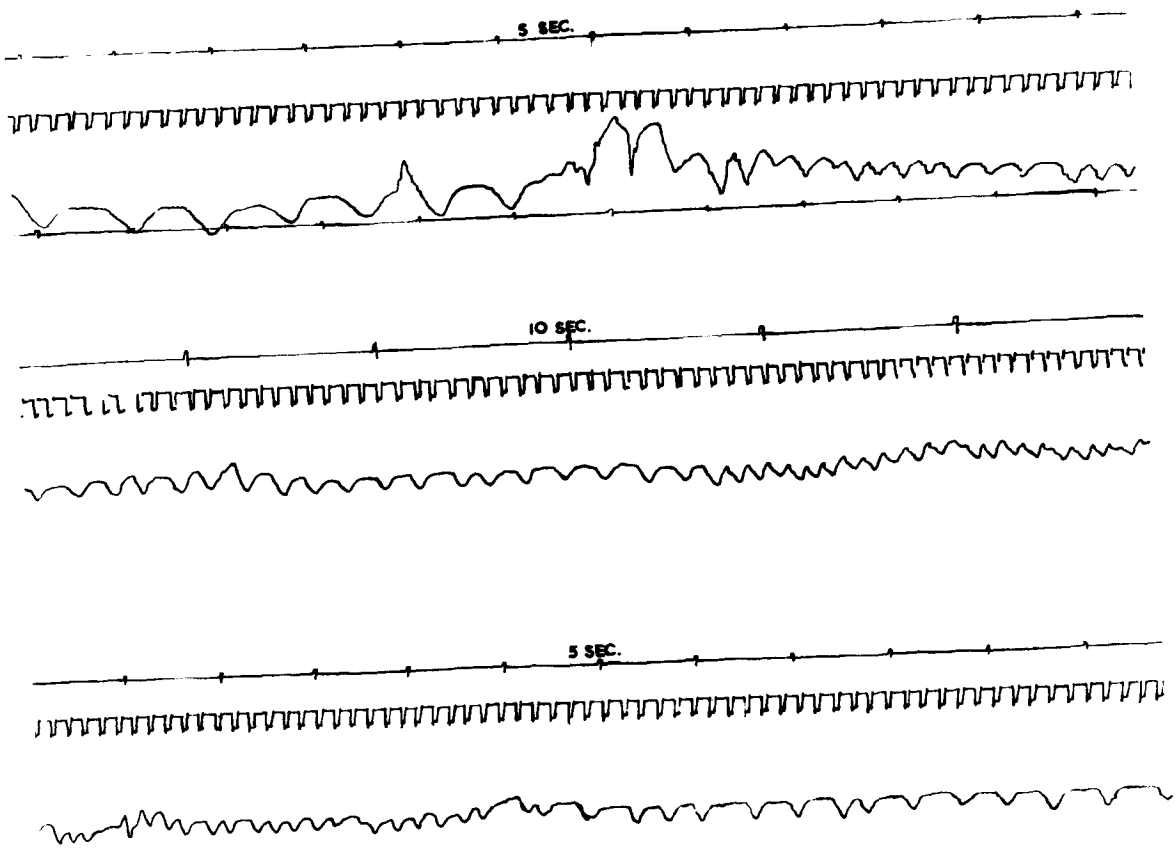


Plate 3. Reproductions of three original kymograph records showing sudden changes in the respiration rate. In each recording the top trace is the time marker, the second trace is the heart beat, and the bottom trace is the flank respiratory movement.

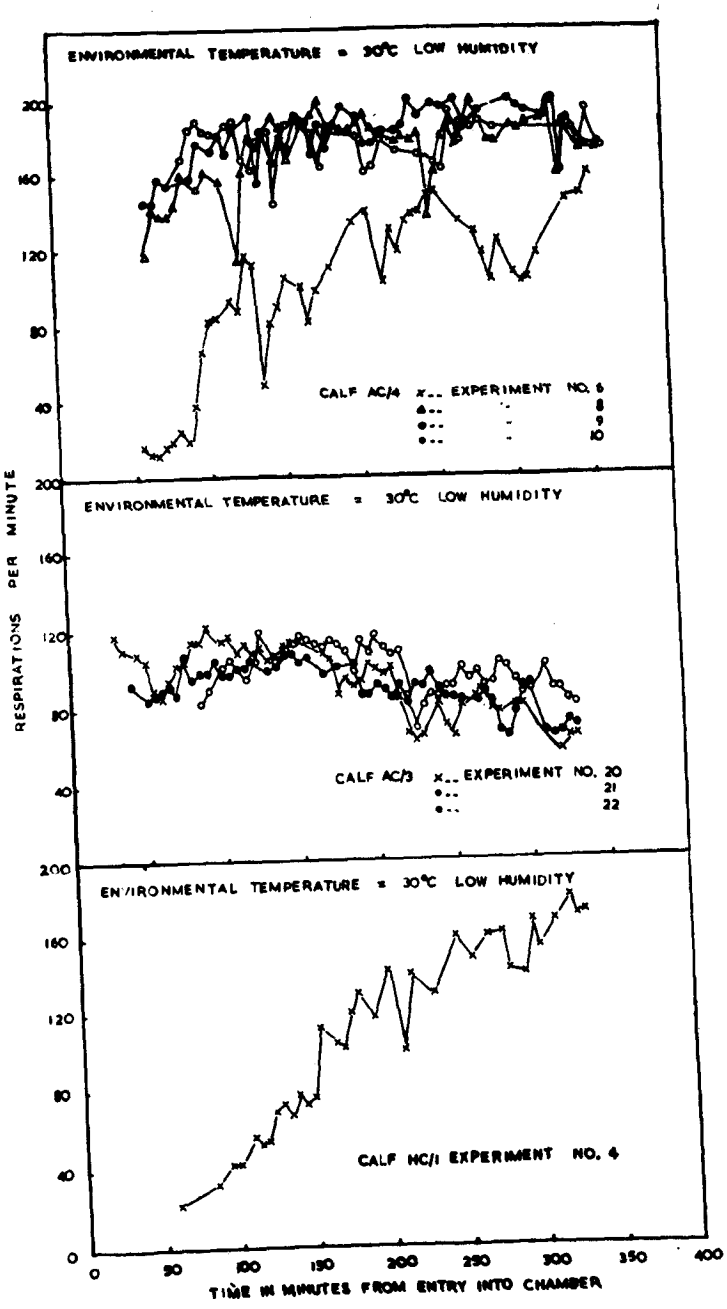


Fig. 2. The effect of time of exposure at an environmental temperature of 30°C. and low humidity on the respiration rate of two Ayrshire calves and one Highland calf. Replicate experiments are shown where these were performed. (Experiment 6 for AC/4 was not included in obtaining the averages recorded in Table 8.)

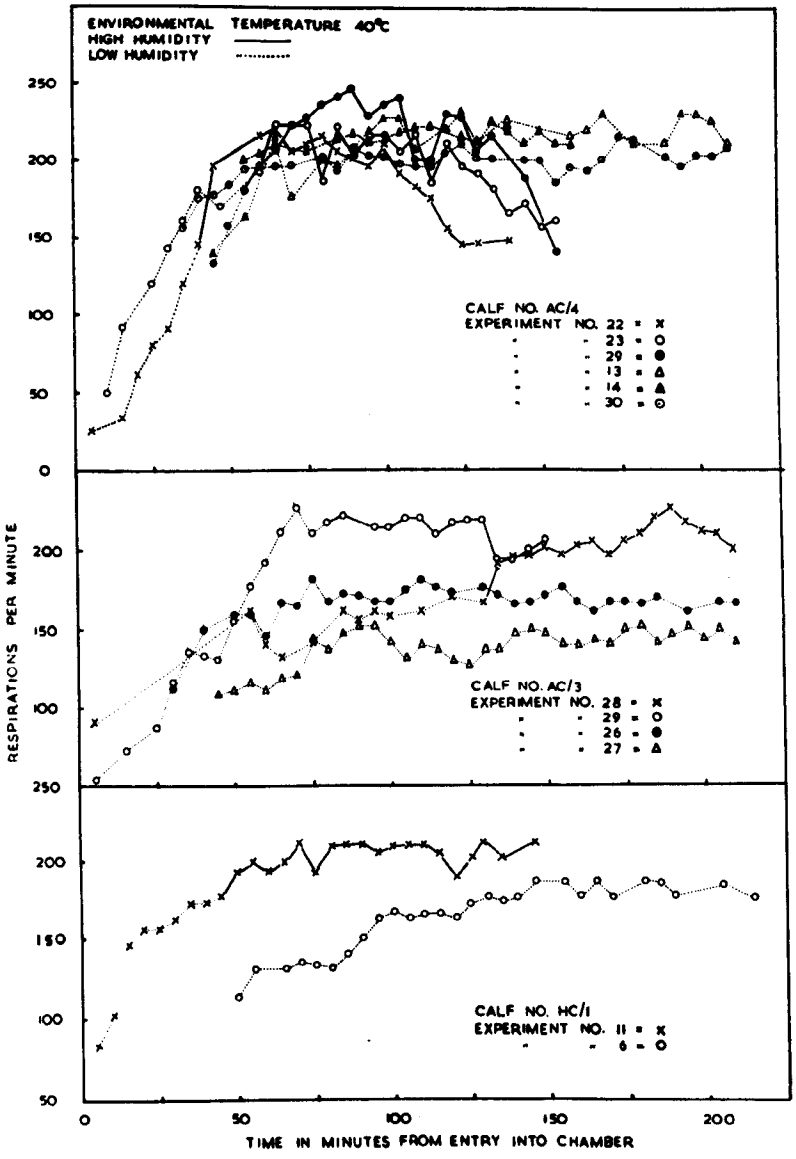


Fig. 3. The effect of time of exposure at an environmental temperature of 40°C. at high and low humidities on the respiration rate of two Ayrshire calves and one Highland calf. Replicate experiments are shown where these were made.

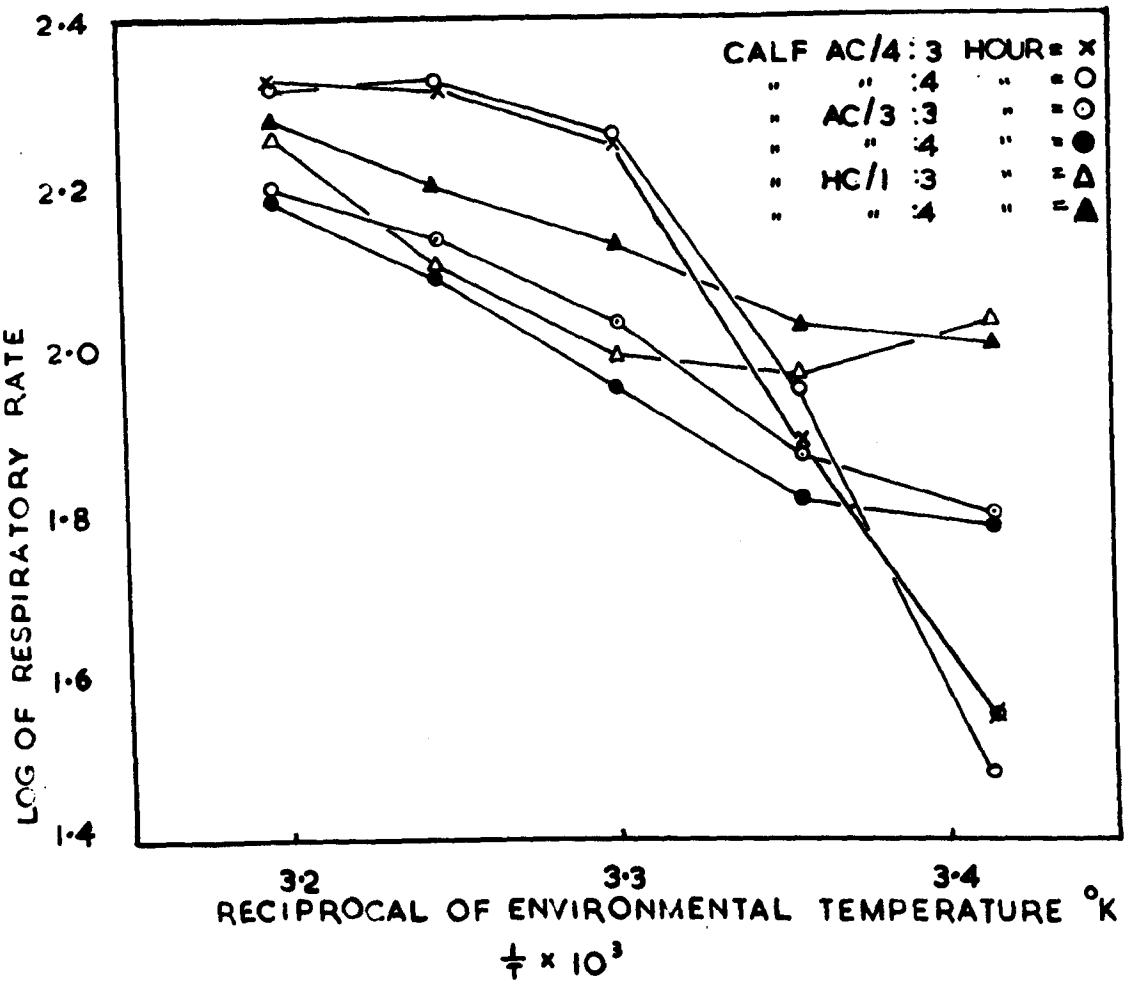


Fig. 4. The relationship between the logarithm of the respiration rate and the reciprocal of the Absolute Temperature of the environment for two Ayrshire calves and one Highland calf.

Table 6. The respiration rates of three calves on different days after approximately one hour's exposure to a thermal environment of 20°C. D.B.T., 17°C. W.B.T.

Calf	Respiration rate in respirations/min. on different days													Mean
AC/2	65	61	29	26	24	12	17	20						32
AC/3	84	69	77	54	40	31	35	33	24	47	77	71	70	55
AC/4	21	20	32	39	34	13	25	39						28

Table 7. The effect of short term exposures to thermal environments from 20 to 40°C. at low and high humidities on the respiration rate (respirations/min.) of three Ayrshire calves

Calf	Humidity	No. of days (n)	Environmental temperature (°C.)				
			20	25	30	35	40
AC/2	Low	3	18 ± 2	22 ± 2	43 ± 4	101 ± 15	151 ± 22
	High	3	53 ± 22	113 ± 22	159 ± 11	206 ± 4	216 ± 16
AC/3	Low	6	49 ± 16	66 ± 17	83 ± 15	94 ± 13	109 ± 7
	High	5	64 ± 16	82 ± 15	112 ± 17	141 ± 10	198 ± 9
AC/4	Low	2	20 ± 2	42 ± 16	90 ± 19	138 ± 7	183 ± 4
	High	2	31 ± 6	59 ± 35	122 ± 23	178 ± 12	215 ± 8

The entries in this table are the means and the standard deviations of the respiration rate over a number of days (n) during the time a calf was at the temperature given at the head of the column.

Table 8. The mean respiration rates of calves AC/4, AC/3 and HC/1 for different thermal environments and times of exposure

Calf	D.B.T. (°C.)	Humidity	Hour					
			1	2	3	4	5	6
			Respirations per minute					
AC/4	20	Low	26	35	36	30	27	26
	25	Low	30	69	77	89	85	80
	30#	Low	131	164	179	181	185	184
	30	High	112	153	173	180	176	170
	35	Low	139	191	207	210	207	204
	35	High	139	188	207	219	216	200
	40	Low	188	211	211	205	215	212
	40	High	134*	211*	170	-	-	-
AC/3	20	Low	57	70	63	60	52	51
	25	Low	79	81	75	66	57	53
	30	Low	95	102	106	90	84	72
	30	High	86	107	105	110	101	85
	35	Low	124	132	135	124	114	95
	35	High	137	167	182	184	183	190
	40	Low	129	155	156	153	140	130
	40	High	131*	189	215	-	-	-
HC/1	20	Low	-	78	108	102	93	85
	25	Low	21	70	94	107	106	101
	30	Low	-	52	98	134	158	169
	30	High	124	139	164	176	185	178
	35	Low	54	98	125	158	183	183
	35	High	155	199	211	202	-	-
	40	Low	122	152	181	190	204	-
	40	High	160*	207	-	-	-	-

Excluding the anomolous Expt. No.6.

* The humidity was low during the early part of each period of exposure under these environmental conditions, and for a different length of time for each. A more precise indication of the behaviour may be seen in Fig. 3.

Table 9. The analyses of variances, within hours, of the respiration rates of the three calves AC/4, AC/3, and HC/1, for a number of experiments taken at random from Tables 3, 4 and 5

Experiment no.	Source of variance	Degrees of freedom	Sum of squares	Mean square	Variance ratio
AC4/1	Total	37	4378		
	Within hr.	33	2421	75	6.5**
	Between hr.	4	1957	489	
AC4/5	Total	41	8213		
	Within hr.	37	6515	176	2.41 NS
	Between hr.	4	1698	425	
AC4/8	Total	50	18464		
	Within hr.	46	7132	155	18**
	Between hr.	4	11332	2833	
AC4/18	Total	50	12904		
	Within hr.	46	3703	80	30**
	Between hr.	4	9201	2300	
AC4/20	Total	53	27108		
	Within hr.	49	10137	200	21**
	Between hr.	4	16970	4200	
AC4/29	Total	20	21343		
	Within hr.	18	10102	550	10**
	Between hr.	2	11241	5600	
AC3/16	Total	55	5812		
	Within hr.	51	3376	66.2	9.2**
	Between hr.	4	2436	609	
AC3/19	Total	50	7513		
	Within hr.	46	1453	31.6	48**
	Between hr.	4	6060	1515	
AC3/24	Total	53	10877		
	Within hr.	49	4605	94.0	16.7**
	Between hr.	4	6272	1568	
HC1/4	Total	41	88479		
	Within hr.	37	9884	267	73.6**
	Between hr.	4	78595	19649	
HC1/9	Total	53	21757		
	Within hr.	48	2285	47.6	81.8**
	Between hr.	5	19472	3894	

**Significant for $P < 0.01$

Table 10. The effect of thermal environment and time of exposure on the respiration rate of calf AC/4*

D.B.T. °C.	Experiment no.	Low humidity conditions Hour no. 1	2	3	4	5	6	High humidity conditions Hour no 1	2	3	4	5	6	Experiment no.
20	1	-	40	49	38	32	31							
		-	3.7	3.0	2.6	2.8	2.9							
	3	16	20	20	16	16	14							
		-	2.2	2.1	0.5	0.5	0.3							
	24	37	46	39	36	34	32							
		3.6	2.9	0.9	1.8	2.4	2.2							
25	4	-	69	76	89	84	75							
		-	7.0	5.5	6.1	4.2	8.4							
	5	-	89	78	91	89	73							
		-	2.7	3.6	4.2	6.7	2.5							
	16	-	50	76	88	82	91							
		-	7.5	2.4	3.9	4.0	2.9							
	17	30	56	66	85	75	80							
		-	8.7	5.1	5.6	5.2	4.6							
30	6**	14	49	94	130	127	130							
		3.0	10.0	6.4	4.6	6.3	10.3							
	8	117	145	183	184	177	181	110	147	174	185	181	177	18
		-	4.8	3.5	1.2	5.6	4.2	-	3.9	3.1	1.5	2.9	2.1	
	9	145	167	178	187	195	191	114	159	172	174	170	164	19
		-	4.6	3.4	3.1	2.3	2.5	12.2	3.6	1.9	3.0	3.6	2.6	
	10	-	180	175	172	180	181							
		-	3.7	4.0	2.8	3.4	3.1							
35	11	137	203	225	229	216	217	-	170	203	223	207	187	20
		16.8	2.6	2.7	2.7	3.9	4.8	-	9.2	2.8	3.3	2.4	3.1	
	12	145	192	203	204	206	199	166	200	207	211	211	208	21
		7.2	2.2	1.7	3.7	2.0	3.6	8.5	2.3	2.1	2.2	1.3	2.2	
	31	136	175	194	197	198	195	111	193	210	219	229	203	32
		14.6	3.8	2.2	2.2	1.9	1.6	19.2	3.7	2.7	3.6	3.2	5.1	
40	13	152	209	221	223	216	-	108	198	139	-	-	-	22
		12.0	5.6	3.4	3.6	3.6	-	X22.2	5.4	-	-	-	-	
	14	199	215	215	-	-	-	135	210	173	-	-	-	23
		3.5	1.9	2.3	-	-	-	X16.2	13.3	5.9	-	-	-	
	15	222	220	204	188	0	-	167	226	196	-	-	-	29
		4.0	7.2	2.8	-	-	-	X13.8	4.7	15.6	-	-	-	
	30	180	199	203	204	214	212							
		5.6	1.5	3.1	2.8	1.5	2.3							

*The entries on this table are the means together with their standard errors of a number of observations made within each hour. The means are respirations per minute.

**This was an anomolous experiment. See remarks in the text.

XThis whole hour at low humidity.

Table 11. The effect of thermal environment and time of exposure on the respiration rate of calf AC/3*

D.B.T. °C.	Experiment no.	Low humidity conditions						High humidity conditions						Experiment no.
		Hour no.						Hour no.						
		1	2	3	4	5	6	1	2	3	4	5	6	
20	16	51 0.6	69 3.4	66 1.9	64 2.1	53 2.3	54 2.0							
	17	63 4.4	70 3.3	59 1.9	57 2.6	52 1.5	48 1.7							
25	18	78 1.8	87 1.7	84 1.4	75 2.6	64 1.4	64 1.9							
	19	85 2.1	74 1.5	65 1.3	57 1.9	51 1.4	47 2.2							
30	20	102 5.2	110 2.3	105 2.2	85 4.5	78 2.9	63 3.5							
	21	- -	96 3.4	111 1.4	97 4.5	94 1.5	88 2.7	86 5.3	107 1.6	105 1.8	110 1.5	101 3.3	85 2.7	23
	22	88 1.7	98 1.7	103 1.5	89 1.5	80 2.4	66 1.4							
35	24	124 1.7	132 1.0	135 1.9	124 2.3	114 3.0	95 3.7	137 7.6	167 3.8	182 2.3	183 1.6	183 2.2	190 2.1	25
40	26	145 8.8	173 1.8	168 1.3	159 3.3	150 5.7	137 5.7	136+ -	153+ 4.7+	218 7.3	- -	- -	- -	28
	27	113 1.9	138 3.0	143 2.0	146 1.2	131 3.4	123 4.4	127+ 19.6+	225 4.7	213 4.0	- -	- -	- -	29

* The entries on this table are the means together with their standard errors of a number of observations made within each hour. The means are respirations per minute.

+ The humidity was held low during these hours.

Table 12. The effect of thermal environment and time of exposure on the respiration rate of calf HC/1*

D.B.T. °C.	Experiment no.	Low humidity conditions Hour no. 1	2	3	4	5	6	High humidity conditions Hour no. 1	2	3	4	5	6	Experiment no.
20	2	-	78	95	92	92	94							
		-	7.3	3.1	2.9	3.2	2.2							
	7	-	-	121	110	95	76							
		-	-	2.1	3.9	2.7	1.6							
25	2	21	30	76	97	100	97							
		-	2.4	4.5	3.9	2.1	2.5							
	8	-	110	113	120	112	105							
		-	4.9	2.1	2.9	2.1	1.2							
30	4	-	52	98	134	158	169	124	139	164	176	185	178	9
		-	4.8	7.2	9.9	4.4	7.8	3.5	2.5	2.1	1.1	2.5	2.2	
35	5	54	98	125	158	183	183	155	199	211	202	-	-	10
		-	6.0	4.0	4.1	2.6	3.8	10.6	4.7	3.4	1.2	-	-	
40	6	122	152	181	190	204	-	160+	207	-	-	-	-	11
		8.0	4.3	1.8	3.9	2.0	-	10.3	2.3	-	-	-	-	

* The entries on this table are the means together with their standard errors of a number of observations made within each hour. The means are respirations per minute.

+ The humidity was low for part of this hour.

Table 13. Analysis of variance of the respiration rate of calf AC/4 in thermal environments of 20°C., 25°C., 30°C. and 35°C. at low humidity, 30°C. and 35°C. at high humidity; between the second and sixth hours of exposure

Influence	Humidity	Temperature °C.	Source of variance	Degrees of freedom	Vari-ance	Variance ratio	Signifi-cance
Temper-ature (T)	Low	20, 25,30, 35	Between T	3	99633	227	xxx
			D.L.R. T*	2	1723	3.92	NS
			Error	8	439		
	High	30,35	Between T	1	7562	42.4	xx
			Error	3	178		
Hours of exposure (H)	Low	20, 25,30, 35	Between H	4	298	4.04	xx
			D.L.R. H*	3	260	3.52	x
			Error	32	59.7		
	High	30,35	Between H	4	655	10.9	xx
			D.L.R. H.*	3	709	11.8	xx
			Error	16	60.0		
Temper-ature x Hour	Low	20, 25,30, 35	H x T	12	111	1.86	NS
			Error	32	59.7		
	High	30,35	H x T	4	24.8	0.33	NS
			Error	12	71.8		
Humidity (HU)	Both	30	Between HU	1	407	4.0	NS
			Error	3	102		
	Both	35	Between HU	1	31.0	0.055	
			Error	4	561		NS
Humidity x Hour	Both	30	H x HU	4	27.5	0.32	NS
			Error	12	85.3		
	Both	35	H x HU	4	59.5	1.23	NS
			Error	16	48.2		
Hour	Both	30	Between H	4	398	5.61	xx
			D.L.R. H*	3	223	3.15	NS
			Error	12	70.9		
	Both	35	Between H	4	586	11.6	xx
			D.L.R. H*	3	613	12.14	xx
			Error	16	48.2		

* D.L.R. = Deviations from linear regression.

x Significant $P < 0.05$
xx Significant $P < 0.01$
xxx Significant $P < 0.001$

Table 14. A comparison of the respiratory behaviour of calves AC/4, AC/3 and HC/1 as affected by environmental temperature, by humidity and by time of exposure in the long term experiments

Factor influencing respiration rate	Calf AC/4	Calf AC/3	Calf HC/1
Temperature	The respiration rate increased with temperature almost linearly from 20°C. to 35°C. but the increase fell off from 35°C. to 40°C.	The respiration rate increased with temperature but a maximum was not reached at 40°C.	The respiration rate increased with temperature but a maximum was not reached at 40°C.
Time of exposure	The respiration rate rose to a maximum in the fourth or fifth hour after which it was constant or fell very slowly until the sixth hour.	The respiration rate rose to a maximum in the third or fourth hour after which it fell away more steeply than that of AC/4.	At the lower temperatures the respiration rate reached a maximum in the third hour but at 30, 35 and 40°C. it continued to rise until after the sixth hour.
Humidity	Humidity had no effect on the respiration rate except at 40°C. high humidity where it caused a steep fall with time after the first hour.	Apparently respiration rate increased with humidity at 35 and 40°C.	The respiration rate apparently increased with humidity at 30, 35 and 40°C.
Interaction of temperature and time of exposure	There was no interaction between the effects of environmental temperature and time of exposure on the respiration rate.	There was no interaction between the effects of environmental temperature and time of exposure on the respiration rate.	Higher temperatures shifted the maximum respiration rate to a later hour.
Interaction of humidity and time of exposure	There was no interaction between the effects of humidity and time of exposure at environmental temperatures of 30°C. and 35°C., but at 40°C. humidity caused a fall in respiration rate after 1 hour.	At 30°C. there was no interaction between the effects of humidity and time of exposure, but at 35°C. and 40°C. the rate of increase of respiration rate with time was raised at all hours at high humidity.	No interaction between the effects of humidity and time of exposure on respiration rate could be detected.

Chapter 3

The Effect of Thermal Environment on the Heart Rate of Calves

Introduction

Very few measurements on the variations of the heart rates of bovines with environmental temperature have been made under controlled condition. The work of Rieck & Lee (1948) showed that environmental temperature had no effect on the heart rate of cows or calves, and that humidity affected the heart rate very slightly in cows but not in calves. Other authors (Regan & Richardson, 1938; Kibler & Brody, 1949; Kibler, Brody & Worstell, 1949) have reported slight decreases in heart rates at higher temperatures. Kibler & Brody point out that in their experiments the heart rate varied in approximately the same way as the heat production of the animals.

Bonsma & Pretorius (1943) in field experiments demonstrated that increases in environmental temperature were associated with decreases in heart rate; but when the heat load was excessive, particularly in strong sunlight, a rise occurred.

In the present studies, the heart rate has been measured in various thermal environments under conditions which preclude any disturbance of the animal by the observer. They were planned in such a way that any changes caused by time of exposure could also be measured.

Methods and Apparatus

In order not to disturb the animal whilst measuring its heart rate, and at the same time to obtain a permanent record, a method based on electrocardiography was used. Cardiac potentials of greatest magnitude, and also least disturbed by muscle potentials are obtained when one electrode (referred to later as the 'apex' electrode) is placed ventrally over the fifth intercostal space where the heart beat is most easily felt.

Three copper electrodes, each about 2 cm. in diameter, were attached to an elastic belt which could be fastened around the animal's thorax just behind the forelegs. The electrodes were spaced approximately 20 cm. apart, the outer two being connected via a screened cable to the input terminals of a balanced electronic amplifier, while the centre electrode was connected to earth at the amplifier. Small patches of hair were clipped from the animal, firstly at the contact point of the 'apex' electrode and then at two positions on the flank of the animal so that when the 'apex' electrode was in position, the other two were over their respective clipped patches. Good contact between the electrodes and the animal's skin was ensured by the application of a small amount of soft soap to the skin beneath the electrodes (Bell, Knox & Small, 1939). It was found that quite a large amount of 50 cycle mains interference was sometimes impressed upon the animal, but this was eliminated by providing an earthed metal gauze mat for the animal to stand on.

The electronic apparatus, which is described in full in Part II, Chapter 10, amplified the small signals from the heart, and caused the R wave to produce a short electrical impulse which actuated a marker pen writing on the kymograph (see Chapter 2 and Plate 3 which shows the trace of the heart impulses, respirations and time marker). Heart rate was counted from these traces in the same manner as described for the respiration rate. The apparatus was frequently monitored with an oscilloscope to ensure that the correct cardiac potentials were actuating the marker.

Results

Table 15 shows the great variations in the heart rates of three calves at an environmental temperature of 20°C. at the beginning of each short term experiment. Each entry in the table is the mean of approximately six measurements over 1 min. made at 5 min. intervals.

Table 16 summarizes the results obtained for the average heart rates of these calves at the standard temperatures and humidities in the short term experiments. None of the calves showed significant variation in heart rate with increasing environmental temperature at low humidity, but there was apparently an increase with temperature at high humidity in all the calves. Although the 'low' and 'high' humidity environmental conditions were in reality the same at 20°C., and also at 25°C., the calf AC/2 had greatly different heart rates under the low and high humidity conditions. It is therefore apparent that some external factor was

affecting the heart rate, and that the magnitude of the effect produced by this unknown factor was far greater than that of the thermal environment.

Table 17 summarizes the results obtained from the long term experiments on calves AC/3, AC/4 and HC/1, all replications under similar conditions being combined to give a mean value of the heart rate of each animal for each hour of exposure to each different thermal environment. Tables 18, 19 and 20 show these results in more detail, the hourly means and their standard errors being given for each replication; whilst Fig.5, which presents every measurement made at 30°C. at low humidity in the long term experiments shows still greater detail. The anomolous experiment No.6 on AC/4 has already been discussed (p.25) and except for its inclusion in Fig.5 and Table 18 it is otherwise ignored. The degree of scatter between consecutive points on the graphs of Fig.5 is large, but when smoothed, as for the hourly means in Tables 18,19 and 20, the replications were found to preserve a typical shape, which varied from animal to animal. As was found for respiration rate, time of exposure played a varying part in its effect on heart rate, and this effect was changed by environmental temperature and humidity. At lower temperatures the heart rate declined during the day, but increasing thermal stress gradually changed this decline to a rise for two of the calves, particularly during the earlier hours of the day. On the whole, the greatest and most consistent effect of temperature on the heart rate lay in altering this pattern of changes

in heart rate associated with time of exposure.

Changes in heart rate of an 'instantaneous' nature such as were observed for the respiration rate could not be found in the individual 1½ min. recordings of the heart rate. This, and the great scatter which occurred between the 5 min. readings, suggest that the changes occurred over a length of time which was long compared with 1 min. but short compared with 5 min.

A series of analyses of variances of the heart rates of the three calves AC/3, AC/4 and HC/1 is presented in Table 21, the same experiments as were used for a similar test on the respiration rates having been selected for this purpose. These show that in all but two of the experiments investigated the variance within hours were very much less than the variances between hours, and that an overall variation in heart rate throughout the day did in fact occur for all the calves.

It has previously been stated that in the experiments at 40°C. at high humidity, the humidity was not raised until some time after the calf's entry into the chamber. Tables 18, 19 and 20 do not take account of this, but Fig.6, in which the heart rates were plotted against the time elapsed from the animal's entry, clearly shows the behaviour of the heart rate under these conditions. In order better to illustrate the effect of humidity at this temperature, the curves for 40°C. at low humidity are included in the graphs. There is no doubt that an increase in humidity at 40°C. caused a great increase in heart rate, although in some instances a full half hour elapsed after raising the humidity before the heart rate began to be affected.

With AC/4, however, the effect was large and immediate.

Since the behaviour of the heart rate was quite consistent for each individual animal and yet varied so much between animals, Table 22 is given which summarizes the differences found in the long term experiments.

Discussion

In past work doubt has always arisen whether the presence of an observer caused variations in the heart rate by disturbing or exciting the animals. This factor has been completely eliminated in the present experiment, but even here very wide variations have been found. In the present experiments, by making a sufficiently large number of measurements during the course of a day, it has been found possible to observe a consistent pattern of variation hour by hour, which has been shown to vary with environmental temperature. This pattern varies much less than does the actual level of the heart rate and appears to be a more reliable indication of the strain created by the heat stress. Blaxter (1943) showed that the heart rates of cows rise during a meal and decline steadily after it and Ritzman & Benedict (1938) showed that the heart rates of steers depend on their plane of nutrition. Kibler & Brody (1949) have pointed out that the heart rates of their cows varied in approximately the same way as the cows' heat production when they were kept for approximately a week at each of a number of different environmental temperatures. It is possible then that the changes in heart rate observed in the present experiments were

related in part to changes in the assimilation and digestion of food during the day.

The present long term experiments indicated that the heart rates of two of the calves increased with environmental temperature, particularly between 25°C. and 30°C. and that under a large heat stress imposed by a high humidity at 40°C. the heart rates of all three rose very greatly. Bonsma & Pretorius (1943) in field experiments on cattle have demonstrated a rise in heart rate with increasing temperature and solar radiation, but an apparent fall in heart rate with increasing environmental temperature in the shade. This fall was, however, closely linked with the time of day and the present author believes it could be attributable to hourly variations similar to those encountered in the present experiments rather than to the increasing environmental temperature. Regan & Richardson (1938), Kibler & Brody (1949) and Kibler, Brody & Worstell (1949) found that lower heart rates were associated with increased environmental temperatures. However, their animals were subjected to continuous thermal stress for many days at a time, and the fall in heart rate was probably due to lowered food intake, and decreased production of milk and heat (all of which were observed) rather than to environmental temperature <u>per se</u>. The effect of increased environmental temperature on the daily pattern of variation in heart rate was least marked in AC/3. Even at 35°C. at high humidity and at 40°C. at low humidity the heart rate of this calf did not rise with time of exposure, although in the other

calves the rise was apparent at 30°C. Using this effect as a heat tolerance test it would appear that AC/3 was the most heat tolerant of the three calves in these long term experiments.

Summary and Conclusions

1. The heart rates of four bull calves have been measured at various environmental temperatures and humidities and for different times of exposure to each thermal environment, involving a total of approximately 3500 measurements of the heart rate.

2. A comparison of the results of long term and short term experiments showed that the latter type of experiment provided unreliable results.

3. The cardiac behaviour varied considerably from animal to animal.

4. Under standardized conditions at 20°C. the mean heart rates of three calves over 30 min. on different days ranged from 63 to 137 beats/min., with an average heart rate for the individual animals of 97, 86 and 75/min.

5. This inherent daily variation in heart rate was sufficient to render uncertain the interpretation of the results concerning the effect of temperature on heart rate in the long term experiments. However, taking into account the fair degree of replication obtained in the long term experiments it appears that the heart rate of two of the calves rose with increasing environmental temperature but that the heart rate of the third did not.

6. At 40°C. an increase in humidity caused a very large increase in the heart rates of all three animals.

7. Time of exposure influenced the heart rates of all three calves, although the effect varied from calf to calf. Generally, the heart rate tended to fall during the course of the day but the fall was considerably modified by environmental temperature, so that under higher stresses it gave place to a rise. It has been suggested that the effect of temperature on the daily pattern of heart rate may provide a better basis for assessing the thermal stress on a calf than does the effect of temperature on the average value of the heart rate.

8. Using this pattern as a guide, the calf AC/3 was found to be much more heat tolerant than the other two calves.

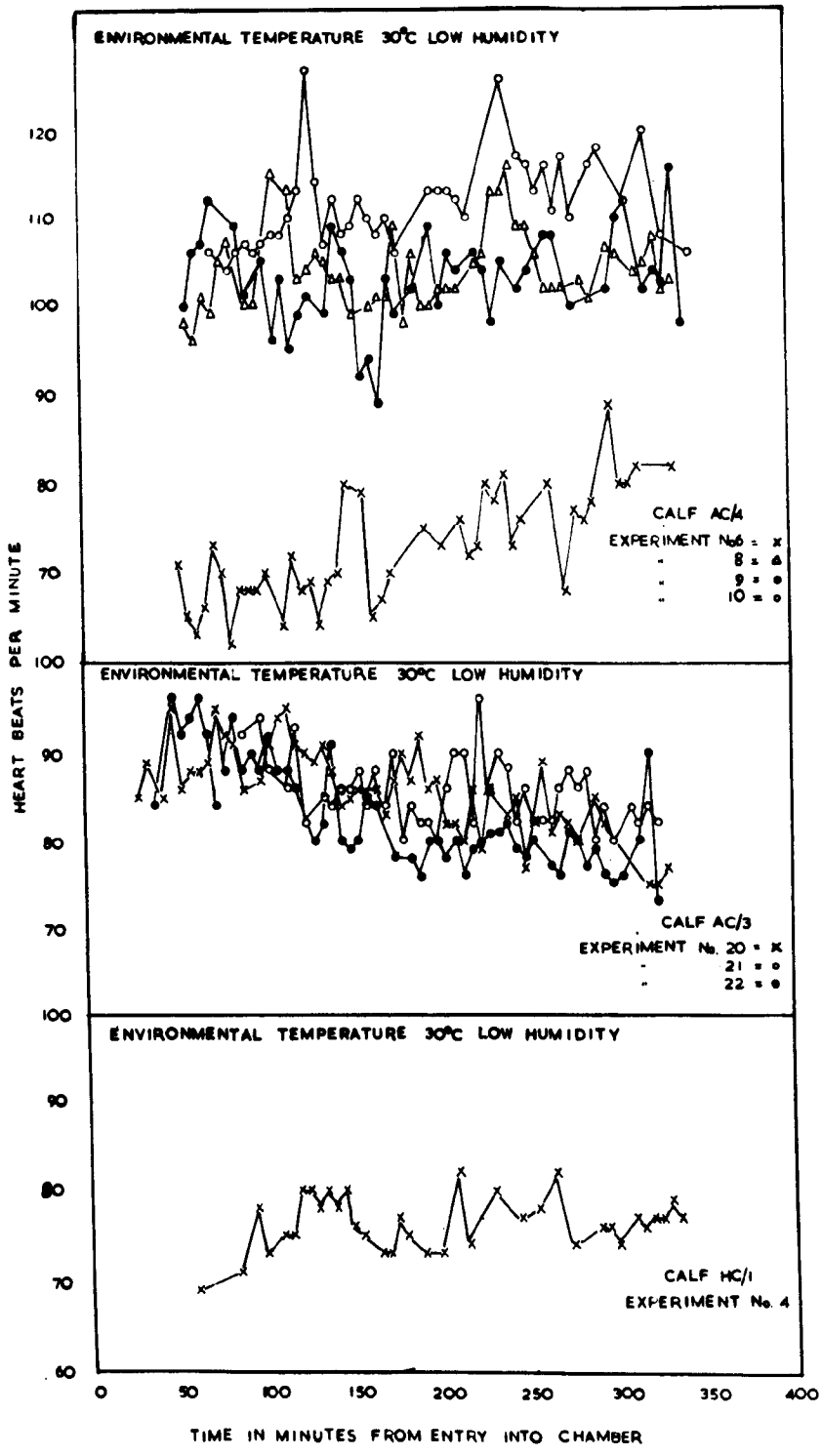


Fig. 5. The effect of time of exposure at an environmental temperature of 30°C. and low humidity on the heart rates of two Ayrshire calves and one Highland calf. Replicate experiments are shown where these were performed.

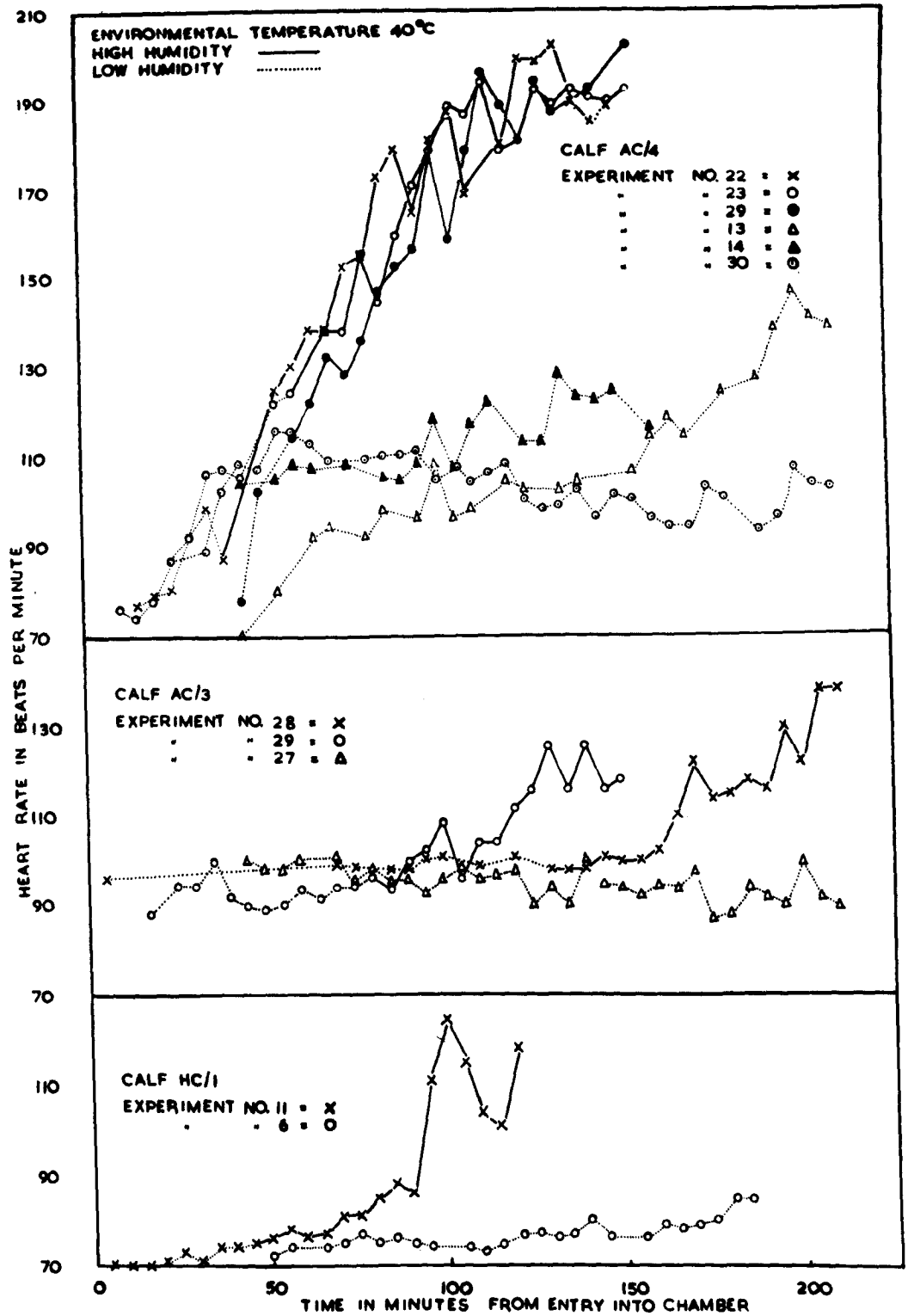


Fig. 6. The effect of time of exposure at an environmental temperature of 40°C. at high and low humidities on the heart rates of two Ayrshire calves and one Highland calf. Replicate experiments are shown where these were performed.

Table 15. The heart rates of three calves on different days after approximately one hour's exposure to a thermal environment of 20°C. D.B.T., 17°C. W.B.T.

Calf	Heart rate in beats/min. on different days															Mean
AC/2	72	90	90	97	105	100	72	68	120	113	137					97
AC/3	137	99	82	94	76	74	74	75	80	79	90	81	82	83	79	86
AC/4	84	63	90	67	78	68	73									75

Table 16. The effect of short term exposures to thermal environments from 20 to 40°C. at low and high humidities on the heart rate (beats/min.) of three Ayrshire calves

Calf	Humidity	No. of days (n)	Environmental temperature °C.				
			20	25	30	35	40
AC/2	Low	3	70 ± 3	68 ± 1	68 ± 4	71 ± 6	75 ± 6
	High	3	123 ± 12	127 ± 10	129 ± 11	134 ± 17	148 ± 23
AC/3	Low	6	91 ± 11	81 ± 9	79 ± 8	78 ± 7	80 ± 5
	High	5	81 ± 5	82 ± 6	83 ± 4	89 ± 7	100 ± 13
AC/4	Low	2	73 ± 11	71 ± 10	72 ± 11	72 ± 6	77 ± 9
	High	2	70 ± 4	69 ± 5	76 ± 6	85 ± 7	138 ± 15

The entries in this table are the means and the standard deviations of the heart rate over a number of days (n) during the time the calf was at the temperature given at the head of the column.

Table 17. The mean heart rates (heart beats/min.) of calves AC/4, AC/3 and HC/1 for different environments and times of exposure

Calf	D.B.T. (°C.)	Humidity	Hour no.					
			1	2	3	4	5	6
AC/4	20	Low	74	74	75	70	68	67
	25	Low	69	75	75	72	73	71
	30 +	Low	99	105	105	108	108	107
		High	73	81	79	80	80	78
	35	Low	93	104	104	106	102	97
		High	82	102	102	110	122	127
	40	Low	106	114	122	137	122	115
		High	98 *	162	190	-	-	-
AC/3	20	Low	81	82	77	75	75	74
	25	Low	78	76	74	70	69	67
	30	Low	90	91	85	83	81	78
		High	95	90	90	86	85	80
	35	Low	89	85	83	83	82	80
		High	97	97	96	98	96	95
	40	Low	99	97	93	92	93	90
		High	95 *	99 *	117	127	-	-
HC/1	20	Low	-	92	85	87	87	87
	25	Low	81	77	77	75	76	78
	30	Low	69	76	76	77	77	79
		High	68	70	69	71	72	74
	35	Low	65	71	74	78	79	81
		High	72	80	99	121	-	-
	40	Low	73	74	78	85	88	-
		High	73 *	98	-	-	-	-

+ Excluding the anomolous Experiment No.6.

* The humidity was low during the early part of each period of exposure to these environmental conditions for a different length of time for each.

Table 18. The effect of thermal environment and time of exposure on the heart rate of calf AC/4*

D.B.T. (°C.)	Experiment no.	Low humidity conditions						High humidity conditions						Experiment no.
		Hour no.						Hour no.						
		1	2	3	4	5	6	1	2	3	4	5	6	
20	1	-	84	90	80	80	79							
		-	1.6	1.6	1.7	2.1	1.6							
	3	64	62	64	62	60	58							
		-	0.4	1.2	1.0	9.7	0.8							
	24	85	76	70	68	64	64							
		3.6	0.8	1.1	1.7	0.9	0.8							
25	4	-	-	79	72	74	72							
		-	-	-	1.6	0.9	1.6							
	5	69	74	72	73	74	72							
		2.5	1.4	2.0	1.1	0.9	0.3							
	16	-	73	73	71	70	70							
		-	0.9	0.7	1.1	1.1	1.0							
30	6+	68	68	70	76	77	79							
		3.0	1.1	0.5	1.2	2.1	1.5							
	8	98	104	103	104	106	103	72	80	80	86	81	81	18
		-	2.18	0.9	1.6	1.5	0.9	-	1.7	0.5	1.4	1.0	1.1	
	9	100	104	99	104	104	106	75	82	79	74	80	76	19
		-	1.9	1.8	1.1	1.4	2.4	3.1	1.2	1.1	0.9	1.1	0.9	
	10	-	107	111	115	115	111							
		-	6.2	1.6	2.3	1.0	2.5							
35	11	98	111	113	116	104	108	78	108	106	119	138	151	20
		4.1	1.4	0.8	1.6	2.7	1.2	-	1.0	1.5	3.1	2.4	1.6	
	12	98	105	109	110	109	99	96	95	103	117	116	118	21
		2.5	1.3	1.0	1.4	1.0	1.3	0.7	0.6	1.2	1.6	2.1	2.0	
	31	83	96	90	93	95	86	72	101	97	93	111	111	32
		2.9	1.8	1.0	0.9	0.7	1.6	4.2	1.8	2.1	1.1	3.2	1.2	
40	13	75	96	111	135	126	-	95/	164	-	-	-	-	22
		5.0	2.1	3.3	2.2	3.0	-	6.7*	4.7	-	-	-	-	
	14	106	110	118	-	-	-	95/	166	190	-	-	-	23
		1.2	2.0	2.6	-	-	-	5.7*	6.2	1.7	-	-	-	
	15	139	142	161	177	-	-	104/	156	190	-	-	-	29
		2.1	3.1	3.7	8.5	-	-	9.6*	7.4	3.7	-	-	-	
	30	106	108	99	101	117	115							
		4.0	0.9	0.9	1.5	2.5	0.9							

*The entries in this table are the means, together with their standard errors of a number of observations as specified on p. 12. The means are beats/min.

+ Anomolous experiment (see text). / The humidity was low during these hours.

Table 19. The effect of thermal environment and time of exposure on the heart rate of calf AC/3*

D.B.T. (°C.)	Experiment no.	Low humidity conditions						High humidity conditions						Experiment no.
		Hour no.						Hour no.						
		1	2	3	4	5	6	1	2	3	4	5	6	
20	16	80 0.7	86 1.0	78 1.1	77 1.1	77 0.7	76 0.9							
	17	81 1.8	78 1.2	75 0.8	74 0.8	73 0.6	72 0.1							
25	18	78 1.2	78 1.2	76 1.1	72 1.0	71 0.7	69 0.7							
	19	78 0.7	73 0.5	71 1.6	68 0.7	68 1.2	68 1.2							
30	20	88 1.6	91 0.9	87 0.8	85 1.1	83 1.0	76 0.7							
	21	- -	91 1.4	85 0.9	86 1.4	84 0.8	82 0.9	95 1.1	90 1.0	90 0.8	86 1.2	85 1.9	80 1.0	23
	22	92 2.6	90 1.0	82 1.4	79 0.6	78 0.6	77 2.0							
35	24	89 1.9	86 0.7	83 1.2	83 0.7	82 0.6	80 0.6	97 0.7	97 1.2	96 1.3	98 1.5	96 1.3	95 1.5	25
40	26	Not measured						97+ -	99+ 0.4+	106 2.5	127 4.0	- -	- -	28
	27	99 0.6	97 0.6	93 1.1	92 1.0	93 1.2	90 1.0	92 0.3+	99 1.8	128 3.9	- -	- -	- -	29

* The entries in this table are the means, together with their standard errors, of a number of observations as specified on p. 12. The means are beats per minute.

+ The humidity was held low during this hour.

Table 20. The effect of thermal environment and time of exposure on the heart rate of calf HC/1*

D.B.T. (°C.)	Experiment no.	Low humidity conditions Hour no. 1	2	3	4	5	6	High humidity conditions Hour no. 1	2	3	4	5	6	Experiment no.
20	1	-	95	87	85	84	-							
		-	-	0.6	1.1	0.9	-							
	2	-	88	83	81	81	80							
			0,9	0.9	1.0	0.8	1.1							
	7	-	-	100	97	96	95							
		-	-	1.4	1.9	2.2	1.9							
25	3	81	82	82	79	80	81							
		-	1.0	0.8	0.5	0.8	1.0							
	8	-	72	71	72	71	74							
		-	0.7	0.9	0.6	0.5	0.8							
30	4	69	76	76	77	77	79	68	70	69	71	72	74	9
		-	1.2	0.9	1.7	0.9	0.6	0.9	0.8	0.5	0.7	0.4	0.7	
35	5	65	71	74	78	79	81	71	80	99	121	-	-	10
		-	0.3	0.6	0.7	0.6	0.6	0.8	1.3	3.4	7.6	-	-	
40	6	73	74	78	85	88	-	73+	98	-	-	-	-	11
		1.0	0.7	0.5	0.5	1.2	-	0.8	5.0	-	-	-	-	

* The entries in this table are the means, together with their standard errors, of a number of observations made within each hour. The means are beats per minute.

\+ The humidity was low for part of this hour.

Table 21. The analyses of variances, within hours, of the heart rates of the three calves AC/4, AC/3 and HC/1 for a number of experiments taken at random from Tables 3, 4 and 5

Experiment no.	Source of variance	Degrees of freedom	Sum of squares	Mean square	Variance ratio
AC4/1	Total	37	1528	-	
	Within hr.	33	799	24.2	148 xx
	Between hr.	4	14429	3607	
AC4/5	Total	44	775	-	
	Within hr.	39	696	17.8	1.12*NS
	Between hr.	5	79	16.0	
AC4/8	Total	48	1275	-	
	Within hr.	44	960	21.8	3.62 x
	Between hr.	4	315	79.0	
AC4/18	Total	50	945	-	
	Within hr.	46	742	16.1	3.16 x
	Between hr.	4	203	50.9	
AC4/20	Total	53	18796	-	
	Within hr.	49	2431	49.6	82.5 xx
	Between hr.	4	16365	4091	
AC4/29	Total	20	24818	-	
	Within hr.	18	8009	444	18.9 xx
	Between hr.	2	16809	8404	
AC3/16	Total	58	1355	-	
	Within hr.	53	565	10.7	14.8 xx
	Between hr.	5	790	158	
AC3/19	Total	51	1150	-	
	Within hr.	46	536	11.7	10.5 xx
	Between hr.	5	614	123	
AC3/24	Total	56	672	-	
	Within hr.	51	414	8.12	6.36 xx
	Between hr.	5	258	51.6	
HC1/4	Total	40	315	-	
	Within hr.	36	274	7.61	1.38 NS
	Between hr.	4	41.9	10.5	
HC1/9	Total	53	379	-	
	Within hr,	48	197	4.10	8.89 xx
	Between hr.	5	182	36.5	

xx Significant for $P < 0.01$ x Significant for $P < 0.05$

* The larger mean square is associated with the greater number of degrees of freedom.

Table 22. A comparison of the behaviour of the heart rates of calves AC/4, AC/3 and HC/1 as affected by environmental temperature, humidity and time of exposure

Factor influencing heart rate	Calf AC/4	Calf AC/3	Calf HC/1
Temperature	Heart rate increased with environmental temperature, particularly between 25° and 30°C.	Heart rate increased with environmental temperature, particularly between 25° and 30°C.	Heart rate possibly decreased with environmental temperature except at the later hours between 35°C. and 40°C. when it rose.
Time of exposure	Heart rate fell with time at the lowest environmental temperature; but at higher temperatures it rose to a maximum near the middle of the day and then fell. At the highest temperatures and humidity it rose rapidly with time.	Heart rate fell with time at all temperatures at low humidity. It was unaffected by time at 35°C. high humidity and rose with time at 40°C. high humidity.	Heart rate fell with time at the lower temperatures but rose with time at the higher temperatures in both high and low humidities.
Humidity	At 30°C.a rise in humidity apparently caused a fall in heart rate; at 35°C.a rise in humidity prolonged the rise and at 40°C.an increase in humidity caused a very large increase in heart rate.	At 30°C.a rise in humidity had very little effect, at 35°C.a fall with time gave place to a constant value at the higher humidity; at 40°C.a high humidity caused a large increase in heart rate.	At 30°C.a rise in humidity apparently caused a decrease in heart rate; at 35°C. and 40°C.an increase in humidity caused a marked increase in heart rate.
Interaction of temperature and time of exposure	A fall of heart rate with time at lower temperatures changed through constancy at intermediate temperatures to a rise followed by a fall during the day, at the higher temperatures.	There was no interaction apparent.	A heart rate constant throughout the day at low temperatures gave place to a steady rise with time at higher temperatures.
Interaction of humidity and time of exposure	At 30°C.there was no interaction; at 35°C. a higher humidity changed the decrease after the fourth hour to an increase; at 40°C. the rate of rise of heart rate was greatly increased by the higher humidity.	At 30°C.there was no interaction; at 35°C. a decrease in heart rate with time was changed by a rise in humidity to a constant value throughout the day. At 40°C.a fall in heart rate with time was converted to a rise with time at the higher humidity.	At 30°C.there was no interaction; at 35°C. the rate of increase of heart rate with time increased with humidity. At 40°C.the rate of rise with time increased slightly during the first hour and then there was a sudden large increase in the heart rate.

Chapter 4

The Effect of Thermal Environment on the Rectal Temperature of Calves

Introduction

For many purposes, for example in clinical studies, the terms rectal temperature and body temperature have been regarded as synonomous. The main reason for this is that the rectal temperature is the most constant of the more easily measured temperatures of the intact animal, and that changes in it reflect changes in the temperature of the deep core of the animal in which lie the principal organs and the main sources of heat production. It is shown in another chapter of this thesis (p.103) that the skin temperature of a calf is usually very different from its rectal temperature. Walther, Bishop & Warren (1941) have demonstrated large differences between internal temperatures at various points in calves. Hardy & Dubois (1938) have studied the distribution of heat storage between the 'body' and the skin, and the meaning of 'body' temperature has been discussed by Dubois (1948). In the experiments described here the rectal temperature has been measured, and following Hardy & Dubois, it has been taken as representative of the temperature of the body of the animal at a distance greater than 1 cm. beneath the surface of its skin.

The normal rectal temperature of homeothermic mammals lies within the range 36°C. to 40°C. different species having different normal rectal temperatures.

For each species there exists a neutral zone of environmental temperature within which the animal can maintain a normal rectal temperature by physical regulation of its heat loss. In a wide range of environmental temperatures below this zone body temperature is maintained by a rise in heat production of the animal, but above the neutral zone there normally exists only a small range before lethal environments are encountered (Brody, 1945).

Gaalaas (1945) has measured the rectal temperature of a large number of cattle in the field at environmental temperatures between 10°C. and 15°C. and obtained a mean value of 38.2°C. with standard deviation 0.3°C. and range 37.2°C. to 39.1°C. Brody (1945) gives almost exactly the same figure for the normal body temperatures of cattle indigenous to temperate regions.

A number of authors (Freeborn, Regan & Berry, 1934; Regan & Richardson, 1938; Rhoad, 1938; Gaalaas, 1945; Rieck & Lee, 1948; Kibler & Brody, 1950b) have measured the effect of environmental temperature on the rectal temperatures of cows or calves in psychrometric chambers or in the field. They have all demonstrated a rise in rectal temperature with environmental temperatures above about 25°C. and Rieck & Lee have demonstrated that humidity has an effect at 40°C. Rhoad (1944) has introduced an 'adaptability coefficient' which measures the adaptation of cattle to a high environmental temperature in terms of their rectal temperature. This has been slightly modified by Gaalaas

(1947) but the results refer to groups of animals rather than to individuals.

Not only does the body temperature vary from place to place within the animal, but the rectal temperature changes at different depths within the rectum. Kriss (1921) has shown that by varying the depth of insertion of the thermometer in the rectum from 10 to 18 cm. the indicated temperature changes from 38.1°C. to 38.7°C. It is thus necessary to standardize carefully the depth of insertion of any thermometer used in determining rectal temperatures.

In these experiments the rectal temperatures of the calves have been measured (1) with a view to investigating their variations, (2) as a partial measure of heat storage in these animals, and (3) as a basis of comparison for other physiological changes within the animals.

Methods

Rectal temperature was measured thermoelectrically with apparatus developed especially for these studies as described in Part II, Chapter 9. An overall accuracy of ± 0.1°C. on individual readings is claimed.

The stem of the thermometer consisted of a length of thick-walled polythene tubing, 7 mm. in diameter and 20 cm. long through which passed the thermocouple wire. Into one end was fixed a smooth copper dome which made good thermal contact with the walls of the rectum. The thermocouple wires were soldered to this copper dome. The polythene tubing had been permanently bent by heating so that after insertion into

the rectum to the standard depth of 15 cm. the outside end fitted neatly to the hollow between the animal's rump and its tail, to the root of which the thermometer was fastened with adhesive tape.

Usually the thermometer was expelled from the rectum by the act of defaecation which occurred two or three times during the course of the day. This was easily noticed and the thermometer replaced in good time to arrive at equilibrium before the next reading was made.

Results

Table 23 gives the mean rectal temperature of each of three calves over 30 min. on different days after exposure for 1 hr to an environmental temperature of 20°C. at the start of each short term experiment and in the 20°C. long term experiments. The averages of these daily means for the individual calves were 39.0, 38.4 and 38.0°C., and the range for all the calves was 37.5 - 39.7°C.

Table 24 summarizes the measurements of rectal temperatures of the same three calves for all the environmental conditions in the short term experiments. It is apparent from this table that the rectal temperature of each calf rose with environmental temperature between 20°C. and 40°C. and more noticeably above 30°C. environmental temperature; and that the rise was greater at high humidity than at low humidity.

Table 25 summarizes all the results from the long term experiments. The time of exposure of a calf to a particular environment is seen to have affected

the rectal temperature, particularly at the higher environmental temperatures, when the rectal temperature continued rising throughout the day. A comparison of these figures with those of Table 24 for the short term experiments showed that the latter gave values of rectal temperature much lower than those reached at the later hours of the long term experiments, presumably because of the short time of exposure to each thermal environment. Even in the long term experiments the rectal temperatures of the calves were still rising at the ends of the periods of exposure, and it appeared that some further time must elapse before the animals could approach equilibrium with their environment.

Tables 26, 27 & 28 present the hourly means and their standard errors of the rectal temperature in each replicate experiment under each environmental condition for each of the animals in the long term experiments. Fig.7 gives all the measurements of rectal temperature at 5 min. intervals at 30°C. at low humidity. The step-like appearance of these curves is due to the fact that measurements were read to the nearest 0.1°C. The comparitively large jumps which occurred were associated with defaecation; it was found that just prior to defaecation the rectal temperature fell slightly and afterwards often temporarily rose to a rather higher value. Experiment no.6 on AC/4 has been discussed earlier (p.25) and in view of the animal's abnormal behaviour in these respects this experiment has been ignored in assessing the effects of thermal environment on the calves, except for its inclusion in Fig.7 and Table 26. It may be

observed from the curves of Fig.7, and from Tables 26, 27 & 28, that although the level of the rectal temperature of a calf was different on different days at the same environmental temperature, the rate of change with time was similar for the different days, but that this rate of change was different for different calves.

The reactions of the calves to an environmental temperature of 40°C. at high humidity are not clearly illustrated in the tables since the humidity was not raised until a variable time after the animals' entries into the chamber, and so Fig.8 is given to show the calves' rectal temperatures in this environment. To show more clearly the effect of humidity the corresponding curves for 40°C. at low humidity are included in the graphs. The rate of rise of rectal temperature was immediately and greatly increased by the increase in humidity, as would be expected since evaporative loss was almost entirely eliminated at this high humidity.

Discussion

Both the short term and the long term experiments showed that the rectal temperature varied from day to day; further, the long term experiments showed a larger increase in the rectal temperature with time of exposure to a new thermal environment. It would therefore appear that the more realistic measure of the effect of thermal environment is the rate of change of rectal temperature with time, rather than the actual value of the rectal temperature. This rate of increase is in part a measure of the heat storage of the animal.

All the calves in the long term experiments showed the same general trends in rate of rise of rectal temperature, but each to a different degree (Tables 26, 27 & 28). Rate of rise of rectal temperature increased with environmental temperature, and also with humidity at 35°C. and 40°C. The threshold environmental temperature at which rectal temperature could definitely be said to start to rise with time varied from animal to animal. Calves AC/4 and HC/1 already exhibited an appreciable rise at an environmental temperature of 25°C; but for AC/3 the rectal temperature was practically constant at 30°C., except for a small rise at the end of the day. Similarly the rate of rise of rectal temperature with time at other environmental temperatures was least for AC/3 and greatest for HC/1.

The behaviour of the rectal temperature at an environmental temperature of 40°C. is of particular interest since at this temperature heat loss by radiation and convection are practically zero (p.93). At 40°C. at high humidity evaporative cooling is also practically eliminated and so the rate of rise of rectal temperature is a measure of the heat production of the calf. Fig.8 therefore provides an indication of the ratio of evaporative heat loss to heat production at 40°C. An estimate of this may be made on the basis of the following equation:

$$\text{\% of heat lost by evaporation at 40°C. low humidity} = \frac{\text{Heat production minus heat storage}}{\text{Heat production}}$$

where the heat production is proportional to the rate of rise of rectal temperature at 40°C. high humidity, and heat storage is proportional to the rate of rise of

rectal temperature at 40°C. low humidity. This gives the percentage of heat loss by evaporation of AC/3, AC/4 and HC/1 as 90%, 70% and 60% respectively.

In these experiments the rectal temperature never reached equilibrium at the higher environmental temperatures. Doubtless had the exposure to a particular environment been extended in time an equilibrium value would have been reached. It is probable, however, that at the highest temperatures this would be possible only by a decrease in the animal's heat production, which would conceal the effects of temperature on the physical heat-regulating system of the animal. Kibler & Brody (1950b) have demonstrated such a fall in heat production in cows which was associated with a voluntarily-reduced food intake.

Summary

1. The rectal temperatures of four bull calves have been measured under controlled environmental temperatures and humidities and for different times of exposure to each thermal environment, involving a total of approximately 3500 measurements of rectal temperature.

2. The short term experiments gave considerably lower values for rectal temperature than did the long term experiments at environmental temperatures of 30°C. and above.

3. The behaviour of the rectal temperature varied considerably from calf to calf.

4. Under standardized conditions at an environmental temperature of 20°C. the mean rectal temperature over

30 min. of three calves ranged from 37.5 to 39.7°C., the averages for the individual calves being 39.0, 38.4 and 38.0°C.

5. The rectal temperatures rose with increasing environmental temperature, although to a different degree for each animal.

6. At the higher environmental temperatures the rectal temperatures of all the calves were still rising at the end of the period of exposure, even in the long term experiments.

7. The rate of rise of rectal temperature with time was a better index of the calf's ability to withstand thermal stress than was the actual rectal temperature.

8. In two of the calves used in the long term experiments the rectal temperature increased with time of exposure even at 25°C., but for the other calf (AC/3) the rectal temperature was hardly affected at 30°C.

9. Increases in humidity at 35°C. and 40°C. increased the rate of rise of rectal temperature with time for all the calves.

10. It has been found possible to estimate the percentage of heat lost by evaporation at 40°C. This was 90%, 70% and 60% for calves AC/3, AC/4 and HC/1 respectively.

11. From a consideration of the effect of environmental temperature on the rate of increase of rectal temperature with time, and also of the calculated evaporative loss at 40°C., the animals may be placed in the order AC/3, AC/4, HC/1 of decreasing heat tolerance.

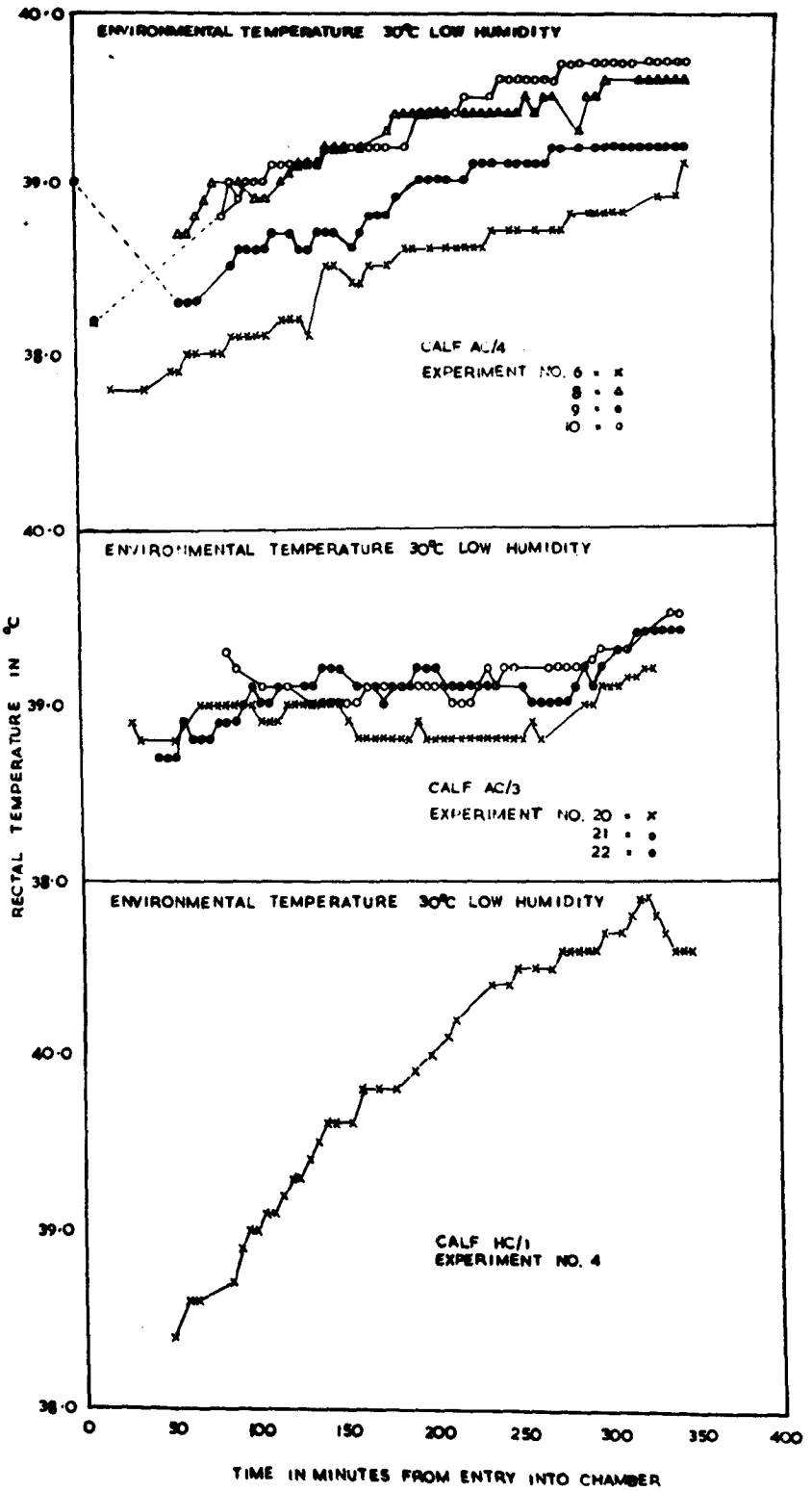


Fig.7. The effect of time of exposure at an environmental temperature of 30°C. and low humidity on the rectal temperature of two Ayrshire calves and one Highland calf. Replicate experiments are shown where these were performed.

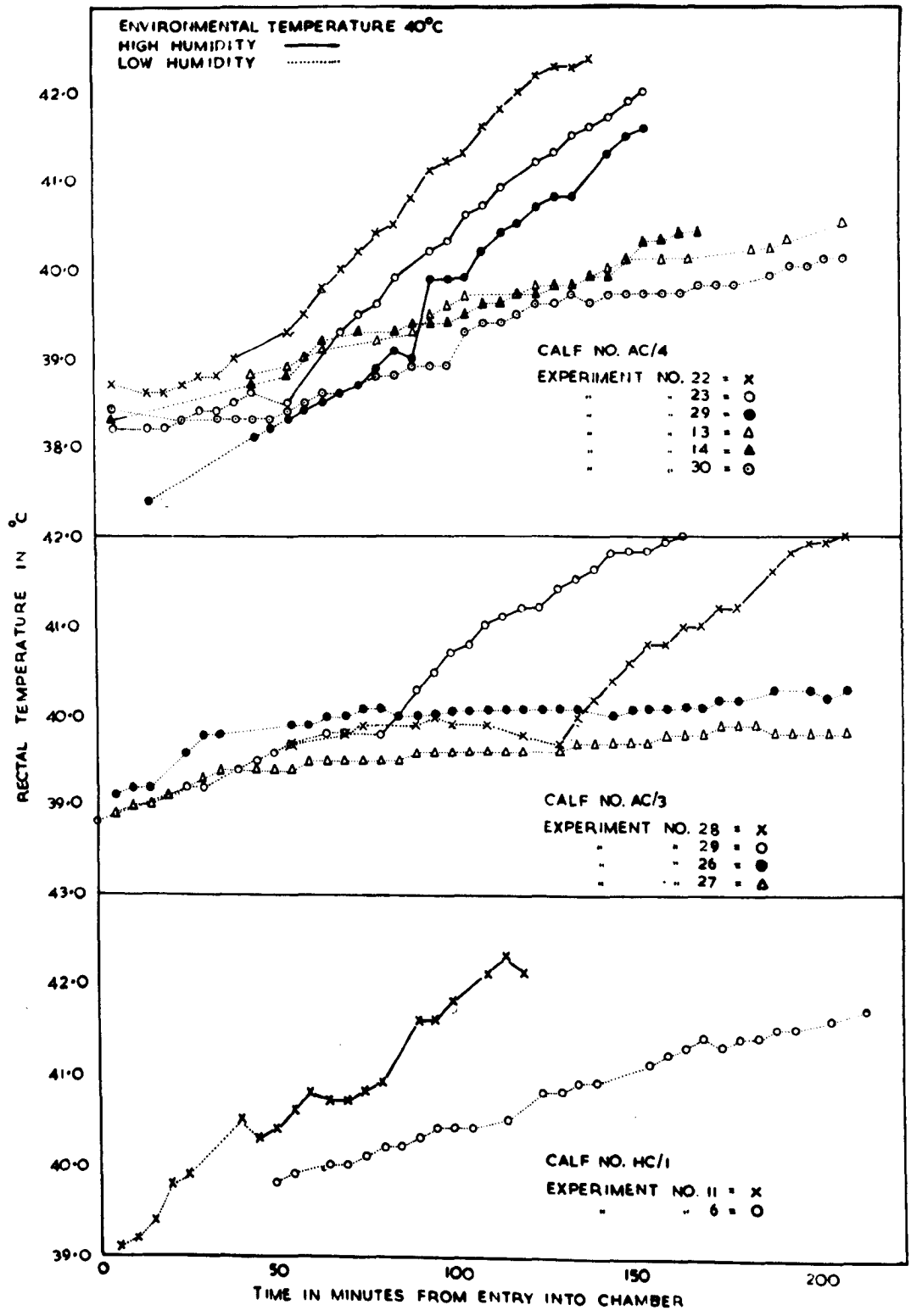


Fig. 8. The effect of time of exposure at an environmental temperature of 40°C. at high and low humidities on the rectal temperatures of two Ayrshire calves and one Highland calf. Replicate experiments are shown where these were performed. (Note that the time scale of these graphs is different from that of Fig.7.

Table 23. The rectal temperatures of three calves on different days after approximately one hour's exposure to a thermal environment of 20°C. D.B.T., 17°C. W.B.T.

Calf	Rectal temperature on different days (°C.)															Mean
AC/2	38.8	39.0	39.7	39.1	38.9	38.7	39.2	39.3	38.7	38.9	39.1	39.3	38.5	38.5		39.0
AC/3	38.9	38.9	38.6	38.5	38.7	38.3	38.2	38.0	38.4	37.8	38.6	38.3	38.3	38.4	38.3	38.4
AC/4	39.0	37.7	38.2	37.9	38.1	37.8	37.5	37.8								38.0

Table 24. The effect of short term exposures to thermal environments from 20 to 40°C. at low and high humidities on the rectal temperature (°C.) of three Ayrshire calves

Calf	Humidity	No. of days (n)	Environmental temperature (°C.)				
			20	25	30	35	40
AC/2	Low	3	38.9±0.3	38.9±0.4	38.9±0.3	39.2±0.4	39.6±0.4
	High	3	38.8±0.5	38.9±0.3	39.2±0.3	39.6±0.1	40.7±0.2
AC/3	Low	6	38.4±0.4	38.5±0.4	38.6±0.4	38.8±0.3	39.4±0.2
	High	5	38.3±0.2	38.3±0.2	38.7±0.2	39.3±0.4	40.6±0.4
AC/4	Low	2	37.9±0.0	37.9±0.1	38.3±0.1	38.6±0.1	39.5±0.1
	High	2	37.6±0.2	37.6±0.0	38.1±0.2	38.6±0.2	39.7±0.2

The entries in this table are the means and the standard deviations of the rectal temperatures over a number of days (n), during the time the calf was at the environmental temperature given at the head of the column.

Table 25. The mean rectal temperature (in °C.) of calves AC/4, AC/3 and HC/1 for different thermal environments and times of exposure

Calf	D.B.T. (°C.)	Humidity	Hour no. 1	2	3	4	5	6
AC/4	20	Low	37.8	38.2	38.1	37.9	38.2	38.2
	25	Low	38.1	37.9	38.0	38.2	38.4	38.6
	30	Low≠	37.9	38.8	39.0	39.3	39.4	39.5
		High	38.2	38.4	38.7	38.9	39.0	39.2
	35	Low	38.3	38.7	39.1	39.4	39.6	39.8
		High	38.1	38.7	39.4	40.3	40.7	41.2
	40	Low	38.6	39.5	40.3	40.9	40.7	40.9
		High	38.4*	40.1	41.8	-	-	-
AC/3	20	Low	38.3	38.4	38.4	38.5	38.7	38.3
	25	Low	38.5	38.4	38.4	38.3	38.5	38.6
	30	Low	38.8	39.0	39.0	39.0	39.1	39.3
		High	38.9	39.0	39.2	39.4	39.3	39.4
	35	Low	39.4	39.5	39.5	39.4	39.6	39.8
		High	39.5	40.0	40.4	40.6	40.9	41.2
	40	Low	39.4	39.8	39.9	40.1	40.1	40.3
		High	39.5*	40.0*	41.2	41.7	-	-
HC/1	20	Low	-	39.2	39.6	39.4	39.5	39.5
	25	Low	-	39.6	39.8	40.0	40.1	40.2
	30	Low	-	38.9	39.6	40.1	40.6	40.7
		High	39.2	39.5	40.2	40.7	41.0	41.2
	35	Low	-	39.6	40.3	40.9	41.1	41.2
		High	39.5	40.8	41.5	-	-	-
	40	Low	39.9	40.3	41.1	41.7	41.9	-
		High	39.8*	41.6	-	-	-	-

≠ Excluding the anomolous Experiment No.6.

* The humidity was low during the early part of each period of exposure under these environmental conditions, and for a different length of time for each. A more precise indication of the behaviour may be seen in Fig.8.

Table 26. The effect of thermal environment and time of exposure on the rectal temperature of calf AC/4*

D.B.T. (°C.)	Experiment no.	Low humidity conditions Hour no. 1	2	3	4	5	6	High humidity conditions Hour no. 1	2	3	4	5	6	Experiment no.
20	1	-	38.96	38.69	38.60	38.65	38.54							
		-	0.05	0.02	0.00	0.03	0.01							
	3	-	38.03	38.00	38.07	38.03	38.00							
		-	0.02	0.01	0.03	0.01	0.00							
	24	37.82	37.65	37.66	37.70	37.78	37.96							
		0.15	0.02	0.02	0.00	0.02	0.02							
25	4	-	38.53	38.49	38.40	38.41	38.58							
		-	0.05	0.01	0.02	0.02	0.05							
	5	38.13	38.14	38.29	38.47	38.53	38.59							
		0.03	0.05	0.05	0.05	0.02	0.03							
	16	-	37.40	37.42	37.86	38.18	38.45							
		-	0.00	0.02	0.07	0.02	0.05							
	17	-	37.79	38.05	38.21	38.32	38.61							
		-	0.12	0.06	0.01	0.03	0.03							
30	6●	37.85	38.07	38.40	38.61	38.74	38.88							
		0.03	0.02	0.05	0.01	0.02	0.15							
	8	-	38.91	39.17	39.40	39.44	39.62	38.07	38.28	38.56	38.90	38.97	39.19	18
		-	0.03	0.02	0.00	0.02	0.01	0.13	0.02	0.03	0.08	0.01	0.04	
	9	-	38.53	38.70	39.02	39.14	39.20	38.43	38.56	38.76	38.88	39.11	39.20	19
		-	0.05	0.02	0.02	0.02	0.00	0.05	0.02	0.03	0.02	0.02	0.00	
	10	-	38.99	39.17	39.40	39.64	39.71							
		-	0.04	0.02	0.03	0.01	0.10							
35	11	38.55	39.09	39.63	40.04	40.15	40.24	-	38.46	39.37	40.24	40.87	41.38	20
		0.04	0.05	0.04	0.03	0.02	0.02	-	0.11	0.07	0.06	0.05	0.05	
	12	38.57	38.71	39.16	39.46	39.74	39.92	38.55	39.29	39.94	40.74	41.03	41.47	21
		0.03	0.03	0.04	0.03	0.02	0.02	0.10	0.10	0.03	0.04	0.03	0.05	
	31	37.80	38.20	38.59	38.82	38.98	39.24	37.66	38.37	38.96	39.85	40.33	40.78	32
		0.03	0.06	0.08	0.03	0.02	0.03	0.07	0.06	0.06	0.06	0.04	0.05	
40	13	38.85	39.44	39.95	40.47	40.91	-							
		0.06	0.09	0.05	0.06	0.03	-							
	14	38.70	39.41	40.06	-	-	-	38.89+	40.89	42.25	-	-	-	22
		0.15	0.04	0.09	-	-	-	0.11+	0.21	0.04	-	-	-	
	15	-	40.24	40.94	41.68	-	-	38.35+	40.10	41.76	-	-	-	23
		-	0.10	0.05	0.08	-	-	0.05+	0.17	0.11	-	-	-	
	30	38.35	39.01	39.70	40.06	40.43	40.87	38.08+	39.52	41.35	-	-	-	29
		0.03	0.10	0.02	0.02	0.05	0.04	0.18+	0.23	0.04	-	-	-	

● This was an anomolous experiment. See remarks in text (p. 25).

+The humidity was low during this hour.

*The entries on this table are the means together with their standard errors of a number of observations made within each hour as specified on p. 12. The means are °C. rectal temperature.

Table 27. The effect of thermal environment and time of exposure on the rectal temperature of calf AC/3*

D.B.T. (°C.)	Experiment no.	Low humidity conditions						High humidity conditions						Experiment no.
		Hour no. 1	2	3	4	5	6	1	2	3	4	5	6	
20	16	38.27 0.01	38.52 0.02	38.56 0.00	38.54 0.02	38.74 0.00	38.80 0.00							
	17	38.37 0.03	38.23 0.02	38.29 0.02	38.40 0.01	38.48 0.03	38.60 0.00							
25	18	38.58 0.02	38.45 0.02	38.39 0.01	38.38 0.01	38.55 0.03	38.62 0.02							
	19	38.50 0.00	38.40 0.03	38.42 0.01	38.30 0.00	38.40 0.01	38.60 0.00							
30	20	38.83 0.03	38.97 0.01	38.91 0.03	38.81 0.01	38.90 0.00	39.15 0.01							
	21	- -	39.16 0.04	39.05 0.02	39.08 0.02	39.22 0.02	39.40 0.03	38.85 0.03	38.97 0.01	39.17 0.01	39.38 0.03	39.33 0.04	39.38 0.02	23
	22	38.75 0.01	38.94 0.00	39.12 0.02	39.13 0.01	39.07 0.03	39.40 0.00							
35	24	39.40 0.00	39.46 0.02	39.45 0.01	39.43 0.01	39.58 0.01	39.78 0.00	39.45 0.05	40.00 0.05	40.38 0.04	40.63 0.03	40.94 0.03	41.17 0.02	25
40	26	39.56 0.12	40.06 0.01	40.08 0.02	40.28 0.01	40.38 0.02	40.60 0.03	39.45 0.08+	39.89 0.02+	40.63 0.15	41.85 0.07	- -	- -	28
	27	39.24 0.06	39.56 0.02	39.75 0.03	39.83 0.01	39.82 0.01	40.07 0.00	39.56 0.08+	40.94 0.14	41.86 0.04	- -	- -	- -	29

* The entries on this table are the means together with their standard errors of a number of observations made within each hour as specified on p.12 . The means are °C. rectal temperature.

+ The humidity was held low during this hour.

Table 28. The effect of thermal environment and time of exposure on the rectal temperature of calf HC/1*

D.B.T. (°C.)	Experiment no.	Low humidity conditions. Hour no. 1	2	3	4	5	6	High humidity conditions. Hour no. 1	2	3	4	5	6	Experiment no.
20	1	-	-	39.89	39.63	39.45	-							
		-	-	0.07	0.06	0.03	-							
	2	-	39.23	39.60	39.55	39.72	39.83							
		-	0.09	0.05	0.05	0.02	0.02							
	7	-	-	39.22	39.12	39.19	39.26							
		-	-	0.01	0.01	0.01	0.02							
25	3	-	39.70	39.93	40.24	40.21	40.13							
		-	0.04	0.01	0.02	0.02	0.02							
	8	-	39.50	39.72	39.83	40.05	40.23							
		-	0.06	0.01	0.02	0.03	0.03							
30	4	-	38.99	39.60	40.12	40.57	40.73	39.23	39.50	40.24	40.70	41.00	41.15	9
		-	0.08	0.06	0.09	0.03	0.04	0.03	0.07	0.04	0.08	0.03	0.03	
35	5	-	39.56	40.25	40.85	41.14	41.20	39.53	40.76	41.50	-	-	-	10
		-	0.03	0.07	0.06	0.03	0.03	0.17	0.10	0.07	-	-	-	
40	6	39.85	40.25	41.12	41.70	41.92	-	39.76	41.62	-	-	-	-	11
		0.16	0.06	0.08	0.05	0.20	-	0.18+	0.18	-	-	-	-	

* The entries on this table are the means together with their standard errors of a number of observations made within each hour as specified on p. 12. The means are °C. rectal temperature.

\+ The humidity was low for part of this hour.

Chapter 5

The Effect of Thermal Environment on the Skin Temperature of Calves

Introduction

The surface of the skin forms a boundary between an animal and its environment. Under the surface and separated from it by the epidermis, lies a region very richly supplied with blood capillaries; below this region is the corium approximately 5 mm. thick and relatively poorly supplied with capillaries (Yang, 1948). Still deeper are layers of subcutaneous fat and muscle of low thermal conductivity; Hardy & Soderstrom (1939) give values of 0.00049 and 0.00047 cal./cm. sec.°C. respectively for dead beef fat and muscle. It is highly probable that this system forms an efficient means of control of the amount of heat which may be brought to the surface for disposal.

The outer surface of the skin of the bovine is almost entirely covered with hair, the length and character of which varies from breed to breed, and also from season to season for the same animal. One of the functions of the hair is to provide a 'local climate' for the skin surface. In cold weather the air trapped and held stationary by the hair forms a cover of very good insulation for the animal. This may be less of an advantage in hot environments where heat loss and not heat conservation is the all-important factor, although the insulating properties of the coat may be modified by arrectores pilorum muscles. Another purpose served by the coat may be to reflect radiation; the heat load imposed by

solar radiation being often in the tropics much greater than the total heat production of the animal (Riemerschmidt, 1943). Several workers (Rhoad, 1940a; Bonsma & Pretorius, 1943; and Riemerschmidt & Elder, 1945) have measured the absorption of solar radiation by the coats of different breeds of cattle. Riemerschmidt & Elder (whose methods are believed to be the most reliable) have demonstrated large differences in absorption of solar radiation ranging from approximately 50% for white tropical cattle to 90% for black temperate cattle.

The evaporation of water from the surface of a body results in a large loss of heat from it, due to the large latent heat of vaporization of water. Several authors have investigated the evaporative loss from the skin of cattle, but doubts must exist as to the accuracy of their findings. The methods used may be divided into three categories:- (a) detection of sweating by analysing skin and hair washings for chlorides (Freeborn, Regan & Berry, 1934 and Regan & Richardson, 1938); (b) absorption with calcium chloride of the moisture in a small container placed over a small portion of the skin (Freeborn, Regan & Berry, 1934; Regan & Richardson, 1938; Rhoad, 1940b); (c) determinations by classical methods of insensible weight losses corrected for respiratory and other losses (Rieck & Lee, 1948; Kibler & Brody, 1950a). All of these authors have reported considerable skin evaporative losses which may amount to as much as 60% to 70% of the total heat production at environmental temperatures above 35°C. (Kibler & Brody, 1950a), but none of the normal solid constituents of sweat have been observed on the skin.

Various authors (e.g. Yang, 1948; Findlay & Yang, 1950) have described glands in the skin of cattle to which no function can be ascribed but which have tentatively been named 'sweat glands'. The secreting area per unit area of skin of these glands is about five times greater than that of human sweat glands. The general consensus of opinion concerning evaporative heat loss from the skin of cattle is that it is a factor of great importance, but that the moisture is derived from water diffusing through the skin rather than from actively secreting sweat glands.

No record can be traced at the time of writing of any measurements of the effect of thermal environment on the skin temperature of cattle under controlled conditions in psychrometric chambers. In the field Bonsma (1940) and Quin & Riemerschmidt (1941) have shown that cattle skin temperatures are higher in the sun than in the shade. The latter authors have also stated that an increase of 1°F. (0.56°C.) in air temperature caused an increase in skin temperature of 0.28°F. (0,16°C.) in the sun and 0.31°F. (0.17°C.) in the shade, and that a rise of 1°F. (0.56°C.) in rectal temperature was associated with an increase of 2.01°F. (1.17°C.) in the sun and 2.60°F. (1.44°C.) in the shade.

In the present work the temperatures of a number of different regions of the skins of four calves have been measured in standard thermal environments.

Methods

Skin temperatures were measured thermoelectrically, the tips of 40 S.W.G. copper constantan thermocouples being attached to the skin at the base of the hairs by a small pellet of rubber latex. The wires passed along the surface of the skin for 5 - 10 cm. before leaving the vicinity of the animal's coat, so minimising heat conduction along the wire. The equipment for the measurement of temperature is described in Part II, Chapter 9. Skin temperatures were measured at eleven places on each calf. Fig. 9 shows the approximate position of each place on the animal and defines the abbreviations used in describing them. The term 'Mean Trunk Temperature' as used below, is the mean of the eight readings obtained in each 5 min. period of exposure from the regions FFR, HFR, BT, BS, FFL, HFL, BR, UD.

Results

Table 29 shows the variations in the mean trunk temperature averaged over 30 min. of each of three calves after 1 hr exposure to an environmental temperature of 20°C. on different days. These temperatures ranged from 31.5 to 36.0°C. with mean values of 33.7, 33.7 and 34.6°C. for the individual calves.

Table 30 gives the average of all measurements of the mean trunk temperature on each calf at each standard environmental condition in the short term experiments. These experiments showed that the mean trunk temperature increased with environmental temperature, the increase being greater at high humidity than at low humidity.

Table 31 summarizes all the measurements of mean trunk temperature made in the long term experiments. It has been found necessary to include in this table time of exposure as a variable, since the skin temperature changed greatly with time. As was found in the short term experiments, the mean trunk temperatures increased with environmental temperature and humidity, although at the later hours the long term experiments gave higher skin temperatures than did the short term experiments.

In Tables 32, 33 and 34 are given the hourly means of the mean trunk temperature for each replicate experiment performed in the long term series of experiments. The general behaviour of the mean trunk temperature was fairly similar for all the calves. The mean trunk temperatures of AC/4 and HC/1 rose with time of exposure at environmental temperatures of 25°C. and above, but this rise did not start until 30°C. for AC/3. The general tendencies were very similar to those observed for the rectal temperature, but on a reduced scale.

Fig. 10 shows all the measurements at 5 min. intervals of the mean trunk temperature of each calf at an environmental temperature of 30°C. at low humidity. Here Experiment no.6 on AC/4 again shows anomolous behaviour. The replicate experiments were in this instance even more consistent than for the other physiological reactions previously discussed, but differences between individual animals again existed.

Fig. 11 shows the behaviour of the calves in the long term experiments at an environmental temperature of 40°C. at both high and low humidities. The increase

in humidity produced a large increase in the rate of rise of mean trunk temperature with time.

The mean temperatures of each skin region of each calf during the fourth hour of exposure, averaged over all replicate experiments, are presented in Table 35. At any one environmental condition no region was at a very different temperature from the others, and all rose with increasing environmental temperature, and with increase of humidity at 35°C.

During the course of the experiments frequent visual examinations of the skin of the calves were made. On no occasion was there any evidence of visible sweating, either in the form of droplets such as might be seen under a X20 simple microscope, or as colouration of a water sensitive dye (quinizarin) dusted on the animals' skins.

Discussion

Table 35 shows that the differences which existed between the skin temperatures of the various regions on the trunk of the calves were not systematically maintained; that is, the temperature of a given region was probably above the average just as often as it was below it. At the lower environmental temperatures there was a tendency for the temperature of the leg to be below the mean trunk temperature, but this difference disappeared above 30°C. On the other hand, ear temperatures which were not far different from mean trunk temperatures at the lower environmental temperatures were consistently below them at environmental temperatures above 30°C. In fact at 40°C. ear temperatures were

below both rectal and environmental temperatures. This may have been due either to a lower blood flow per unit surface area in the ear or to a higher evaporative loss from the ears than from the rest of the body.

Evidence that there was evaporative loss from the trunk is available from Figs. 8 and 11. At 40°C. environmental temperature at low humidity the mean trunk temperatures of all the animals were consistently of the order of 1°C. below rectal temperature and for three or more hours were below environmental temperature. This depression of skin temperature was to a great extent eliminated at the higher humidity, mean trunk temperature for the most part lying between rectal and environmental temperatures. The only reasonable explanation of this change is that evaporation of water from the skin took place at the lower humidity and produced cooling of the skin.

Fig.12 gives a series of graphs of the differences between mean trunk temperature (taken from Tables 32, 33 and 34) and environmental temperature, plotted against environmental temperature, for each calf used in the long term experiments and for various times of exposure. All the animals responded in the same manner, and the temperature difference fell linearly from 15°C. to 0°C. as environmental temperature rose from 20°C. to 40°C. For radiative and convective losses, to a good degree of approximation over the temperature range encountered here, the rate of loss of heat is proportional to the excess temperature of the body over its environment

(Newton's Law of Cooling). Thus these same curves, with different ordinate units, are the non-evaporative heat loss curves, these losses being zero at approximately 40°C. environmental temperature. This compares with a temperature of about 34 - 35°C. for zero losses from clothed or nude humans (Gagge, Winslow & Herrington, 1938).

In Fig. 13 are plotted the averages over all replications of the mean trunk temperatures during the fourth hour of exposure to the various environmental temperatures at low humidity. These points do not deviate significantly from straight lines, the average change in skin temperature being approximately 1°C. for each 4°C. change in environmental temperature. For comparison are included similar curves for the average skin temperature of nude and clothed humans, taken from the data of Gagge, Winslow & Herrington (1938). The change in slope above about 32°C. for nude man is due to sweating; such a change is not obvious in the data for bovines. The change in slope for clothed man is rather less than for naked man. It is possible that the coats of the calves provided greater thermal insulation than the clothes of the man, and therefore no definite conclusions concerning sweating can be drawn from these results. The higher overall skin temperature of the calves compared with humans may be explained partly by the higher insulation of the bovine coat, and partly by the higher rectal temperatures of the calves, although other factors almost certainly enter into the problem. However, considering the animal and its coat

as a whole, evaporative losses from the skin of these calves were obviously not at all as efficient as sweating in man.

In Fig. 14 are plotted the differences between rectal and mean trunk temperature for the different environmental temperatures at low humidity, averaged over all replications. The deviations from linearity of the curves for AC/4 and AC/3 are both highly significant, but no test could be made on that for HC/1 owing to lack of replication. The heat carried from the interior to the surface of the body is proportional to the product of temperature difference and thermal conductivity. If all the heat produced by the animal were to be lost through its skin, then Fig.14 would show that the thermal conductivity of AC/3 and AC/4 must have increased by a factor of approximately five as the environmental temperature changed from 20°C. to 40°C. Since the major portion of that heat would be carried in the blood stream, cutaneous circulation would have had to change at least fivefold to carry the same amount of heat. In view of the great increase in respiration rate it is probable that at the higher temperatures much heat was lost from the respiratory tract. Until the partition of the evaporative losses between respiratory tract and skin has been determined experimentally little more can be said concerning this.

Summary

1. The temperatures of 11 regions of the skin of each of four bull calves have been measured at various environmental temperatures and humidities and for different time of exposure. A total of approximately 38,000 measurements of skin temperature were made.

2. A comparison of the results of the short term and long term experiments revealed that in the former type of experiment the values of skin temperatures obtained were lower at the higher environmental temperatures.

3. Under standardized conditions at an environmental temperature of 20°C. the mean trunk temperatures of three calves ranged from 31.5 to 36.0°C. with means for the individual calves of 33.7, 33.7 and 34.6°C.

4. The temperatures of all regions of the skin of all four calves rose approximately linearly with increasing environmental temperature. They also rose with increase of humidity at 35°C. and 40°C. environmental temperature.

5. The time of exposure to a given thermal environment affected the skin temperature of each calf differently, the effect being modified by the environmental temperature and humidity. Thus the mean trunk temperature of calves AC/4 and HC/1 rose with time at 25°C. and above, whilst that of AC/3 was only just beginning to rise with time at an environmental temperature of 30°C.

6. For no area of skin on the trunk whose temperature was measured was the temperature consistently above or below the mean trunk temperature.

7. At environmental temperatures below 30°C., the leg temperatures were consistently below the mean trunk temperature; at and above 30°C. the ear temperatures were consistently below the mean trunk temperatures.

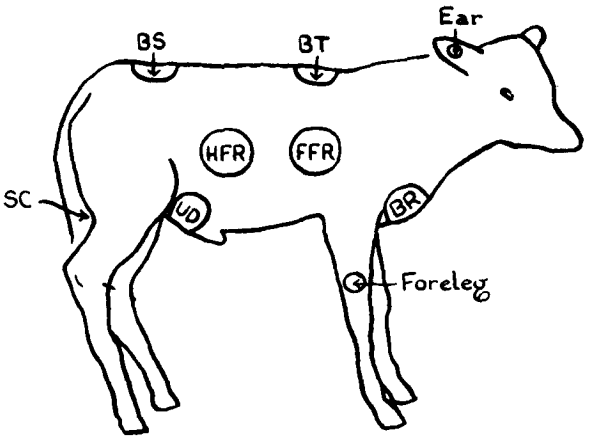
8. After exposure for 4 hr. (when the skin temperatures were approximately in equilibrium) the mean trunk temperatures of each of the three calves used in the long term experiments increased by approximately 1.0°C. for each 4°C. rise in environmental temperature between 20°C. and 40°C. at a constant absolute humidity.

9. The loss of heat by radiation and convection from the skin fell linearly as the environmental temperature increased from 20°C. to 40°C. At this latter temperature the differences between mean trunk temperature and environmental temperature were approximately zero so that these losses were also zero.

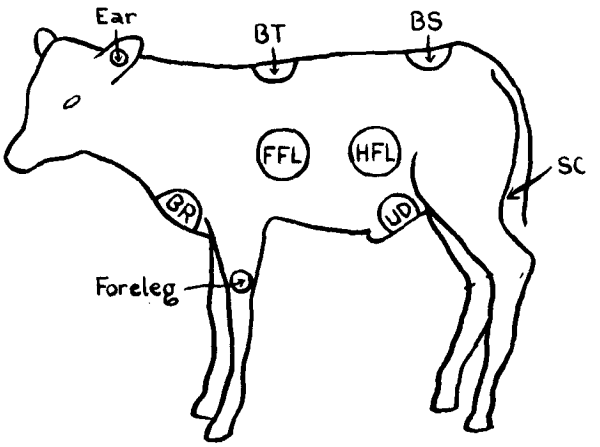
10. There appeared to be no upper limit to the skin temperatures of any of the calves such as is produced by sweating in man. It is therefore probable that the evaporation of water from the skin plays a much less important part in the heat regulation of calves than it does in that of man.

11. The use of a water sensitive dye dusted on the skins of the calves as an indicator of sweating provided no positive evidence of copious sweating such as is encountered in man. Further, visual examination of the skin with a simple microscope did not reveal any sweat droplets on the skin.

12. On the other hand, some evidence was obtained that evaporation of water from the skin did occur. It is therefore probable that this water passed through the surface of the skin in the vapour phase.



RIGHT SIDE VIEW



LEFT SIDE VIEW

FFR. . . . . .Front flank right
FFL. . . . . " " left
HFR. . . . . .Hind flank right
HFL. . . . . " " left
BT. . . . . .Back thoracic
BS. . . . . " sacral
BR. . . . . .Breast
UD. . . . . 'Udder' region
SC. . . . . .Scrotum (to right or left of scrotal raphe)

Fig. 9. **The positions of the various skin regions at which temperatures were measured on the calves.**

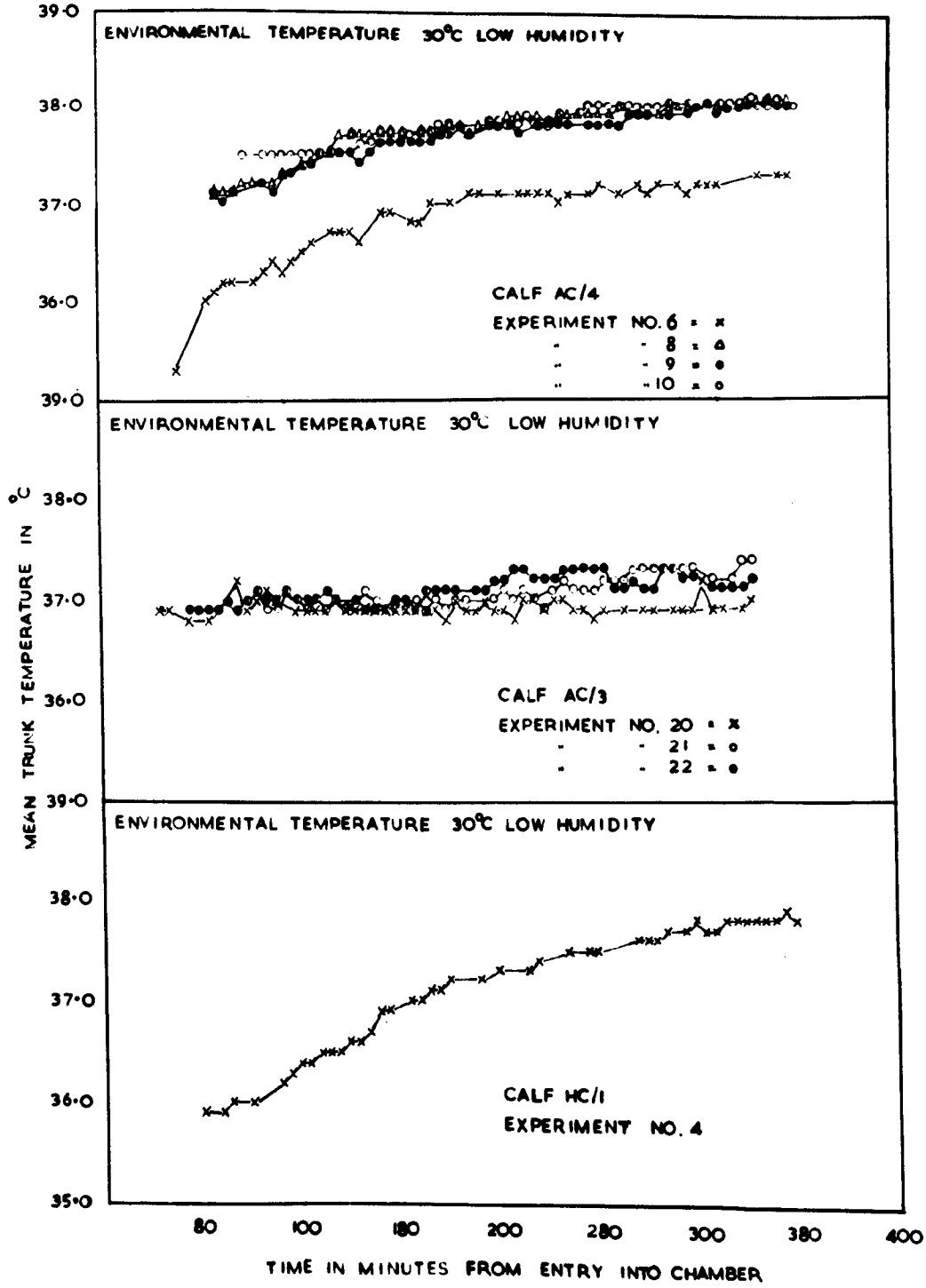


Fig. 10. The effect of time of exposure at an environmental temperature of 30°C. and low humidity on the mean trunk temperatures of two Ayrshire calves and one Highland calf. Replicate experiments are shown where these were performed.

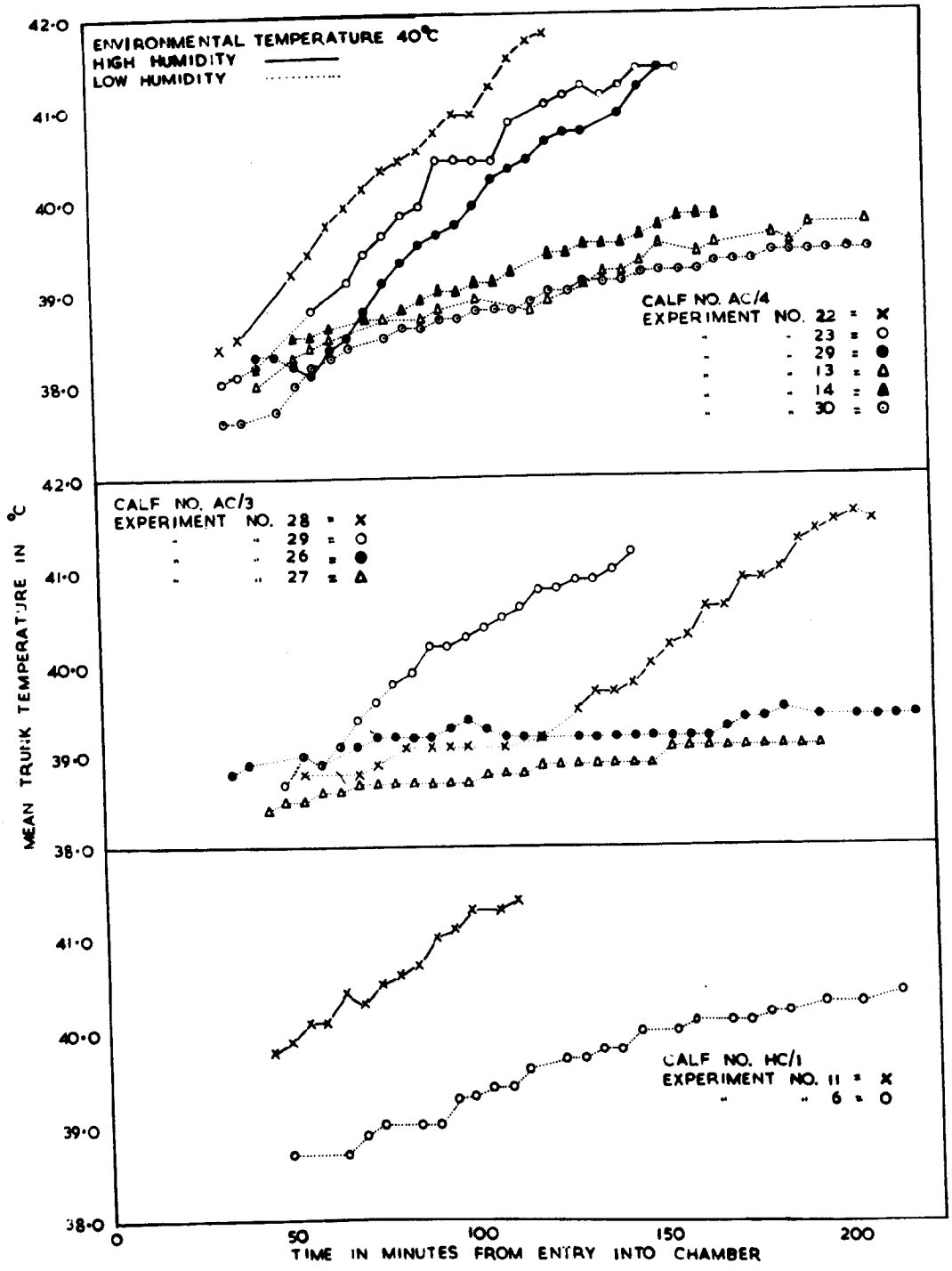


Fig. 11. The effect of time of exposure at an environmental temperature of 40°C. at high and low humidities on the mean trunk temperatures of two Ayrshire calves and one Highland calf. Replicate experiments are shown where these were performed.

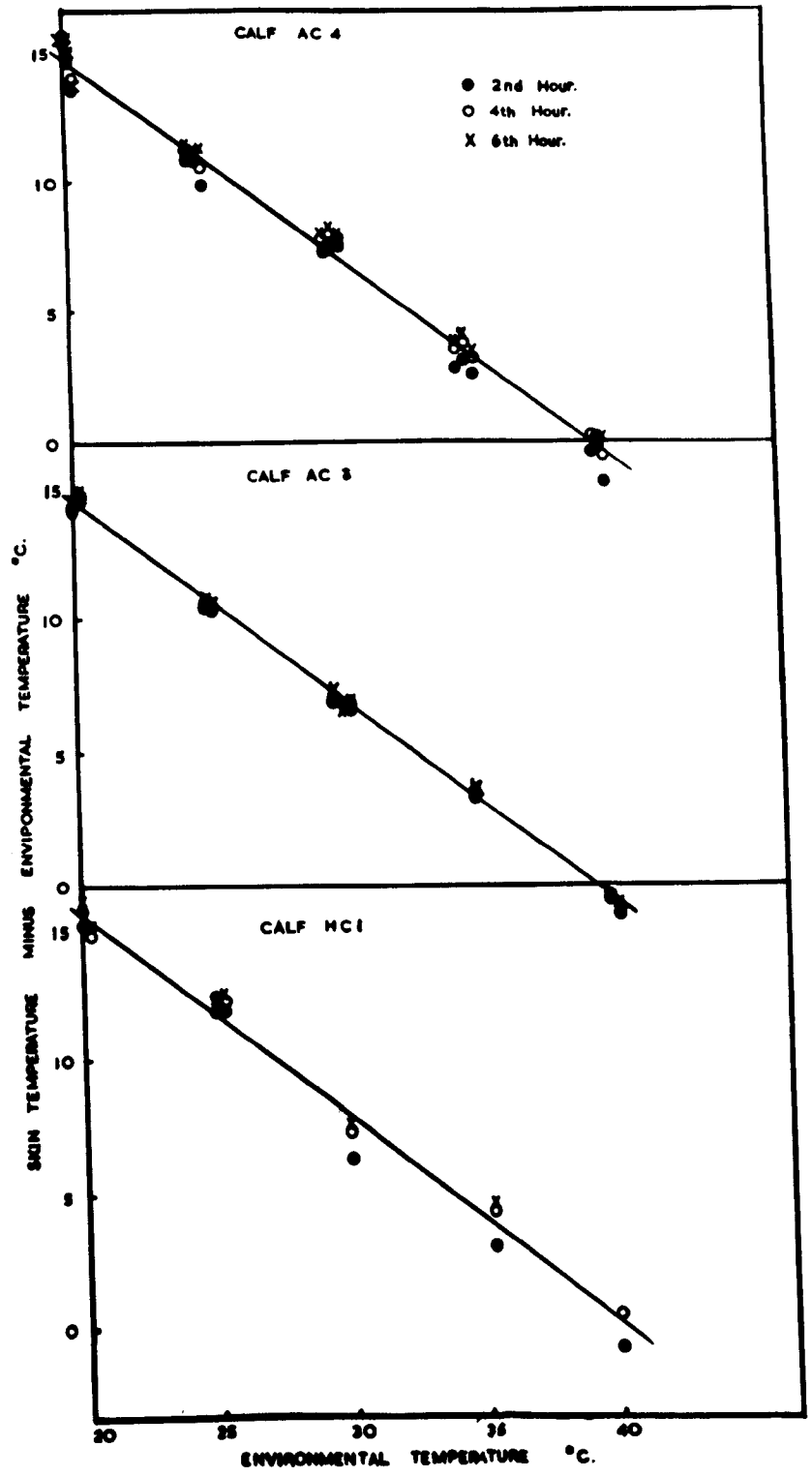


Fig. 12. The effect of environmental temperature on the difference between mean trunk temperature and environmental temperature for two Ayrshire calves and one Highland calf. For clarity the points from different replications are displaced slightly from their appropriate abscissae.

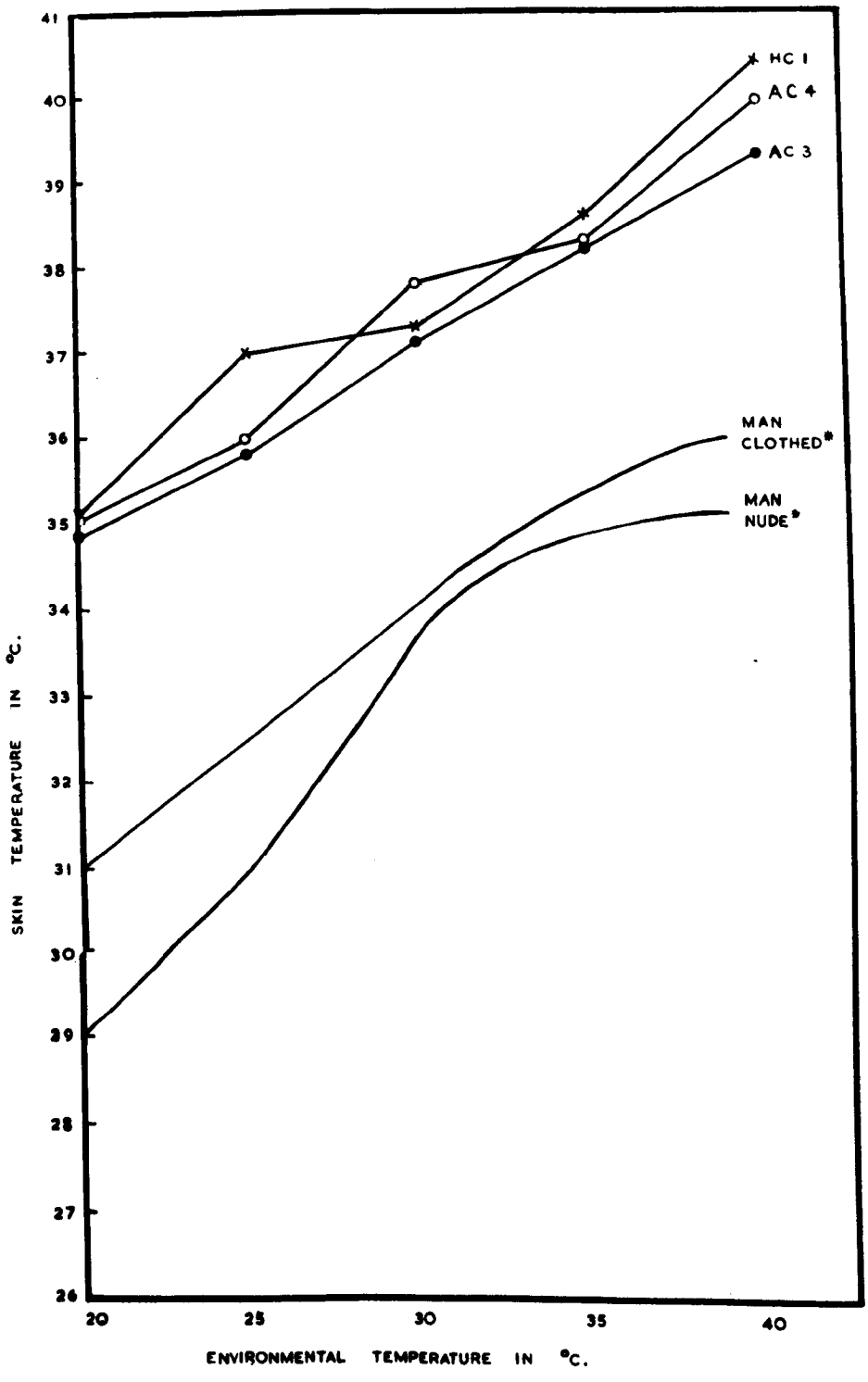


Fig. 13. The effect of environmental temperature on the mean trunk temperature of two Ayrshire calves, one Highland calf and Man. (The curves for Man were taken from Gagge, Winslow & Herrington, 1938).

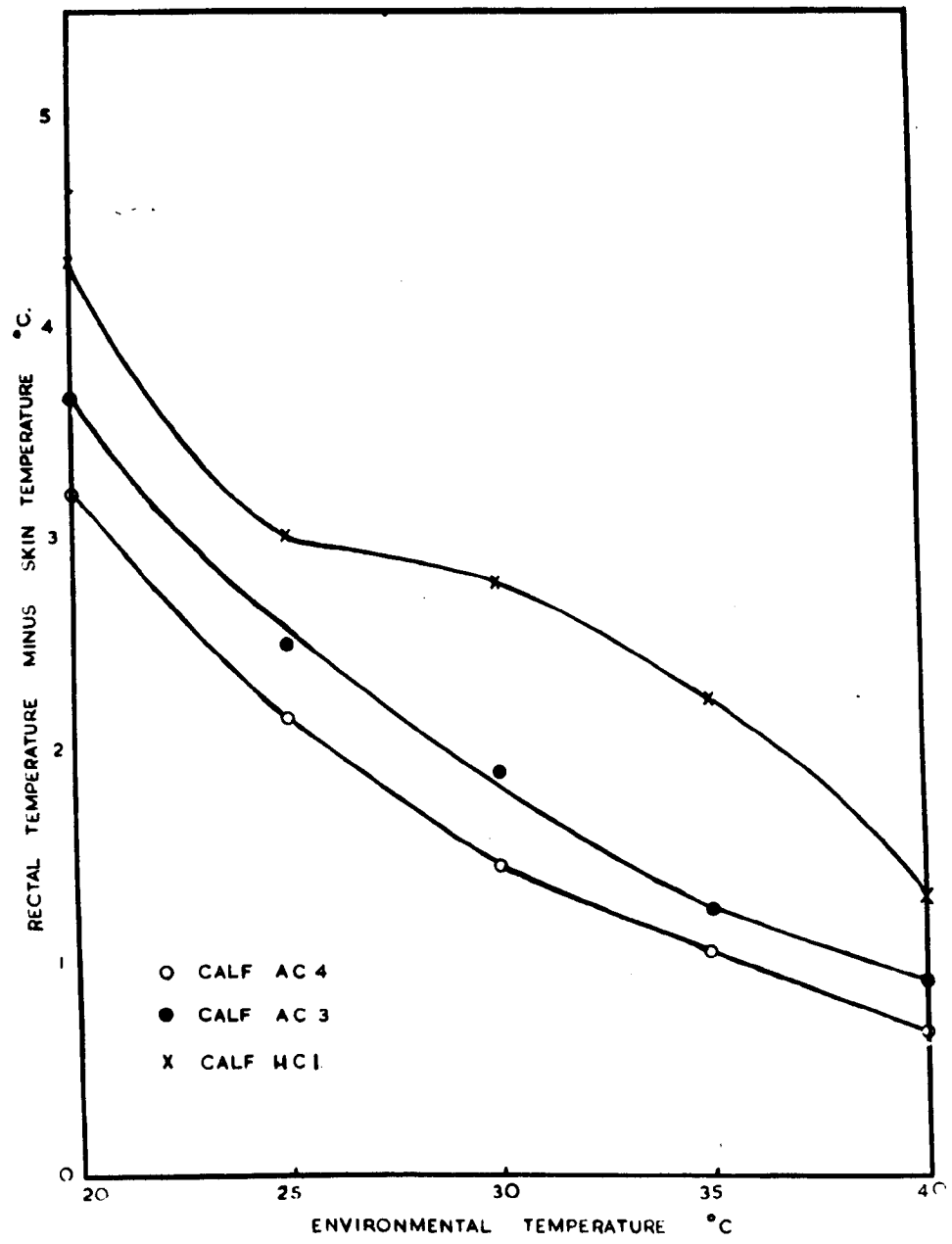


Fig. 14. The effect of environmental temperature on the difference between rectal temperature and mean trunk temperature for two Ayrshire calves and one Highland calf. The points refer to the fourth hour of exposure and are the mean of all replications for each condition.

Table 29. The mean trunk temperature of three calves on different days after approximately one hour's exposure to a thermal environment of 20°C. D.B.T., 17°C. W.B.T.

Calf	Mean trunk temperature on different days (°C.)															Mean
AC/2	34.7	34.4	34.4	33.6	32.6	33.6	31.5	33.2	33.8	34.5	33.9	33.7	33.4	33.8		33.7
AC/3	33.1	33.8	33.1	33.0	32.8	32.0	31.9	34.0	34.0	35.0	33.9	34.1	34.4	35.0	36.0	33.7
AC/4	35.3	34.3	34.8	34.5	34.1	34.8	34.1	34.7								34.6

Table 30. The effect of short term exposure to thermal environments from 20 to 40°C. at low and high humidities on the mean trunk temperature (°C.) of three Ayrshire calves

Calf	Humidity	No. of days	Environmental temperature (°C.)				
			20	25	30	35	40
AC/2	Low	3	33.8 ± 0.7	34.7 ± 0.4	36.1 ± 0.3	37.5 ± 0.4	39.1 ± 0.4
	High	3	33.6 ± 0.3	35.0 ± 0.2	36.5 ± 0.2	37.9 ± 0.2	40.2 ± 0.2
AC/3	Low	6	32.7 ± 0.2	34.0 ± 0.5	35.3 ± 0.3	36.7 ± 0.3	38.4 ± 0.5
	High	5	34.1 ± 0.6	35.1 ± 0.4	36.6 ± 0.4	38.3 ± 0.7	41.4 ± 0.1
AC/4	Low	2	34.4 ± 0.4	35.2 ± 0.6	36.5 ± 0.6	37.7 ± 0.2	39.0 ± 0.2
	High	2	34.4 ± 0.4	35.4 ± 0.1	36,9 ± 0.2	38.1 ± 0.3	39.8 ± 0.1

The entries in this table are the means and standard deviations of the mean trunk temperature over a number of days (n), during the time the calf was at the environmental temperature given at the head of the column.

Table 31. The mean trunk temperature (in °C.) of calves AC/4, AC/3 and HC/1 for different thermal environments and times of exposure

Calf	D.B.T. (°C.)	Humidity	Hour no.					
			1	2	3	4	5	6
AC/4	20	Low	34.8	34.9	35.0	34.9	34.9	34.9
	25	Low	35.3	35.7	35.9	36.1	36.3	36.5
	30	Low+	37.2	37.4	37.7	37.8	37.9	38.0
		High	37.1	37.3	37.5	37.6	37.7	37.8
	35	Low	37.4	37.7	38.0	38.4	38.5	38.7
		High	37.5	38.1	38.8	39.4	39.8	40.1
	40	Low	38.4	39.0	39.3	40.0	40.0	40.2
		High	38.4*	40.0	41.4	-	-	-
AC/3	20	Low	34.7	34.6	34.7	34.8	35.0	35.1
	25	Low	36.0	36.0	35.9	35.8	35.9	36.1
	30	Low	37.0	37.0	37.0	37.1	37.2	37.2
		High	37.1	37.3	37.5	37.6	37.7	37.8
	35	Low	38.1	38.1	38.2	38.2	38.3	38.4
		High	38.4	38.9	39.1	39.3	39.6	39.8
	40	Low	38.7	39.0	39.2	39.3	39.3	39.4
		High	38.9*	39.6*	40.6	41.4	-	-
HC/1	20	Low	-	35.2	35.2	35.1	35.2	35.8
	25	Low	-	36.6	36.9	37.0	37.1	37.2
	30	Low	-	36.3	36.9	37.3	37.7	38.0
		High	37.5	37.8	38.3	38.6	38.8	39.0
	35	Low	-	37.7	38.3	38.6	38.9	39.1
		High	38.7	39.5	40.2	40.6	-	-
	40	Low	38.8	39.3	39.9	40.4	40.7	-
		High	-	40.9	-	-	-	-

* The humidity was low during the early part of each period of exposure under these environmental conditions and for a different length of time for each.

\+ Excluding Experiment No.6.

Table 32. The effect of thermal environment and time of exposure on the mean trunk temperature of Calf AC/4*

D.B.T (°C.)	Experiment no.	Low humidity conditions Hour no. 1	2	3	4	5	6	High humidity conditions Hour no. 1	2	3	4	5	6	Experiment no.
20	1	-	35.3	35.6	35.6	35.5	35.4							
	3	35.0	35.0	35.0	34.9	35.0	35.1							
	24	34.6	34.3	34.3	34.5	34.3	34.4							
25	4	-	35.8	35.9	35.9	36.1	36.2							
	5	35.2	35.9	36.1	36.2	36.4	36.5							
	16	-	35.1	35.3	35.8	36.2	36.6							
	17	-	35.8	36.1	36.4	36.5	36.7							
30	6x	36.0	36.4	36.8	37.1	37.2	37.2							
	8	37.1	37.3	37.7	37.9	37.9	38.1	-	37.4	37.6	37.8	37.8	38.0	18
	9	37.2	37.4	37.6	37.8	37.9	38.0	37.1	37.2	37.4	37.5	37.6	37.7	19
	10	-	37.5	37.7	37.8	38.0	38.0							
35	11	37.7	38.2	38.5	38.9	39.1	39.2	37.0	37.7	38.6	39.4	40.0	40.4	20
	12	37.3	37.5	37.9	38.3	38.5	38.7	38.0	38.5	39.2	39.7	39.8	40.1	21
	31	37.0	37.3	37.6	37.9	38.0	38.2	37.4	38.0	38.6	39.2	39.8	40.2	32
40	13	38.3	38.7	39.3	39.8	40.1	-	38.9+	40.6	41.7	-	-	-	22
	14	38.4	38.9	39.6	-	-	-	38.1+	40.0	41.5	-	-	-	23
	15	39.1	39.6	40.2	40.8	-	-	38.2+	39.4	41.1	-	-	-	29
	30	37.8	38.6	39.2	39.4	39.8	40.2							

* The entries in this table are the mean skin temperatures calculated from a number of observations made within each hour for each of eight locations on the trunk as specified on p. 89 . The units of measurement are °C.

x This was an anomolous experiment; see remarks in the text (p. 25).

+ The humidity was held low during this hour.

Table 33. The effect of thermal environment and time of exposure on the mean trunk temperature of calf AC/3*

D.B.T. (°C.)	Experiment no.	Low humidity conditions						High humidity conditions						Experiment no.
		Hour no.						Hour no.						
		1	2	3	4	5	6	1	2	3	4	5	6	
20	16	34.4	34.3	34.3	34.5	34.7	34.9							
	17	35.0	34.8	35.0	35.1	35.2	35.2							
25	18	36.0	36.1	35.8	35.7	35.9	36.1							
	19	36.1	36.0	35.9	35.8	36.0	36.1							
30	20	37.0	37.0	37.0	37.0	37.0	37.1							
	21	-	37.0	37.1	37.1	37.2	37.4	37.1	37.3	37.5	37.6	37.7	37.8	23
	22	37.0	37.1	37.1	37.2	37.2	37.3							
35	24	38.1	38.1	38.1	38.2	38.2	38.4	38.4	38.9	39.1	39.3	39.6	39.8	25
40	26	39.0	39.2	39.2	39.4	39.4	39.6	38.9+	39.1+	40.1	41.4	-	-	28
	27	38.5	38.8	39.1	39.1	39.1	39.3	39.0+	40.1	41.1	-	-	-	29

* The entries in this table are the mean skin temperatures calculated from a number of observations made within each hour (see p.12), for each of eight locations on the trunk as specified on p.89 . The means are skin temperatures in °C.

\+ The humidity was held low during this hour.

Table 34. The effect of thermal environment and time of exposure on the mean trunk temperature of calf HC/1*

D.B.T. (°C.)	Experiment no.	Low humidity conditions Hour no. 1	2	3	4	5	6	High humidity conditions Hour no. 1	2	3	4	5	6	Experiment
20	1	-	-	35.0	34.6	34.4	-							
	2	-	35.2	35.4	35.7	35.9	36.1							
	7+	-	-	35.1	35.1	35.2	35.5							
25	3	-	36.5	36.9	37.1	37.1	37.2							
	8	-	36.6	36.8	36.9	37.1	37.2							
30	4	-	36.3	36.9	37.3	37.6	37.8	37.5	37.8	38.2	38.6	38.8	39.0	9
35	5	-	37.7	38.3	38.6	38.9	39.1	38.7	39.5	40.2	40.6	-	-	10
40	6	38.7	39.3	39.9	40.4	40.7	-	-	40.9	-	-	-	-	11

* The entries in this table are the mean skin temperatures calculated from a number of observations made within each hour (see p. 12) for each of eight locations on the trunk as specified on p. 89 . The means are skin temperatures in °C.

+ UD not included in the means for this experiment.

Table 35. The mean temperatures of various regions of the skins of calves AC/4, AC/3 and HC/1 during the fourth hour of exposure to different thermal environments

(For the meanings of the initials FFR, HFR, etc. see Fig.9)

Calf	(°C) T*	Humidity	Temperature of region in °C.											
			FFR	HFR	BT	BS	FFL	HFL	BR	UD	RE	LE	LEG	Sc
AC/4	20	Low	35.1	34.7	34.5	34.8	35.8	35.5	34.8	34.6	34.8	35.2	33.6	32.3
	25	Low	36.2	35.9	35.8	36.4	36.1	36.4	35.6	36.2	35.4	35.7	35.2	34.3
	30	Low+	38.2	37.9	37.9	38.0	37.8	37.6	37.3	37.7	36.9	36.6	37.4	36.1
		High	37.2	37.5	38.1	37.7	37.6	37.7	37.7	37.8	36.8	36.9	37.3	35.0
	35	Low	38.8	38.4	38.4	38.6	38.3	38.1	37.6	38.5	37.4	37.3	38.6	36.9
		High	39.4	39.3	39.4	39.6	39.1	39.3	39.1	39.9	38.7	38.1	39.5	37.4
	40	Low	40.4	40.3	40.2	40.4	39.6	40.0	39.6	39.9	39.0	39.0	40.4	39.4
AC/3	20	Low	35.1	35.2	35.5	35.4	34.5	35.6	31.8	35.4	35.3	34.8	34.3	29.6
	25	Low	36.5	36.0	36.4	36.3	36.2	35.7	33.7	35.6	35.8	35.5	34.9	32.8
	30	Low	37.7	37.3	37.0	37.5	37.0	36.9	36.3	37.1	36.9	36.8	36.5	34.5
		High	37.9	37.6	37.4	37.9	37.8	37.7	37.2	37.3	36.9	37.9	37.6	35.0
	35	Low	38.7	38.4	37.9	38.4	38.2	38.1	37.6	38.2	37.5	37.4	37.6	36.1
		High	39.5	39.3	39.2	39.6	38.5	39.7	39.0	39.4	38.5	38.2	39.3	37.7
	40	Low	39.6	39.7	39.8	39.5	38.4	39.2	39.1	38.9	38.1	38.1	39.4	38.4
HC/1	20	Low	35.3	35.3	35.3	35.7	35.7	34.7	34.9	32.3	35.0	35.5	32.9	32.5
	25	Low	37.5	37.6	36.6	37.4	37.8	37.3	36.5	36.1	36.4	35.8	35.5	36.1
	30	Low	38.7	38.2	35.7	37.4	38.0	38.3	37.4	35.0	36.8	36.6	37.6	35.0
		High	38.5	38.4	38.4	39.0	38.8	38.5	39.2	37.8	37.9	37.8	38.3	35.5
	35	Low	39.0	39.6	38.6	38.2	38.7	39.8	38.0	37.2	36.6	37.5	37.7	37.2
		High	40.9	40.0	40.8	39.8	41.1	41.5	39.7	41.3	41.1	40.5	39.7	-
	40	Low	41.1	40.9	40.5	40.7	39.5	40.5	40.2	39.8	38.7	38.8	41.1	40.1

* T is Environmental temperature.

+Excluding Experiment No.6.

Chapter 6

The Effect of Thermal Environment on the Surface Temperature of the Scrotum of Calves

Introduction

It is well known that spermatogenesis is adversely affected by high testicular temperatures (e.g. Phillips & McKenzie, 1934) and that under normal environmental temperatures the scrotum acts as a thermostat which attempts to maintain a fairly constant thermal environment for the testicles. Riemerschmidt & Quin (1941) have studied the effect of air temperature on the scrotal temperature of a bull in the field in the tropics and found the scrotal surface temperature to increase from approximately 32°C. at air temperatures of 20°C. to approximately 36°C. at air temperatures of 40°C. The bull was in direct sunlight during part of their experiments, but its scrotum was in shadow.

In the present series of experiments the temperature of the scrotum of each calf was measured at a point adjacent to one of the testicles.

Method

A 40 S.W.G. copper constantan thermocouple, (part of the temperature measuring system described in Part II, Chapter 9) was attached to the surface of the scrotum to the right or left of the scrotal raphe, by a small pellet of rubber latex, the thermocouple wire running along the surface of the scrotum for some distance to minimize thermal conduction along the wire. Readings were taken of the scrotal temperature at five

minute intervals throughout a calf's exposure to the standard environments.

Results

Table 36 gives the means of the measurements of the temperature of the surface of the scrotum during a 30 min. period near the start of each of the short term experiments, when the environmental temperature was 20°C., and for a corresponding period in the 20°C. long term experiments. The range of the measurements for the different days was 28.0 to 33.5°C. with means of 29.9 and 32.2°C. respectively for each calf.

Table 37 summarizes all the measurements of scrotal temperature made in the short term experiments. Scrotal temperature rose with environmental temperature and rose more rapidly under high humidity conditions than under low humidity conditions.

Tables 38, 39 and 40 give the hourly means of the scrotal temperatures of the three calves used in the long term experiments, each experiment performed being included. These tables show that scrotal temperatures were increased by increases in environmental temperature, and by an increase in humidity at 35 and 40°C. At the higher environmental temperatures and humidity scrotal temperatures rose during the period of exposure, but the environmental temperature at which scrotal temperature rose consistently with time varied from animal to animal. Thus for HC/1 this temperature was 25°C; for AC/4 the scrotal temperature rose with time at 30°C. but stayed at an approximately constant, though elevated level for the latter half of the period,

and showed a consistent rise only at and above the lower humidity at 35°C; whereas for AC/3 the steady rise was apparent only at 35°C. at high humidity and at 40°C.

The various types of behaviour at an environmental temperature of 30°C. at low humidity are shown in detail in Fig.15, in which are plotted all the measurements of scrotal temperature taken at 5 min. intervals under this condition in the long term experiments. The behaviour of the scrotal temperature of AC/4 in experiment no.6 (in which the animal was physiologically upset) was far less different from the corresponding replicate experiments on this calf than were the physiological reactions discussed in the earlier chapters. The curious behaviour of AC/3, in which the scrotal temperature fell to a minimum and subsequently rose, also occurred at the higher humidity at 30°C. and at 35°C. at low humidity. A possible explanation of this behaviour may lie in the extension of the scrotum of this animal, which was observed to change to a greater degree than that of the other animals with both time of exposure and environmental temperature.

The effect of an increase in humidity at an environmental temperature of 40°C. is best seen in Fig.16. Here scrotal temperatures taken at 5 min. intervals are plotted against time of exposure for each humidity and each replicate experiment. The effect of raising humidity in causing an increased rate of rise of scrotal temperature was large and almost immediate. At the

end of the period of exposure under this high humidity, the scrotal temperatures of both calves, although slightly above environmental temperature and rising were still considerably below rectal temperature. From Table 35 it may be seen that the scrotum was almost always at a lower temperature than any other region of the skin.

Summary

1. The temperatures of the surfaces of the scrotums of three bull calves have been measured under various controlled environmental temperatures and humidities, and for different times of exposure, involving a total of approximately 3000 measurements of scrotal temperature.

2. The results obtained in the short term experiments were generally lower and less consistent than those obtained in the long term experiments.

3. Under standardized conditions at an environmental temperature of 20°C. the scrotal temperatures of two calves ranged from 28.0 to 33.5°C. with means of 29.9°C. and 32.2°C. respectively.

4. The scrotal temperatures of the three calves rose with environmental temperature, and with humidity at 35°C. and 40°C.

5. The effect of time of exposure on the scrotal temperature was different for each calf, and was modified by the environmental temperature and humidity. Thus one calf (HC/1) showed a rise with time at 25°C.; for another (AC/4) the rise occurred only at 30°C. and

above; whilst the scrotal temperature of AC/3 fell during the first half of the day even at 35°C. at low humidity, and only rose consistently at the higher humidity at 35°C. and at both humidities at 40°C.

6. Throughout the experiments the temperature of the scrotum was lower than the rectal temperature and that of almost all the other regions of the skin.

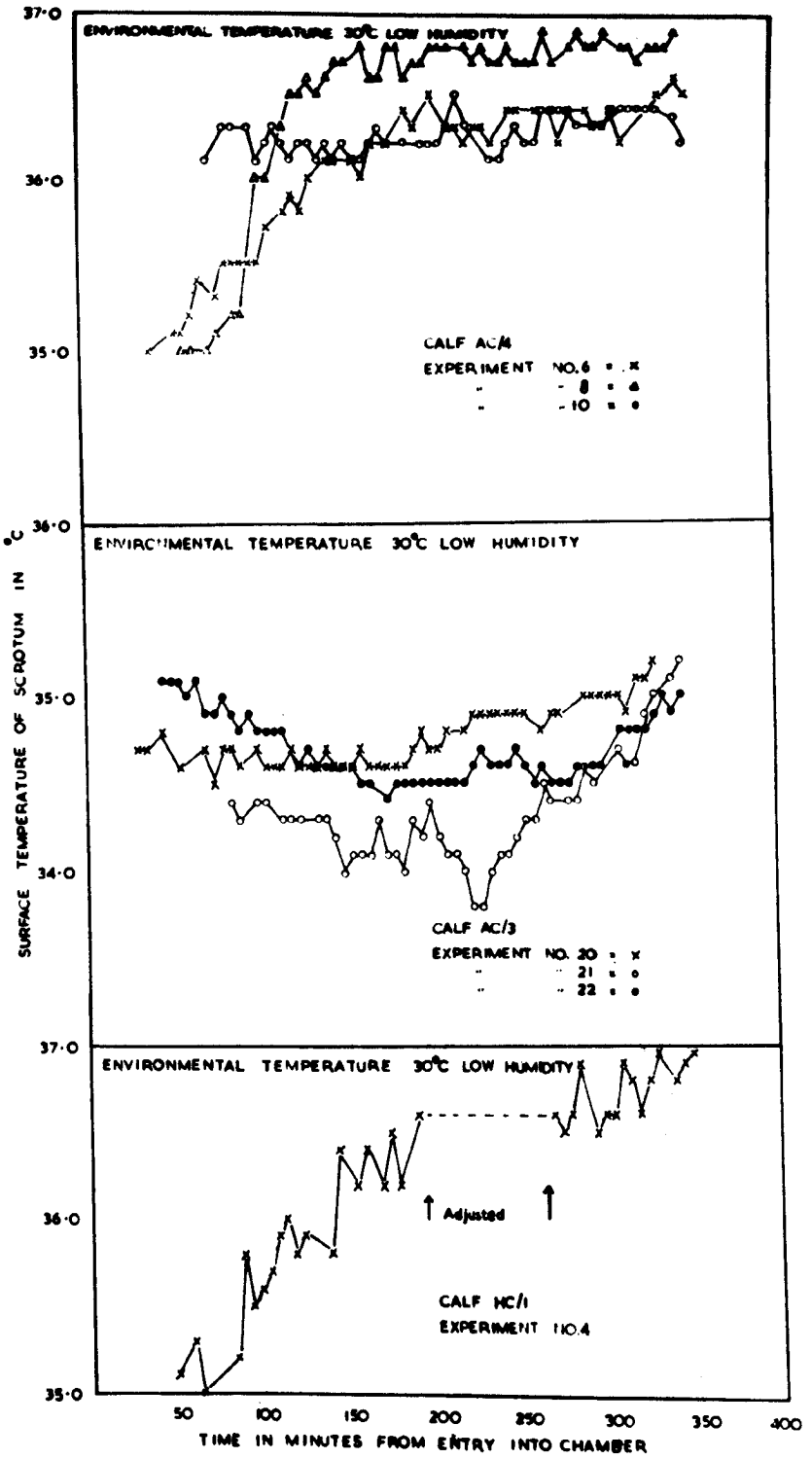


Fig. 15. The effect of time of exposure at an environmental temperature of 30°C. at low humidity on the scrotal surface temperature of two Ayrshire calves and one Highland calf. Replicate experiments are shown where these were performed. In the experiment on HC/1 the thermocouple was accidentally displaced during the period marked 'Adjusted'.

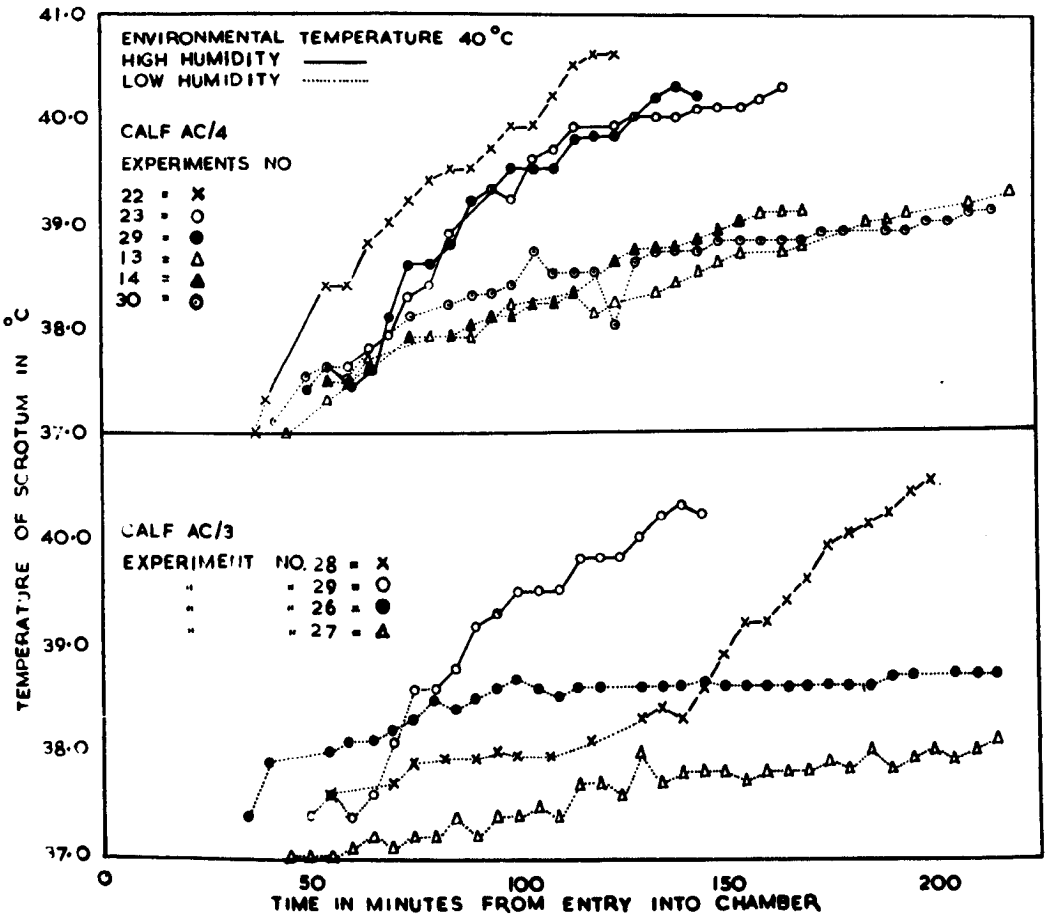


Fig. 16. The effect of time of exposure at an environmental temperature of 40°C. at high and low humidities on the scrotal surface temperature of two Ayrshire calves. Replicate experiments are shown where these were performed.

Table 36. The surface temperature of the scrotums of two calves on different days after approximately one hour's exposure to a thermal environment of 20°C D.B.T. and 17°C. W.B.T.

Calf	Mean surface temperature of scrotum (°C.)										Mean
AC/3	29.9	28.0	30.0	30.4	28.8	32.2	30.0	31.2	28.4	30.0	29.9
AC/4	32.6	32.5	31.8	33.2	31.1	31.0	33.5	32.1			32.2

Table 37. The effect of short term exposures to thermal environment from 20 to 40°C. on the mean surface temperature of the scrotum (°C.) of two Ayrshire calves

Calf	Humidity	No.of days	Environmental temperature (°C.)				
			20	25	30	35	40
AC/3	High	5	30.6 ± 1.1	32.6 ± 0.8	34.3 ± 0.3	36.3 ± 0.7	40.5 ± 1.4
AC/4	Low	2	31.6 ± 0.2	32.8 ± 0.1	34.1 ± 0.4	36.6 ± 0.3	37.7 ± 0.1
	High	2	32.8 ± 1.0	33.5 ± 0.4	34.2 ± 0.4	37.6 ± 0.4	39.5 ± 0.0

The entries in this table are the means and the standard deviations of the scrotal temperature over a number of days (n) during the time the calf was at the environmental temperature given at the head of the column.

Table 38. The effect of thermal environment and time of exposure on the scrotal temperature of calf AC/4*

D.B.T. (°C.)	Experiment no.	Low humidity conditions Hour no. 1	2	3	4	5	6	High humidity conditions Hour no. 1	2	3	4	5	6	Experiment no.
20	1	-	33.6	33.4	33.5	33.2	33.2							
	3	31.5	31.4	31.1	31.0	31.2	31.1							
	24	33.1	33.0	32.3	32.5	32.3	32.7							
25	5	34.8	35.1	35.2	35.3	35.3	35.4							
	16	-	34.2	34.1	34.3	34.3	34.4							
	17	-	33.5	33.4	33.3	33.3	33.5							
30	6x	35.1	35.5	36.0	36.3	36.3	36.4	35.0	34.9	35.1	35.0	35.1	35.1	18
	8	35.0	35.4	36.6	36.8	36.8	36.8	34.6	34.9	34.9	34.9	35.0	35.2	19
	10	-	36.2	36.2	36.2	36.3	36.4							
35	11	35.9	36.5	37.0	37.2	37.6	37.9	36.2	36.7	37.0	37.2	37.5	37.5	20
	12	36.1	36.6	36.8	37.1	37.3	37.6	36.5	36.8	37.1	37.4	37.4	37.7	21
	31	35.6	36.1	36.3	36.4	36.5	36.6	36.3	36.9	37.3	37.7	38.1	38.3	32
40	13	37.3	38.0	38.5	39.2	39.6	-	37.7+	39.7	40.7	-	-	-	22
	14	37.3	38.0	38.9	-	-	-	36.8+	39.0	40.1	-	-	-	23
	15	38.1	38.8	39.3	39.9	-	-	38.4+	39.3	40.1	-	-	-	29
	30	37.3	38.3	38.6	39.0	39.3	39.7							

* The entries in this table are the mean temperatures in °C. of the scrotum, calculated from a number of observations on the scrotum made within each hour.

x This was an anomolous experiment. For explanation see text (p. 25).

\+ The humidity was held low during this hour.

Table 39. The effect of thermal environment and time of exposure on the scrotal temperature of calf AC/3*

D.B.T. (°C.)	Experiment no.	Low humidity conditions						High humidity conditions						Experiment no.
		Hour no.						Hour no.						
		1	2	3	4	5	6	1	2	3	4	5	6	
20	16	28.2	28.6	28.3	29.1	29.0	28.8							
	17	30.4	30.4	30.4	30.2	30.6	30.7							
25	18	32.3	32.4	32.8	32.7	33.2	32.8							
	19	32.7	32.9	32.8	32.8	32.9	33.2							
30	20	34.7	34.6	34.6	34.7	34.9	35.1							
	21	-	34.4	34.2	34.0	34.4	34.9	35.0	34.8	34.6	35.0	35.2	35.5	23
	22	35.1	34.9	34.6	34.5	34.6	34.9							
35	24	36.2	36.1	36.1	36.1	36.3	36.5	36.7	37.2	37.5	37.7	38.0	38.2	25
40	26	37.9	38.5	38.6	38.7	38.8	38.9	37.6+	37.9+	39.1	40.4	-	-	28
	27	37.0	37.4	37.8	38.0	37.5	37.9	37.5+	39.0	40.1	-	-	-	29

* The entries in this table are the mean temperatures in °C. of the scrotum, calculated from a number of observations on the scrotum made within each hour.

+ The humidity was held low during this hour.

Table 40. The effect of thermal environment and time of exposure on the scrotal temperature of calf HC/1*

D.B.T. (°C.)	Experiment no.	Low humidity conditions						High humidity conditions						Experiment no.
		Hour no.						Hour no.						
		1	2	3	4	5	6	1	2	3	4	5	6	
20	1	-	-	31.3	30.7	29.9	-							
	2	-	33.6	34.3	34.3	34.5	34.5							
25	3	-	35.9	36.2	36.1	36.6	36.8							
30	4	35.2	35.5	36.0	-	36.5	36.8	34.7	35.0	35.6	35.5	35.6	35.5	9
35	5	35.3	36.4	36.9	37.2	37.6	37.8	36.8	37.7	38.4	-	-	-	10
40	6	37.5	38.4	39.5	40.1	40.4	-	Not recorded						

* The entries in this table are the mean temperatures of the scrotum in °C. calculated from a number of observations on the scrotum made within each hour.

Chapter 7

General Discussion and Conclusions

The preceding chapters have shown the great effect that thermal environment has on various physiological reactions of calves. It is now proposed to discuss the implications of these findings in their effect on the animal as an integrated organism.

It is to be expected that there exists an environmental temperature below which it is the animal's concern to conserve heat, and above which the animal must actively eliminate heat. There are probably only two ways in which the animal may conserve heat at lower environmental temperatures; by increasing the thermal insulation of its coat, or by decreasing the amount of heat carried to the surface by its bloodstream. The former reaction would tend to increase its skin temperature, and the latter to decreaase it. For man this critical point is near 24°C. As the environmental temperature decreases below this, considerable vasoconstriction occurs first in the lower extremities, and then at a rather lower temperature, in the hands and arms. The reaction results in a large fall in the skin temperature of the affected regions.

Some isolated experiments have been performed on the calf AC/3, in which the environmental temperature, initially at 12°C., was allowed to rise slowly. Fig. 17 shows the results of a typical experiment in which the animal's ear temperature was originally approximately 18°C. and changing in an undulatory manner, but

at an environmental temperature of 18°C. it suddenly jumped to 35°C. It is possible to calculate an approximate value for the relative increase in blood flow which would cause this change.

The conditions before and after the change were (see Fig.17) :-

	°C.	
	Before	After
Environmental temperature	18	20
Right ear temperature	22	35
Rectal temperature	38	38
Ear minus environmental T. (a)	4	15
Rectal minus ear temperature (b)	16	3
Ratio b/a	4	1/5

The ratios b/a are the ratios of the thermal conductances from body to ear and from ear to environment. Since the latter conductance must remain constant, the former changed by a factor of 20. Such a change is equivalent to an increase in blood flow to the ear by a factor of approximately 20 and indicates that the calf's ear may perform the same thermoregulatory functions as the extremities of man. No similar change has been noted in the present work at any other region of the skin at environmental temperatures in the range 20 to 40°C.

If the effective thermal conductance on either side of the skin surface, with respect to the deep core of the body and to the environment be K_1 and K_2 respectively, and the evaporative loss from the skin remains constant, then the heat flow per unit area (H) to and from the skin is given by :

$$H = K_1 (T_R - T_S) = K_2 (T_S - T_E)$$

or

$$\frac{K_1}{K_2} = \frac{T_S - T_E}{T_R - T_S} = r$$

where T_R is the rectal temperature

T_S is the skin temperature

T_E is the environmental temperature

This equation was first used by Burton (1934) who named r the Thermal Circulation Index. This index has been calculated from the results obtained in the long term experiments on calves AC/3, AC/4 and HC/1 and its hourly average values for all of these experiments are given in Tables 41, 42 and 43. The value for T_E has been taken as the mean of the air temperature and the average wall temperature, and for T_S as the mean trunk temperature. It is evident that there was no significant effect of temperature on the value of r at environmental temperatures below 30°C., but that above this temperature r decreased. This decrease may have been due a decrease in the cutaneous blood flow, an increase in evaporation of water from the skin, or a reduction in the insulation of the coat. It is unlikely that a fall in the cutaneous blood flow occurred at the higher environmental temperatures, since this would decrease the flow of heat to the skin; further, it is unlikely that the insulation of the coat could fall to the extent indicated by the values of r in the tables. Thus it is probable that the greater part of the change in the value of r above 30°C. was due to increased evap-

oration from the skin. This view is supported by the negative values at 40°C., which can only have been caused by evaporation; and also by the higher values of r at the higher humidities, where evaporation was partly or wholly suppressed.

It is probable that evaporation of water from the skin cannot be a fully-effective heat loss mechanism since no 'running sweat' was observed at any time. It is, however, possible but unlikely that the physiological system controlling the output of sweat might be so efficient that no more than the exact amount of sweat required was secreted; if this were so the sweating mechanism in the bovine would be very different from that in humans. It is very probable, then, that the respiratory passages take over a large part of this function in the bovine. The large increase in respiration rate at high environmental temperatures indicates increased heat losses via this channel, but until experiments are performed in which both skin and respiratory moisture are accurately determined by direct methods, some doubt must remain concerning their relative importance.

An attempt has been made in the present work to find possible correlations between respiration rate and rectal temperature, rate of change of rectal temperature, skin temperature, temperature gradient through the skin, and the thermal circulation index, but these reactions are all so closely linked with environmental temperature that it is impossible to draw any significant conclusion. It is probable, however, that respiration rate is not

governed directly by rectal temperature since a correlation diagram showed very wide variations in respiration rate at approximately constant rectal temperatures, and also approximately equal respiration rates over a wide range of rectal temperatures.

The effect of time of exposure on the responses of the animals has been clearly demonstrated in the preceding chapters. In these experiments it has not been possible to separate the effects of time of exposure to the thermal environment from other effects of time, e.g. normal diurnal variations in the animal, or time after feeding. Since conditions were standardized for all the animals, and each showed marked individuality in its responses to the interaction of time and temperature it is highly probable that a large part of these changes was caused by the duration of exposure rather than by other time factors. It is also clear that the differences between the results obtained in the long term and the short term experiments respectively were due to the relative times of exposure to a given environment, and that the 'present' condition of an animal is to a large extent due to its past experience.

If an animal is to live in any particular environment it must at some time reach a condition of equilibrium in it. In the present experiments some reactions have been shown to reach equilibrium more rapidly than others, or to show changes of different types. Thus the skin temperature initially changed rapidly and grossly in response to the environment, but this was followed by a more subtle change influenced

in part at least by the slower response of the rectal temperature to environmental changes. Even in the long term experiments, at the higher temperatures, the animal had not completely reached equilibrium with its environment after six hours of exposure. On the other hand, animals in experiments in which they were continuously exposed to the same environment for periods of two or three weeks, as those in the experiments of Brody et al. (e.g. Kibler & Brody, 1949) must have reached some degree of equilibrium. Those animals were reported to have shown signs of acclimatization to their environment in the sense that a comparable group of animals suddenly exposed to the higher stresses showed exaggerated physiological responses compared with those kept in it for the whole experimental period. Further, another form of adaptation was almost certainly present in Brody's animals; their food consumption was voluntarily reduced at the higher environmental temperatures, and with it their heat production. The present experiments emphasize that in planning environmental studies on animals the full effect of time must be investigated or allowed for, particularly in field work where on many occasions thermal conditions may well approximate to the present short term experiments.

In the preceding chapters it has been consistently shown that it is possible to place the animals in the order HC/1, AC/4 and AC/3 in increasing order of heat tolerance, on a number of different scales. The breed difference of HC/1 is an obvious and expected

explanation for its low tolerance, since the Highland breed has a thick coat and is normally found in the more exposed parts of Britain. A possible explanation of the superiority of AC/3 is that it was the subject of a large number of short term experiments which in this instance preceded the long term experiments, and hence the animal may have become acclimatized to thermal stress at an early period.

It is difficult to define at this stage exactly what is the meaning of 'heat tolerance'. In broad terms it must be a reference to the overall economic efficiency of an animal in a particular thermal environment which imposes some stress on the animal. Practically, this may be measured by the total milk production, or fertility or growth rate of the animal; or by cost per unit of product, depending on the sphere of usefulness of the animal. To what extent these properties are reflected in the various physiological reactions to heat stress is at present unknown. The associations between production efficiency and the physiological reactions have to some extent been investigated, but the causal relationships are of a very complex nature. Thus the Iberia Heat Tolerance Test of Rhoad (1944) uses the difference in rectal temperature from a nominal value of 101°F. (38.3°C.) when subjected to a more or less standardized thermal environment in the field. This has proved a most useful index of heat tolerance for beef cattle, but no papers have been published on the correlation between heat tolerance coefficients and milk production. In view

of the increase in rectal temperature normally associated with the heat increment of lactation (Blaxter & Price, 1945) it is quite possible that a high milk yield would be associated with a low Iberia Heat Tolerance coefficient. Possibly a more realistic heat tolerance coefficient would be based on the rate of rise of rectal temperature when the animal is moved from one standardized thermal environment to another.

It has been shown earlier in this chapter that the respiration rates of the calves were probably not primarily determined by their rectal temperatures. An independent heat tolerance coefficient based on respiration rate is thus possible. The question arises whether an animal with a high respiration rate, and therefore presumably losing more heat by respiratory evaporation, is more heat tolerant than one with a lower rate which may be receiving a smaller stimulus due to heat stress. The answer to this is as yet unknown, although the indications of the present experiments are that the animal with the lower respiration rate is the more heat tolerant.

The heart rate is useful as an index of heat tolerance in the lengthy laboratory experiments described here, where the interactions of time and temperature can be closely watched. Heart rate is so dependent on other factors, however, and varies to such an extent during the day that no simple procedure can be used to determine a heat tolerance coefficient based on heart rate; also, state of lactation and milk yield themselves imposing an unknown and variable stress on

the heart could possibly lead to erroneous values or interpretations of such a coefficient.

Skin temperature does not hold much promise of use as the sole basis of a heat tolerance coefficient since it depends so much on various other factors. If these factors could be separated into their various components such a coefficient might be of value, but until more laboratory research has been carried out on these components, and blood flow, evaporation of water from the skin, and permeability of the coat to water vapour have been investigated, little more can be said.

In conclusion, it is fitting to compare the thermal reactions of the bovine with those of man, on which subject the knowledge of thermoregulation is greatest. Firstly, one of man's chief heat regulating mechanisms is the ability to put on or discard clothing in order to change his local environment; this type of control is not possible for the bovine although over long periods it can modify its growth of hair. Secondly, the mode of life of man is such that his normal metabolism is comparatively low, but is subject to sudden very large increases during exercise. The bovine is not normally subjected to these large intermittent internal stresses but the milking cow has a heat production (associated with the extra metabolism of lactation) more than twice basal (Brody, 1945), which imposes a heavy and continuous stress upon it. Thirdly, overproduction of sweat which is so apparent in man, has not been observed in the bovine, nor have the skin temperature responses which accompany sweating in man.

The rectal temperature of the bovine appears to fluctuate more than that of man as measured for example by Gagge, Winslow & Herrington (1938); and its respiration rate varies over far wider limits, much greater than could be accounted for by any increase in oxygen demand created by an increase in heat production. Thus thermoregulation in the bovine is different in a number of respects from that in man, the most important probably being the relative uses they make of the evaporation of water as a means of losing excess heat.

Summary

1. The existence of a vasomotor response to environmental temperature in the ear of a calf has been demonstrated. As the environmental temperature rose above 18°C. the ear temperature jumped from approximately 20 to 35°C. It is believed that this was due to a 20-fold increase in blood flow in the ear.

2. The thermal circulation index for the skin of the trunks of three calves has been determined. This index was approximately constant below 30°C., but above 30°C. it fell with increasing environmental temperature to negative values at 40°C.

3. From a comparison of the results obtained for rectal temperature and respiration rate in the long term experiments it appeared that the rectal temperature was not the dominant stimulus causing changes in the respiration rate.

4. The use of the physiological reactions here studied as a basis for a heat tolerance test has been

discussed. At present only rectal temperature or respiration rate might form such a basis.

5. The thermoregulation of the bovine has been compared with that of man and a number of important differences emphasised.

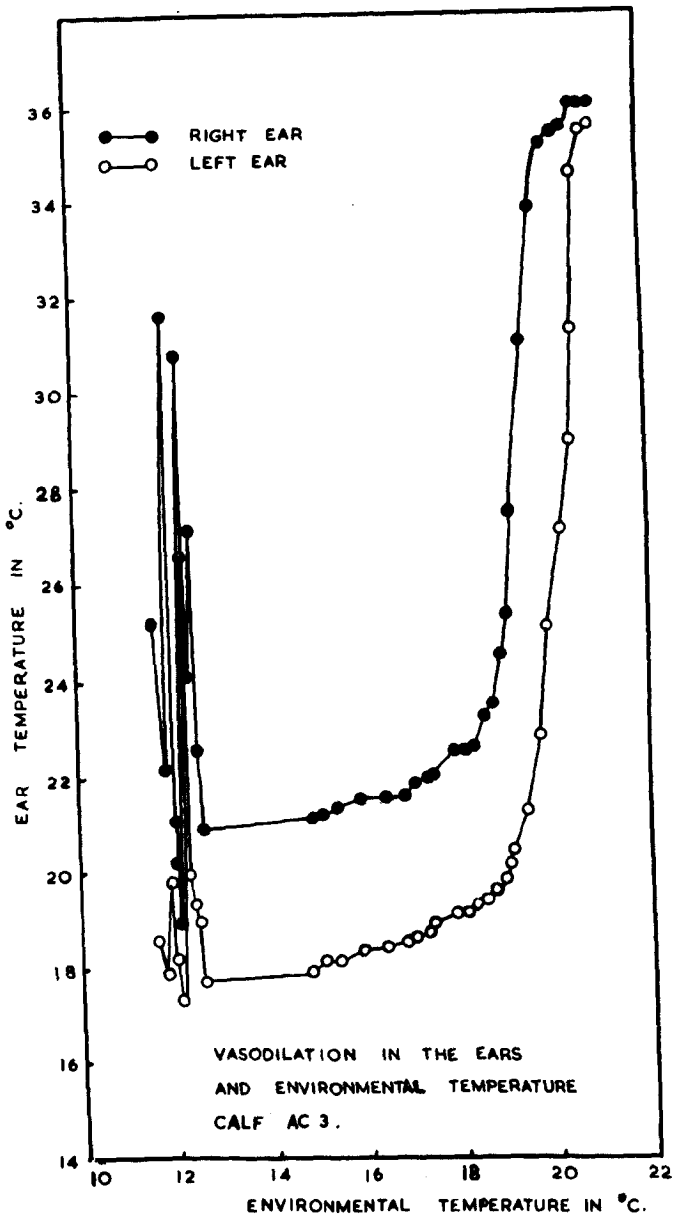


Fig. 17. The effect of environmental temperature on the surface temperature of the pinnae of the right and left ears of an Ayrshire calf (AC/3), demonstrating the onset of vasodilatation in the ear.

Table 41. The effect of thermal environment and time of exposure on the value of the thermal circulation index, r, for calf AC/4*

D.B.T. (°C.)	Experiment no.	Low humidity conditions Hour no. 1	2	3	4	5	6	High humidity conditions Hour no. 1	2	3	4	5	6	Experiment no.
20	1	-	4.2	5.0	5.1	4.9	4.9							
	3	-	4.9	4.9	4.7	4.9	5.1							
	24	4.4	4.1	4.1	4.3	4.0	3.9							
25	4	-	3.9	4.3	4.4	4.7	4.6							
	5	3.7	4.8	5.1	5.0	5.2	5.4							
	16	-	4.4	4.7	5.0	5.6	6.1							
	17	-	5.3	5.6	6.0	6.4	6.1							
30	6x	3.1	3.6	4.2	4.4	4.3	4.2							
	8	-	4.5	5.3	5.2	5.3	5.2	-	8.0	8.1	6.9	6.8	6.4	18
	9	-	6.2	6.8	6.1	6.1	6.6	5.2	5.2	5.1	5.2	4.9	5.0	19
	10	-	5.0	5.1	4.8	4.8	4.7							
35	11	3.2	3.3	3.1	3.3	4.0	4.0	-	2.8	3.8	4.3	4.8	5.2	20
	12	2.1	2.3	2.4	3.1	2.9	3.1	4.3	4.3	5.5	4.6	3.7	3.7	21
	31	2.6	3.0	3.1	3.5	3.4	3.2	4.4	6.2	7.9	5.4	7.4	8.6	32
40	13	-1.2	-0.2	-0.1	0.2	0.1	-	9.8+	0.6	2.3	-	-	-	22
	14	-0.4	-0.1	-0.2	-	-	-	ø	ø	2.9	-	-	-	23
	15	-	-0.6	-0.1	0.3	-	-	ø	ø	1.8	-	-	-	29
	30	-5.6	-2.7	-1.6	-0.7	-0.3	0.1							

* Values of r have been calculated from the mean values for TS and TR as given in Tables 26 and 32, whilst values for TE were obtained as detailed on p.125. For an explanation of the meaning of r see p.125.

x This was an anomolous experiment; see p.25 .

+ The humidity was held low during this hour.

ø Indeterminate.

Table 42. The effect of thermal environment and time of exposure on the value of the thermal circulation index, r, for calf AC/3*

D.B.T. (°C.)	Experiment no.	Low humidity conditions Hour no. 1	2	3	4	5	6	High humidity conditions Hour no. 1	2	3	4	5	6	Experiment no.
20	16	3.7	3.4	3.3	3.5	3.6	3.7							
	17	4.4	4.3	4.5	4.4	4.5	4.4							
25	18	4.0	4.5	4.3	4.1	3.9	4.2							
	19	4.4	4.3	4.2	4.1	4.3	4.2							
30	20	3.5	3.5	3.5	3.7	3.5	3.2	4.0	4.3	4.2	4.1	4.6	4.7	23
	21	-	3.1	3.5	3.6	3.8	3.7							
	22	3.7	3.6	3.2	3.6	3.7	3.2							
35	24	2.6	2.4	2.6	2.7	2.6	2.5	3.0	3.2	3.0	3.0	3.2	3.5	25
40	26	-0.9	-0.7	-0.7	-0.5	-0.4	-0.2	-1.2+	-1.1+	-0.4	2.8+	-	-	28
	27	-2.0	-1.6	-1.4	-1.2	-1.3	-0.9	-1.2+	-0.1	1.2	-	-	-	29

* Values for r have been calculated from the mean values for TS and TR as given in Tables 27 and 33, while values for TE were obtained as detailed on p.125. For explanation of the meaning of r see p.125.

+ The humidity was held low during this hour.

Table 43. The effect of thermal environment and time of exposure on the value of the thermal circulation index, r, for calf HC/1*

D.B.T. (°C.)	Experiment no.	Low humidity conditions						High humidity conditions						Experiment no.
		Hour no.						Hour no.						
		1	2	3	4	5	6	1	2	3	4	5	6	
20	1	-	-	2.6	2.8	2.8	-							
	2	-	3.7	3.7	4.1	4.2	4.3							
	7	-	-	3.6	3.7	3.8	4.0							
25	3	-	3.6	4.0	3.9	4.0	4.1							
	8	-	4.1	4.0	4.1	4.1	4.0							
30	4	-	2.4	2.5	2.6	2.6	2.6	4.3	4.5	3.9	4.0	4.0	4.1	9
35	5	-	1.6	1.8	1.9	2.0	2.1	2.5	3.7	4.1	4.0	-	-	10
40	6	-1.0	-0.7	0	0.3	0.5	-	-	1.1	-	-	-	-	11

* Values for r have been calculated from the mean values for TS and TR as given in Tables 28 and 34, while values for TE were obtained as detailed on p.125. For explanation of the meaning of r, see p.125.

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PART II

Apparatus and Methods Developed for the Work of Part I

Chapter 8

The Control of Temperature and Humidity in the Psychrometric Chamber

The Psychrometric Chamber has already been discussed in the General Introduction (p.4). Although the room was equipped by a firm of contractors, the present writer found that he had to develop special apparatus and control systems to make the room work satisfactorily. Some of these items are described in this and the following chapters. The two control systems described in the present chapter were developed from the original contractors' installation of controllers which not only worked unsatisfactorily, but usually failed to work at all.

The original air-temperature controller had an ON-OFF action provided by a bimetal thermostat; auxiliary heat was adjusted manually with the aid of a tapped choke; no indication of temperature was provided. The first modification replaced the choke with a Variac transformer. This Variac was then controlled automatically so that it appropriately adjusted the power input to the auxiliary heaters if either the ON time or the OFF time of the thermostat exceeded a present value. The bimetal thermostats proved unsatisfactory because (a) they gave no indication of temperature, (b) they were subject to contact wear, (c) they did not retain their calibration and were difficult to adjust accurately to the desired temperature, (d) they were rather inaccessible and gave rise to great difficulties when the air temperature was adjusted frequently, as

in the short term experiments. It was therefore decided to change to an electrical resistance thermometer (thermistor) as detecting element with a control unit utilising magnetic amplifiers to operate a relay providing ON-OFF action, and to retain the floating action provided by the automatically-controlled Variac transformer. Accurate and remote setting of the desired temperature thus became possible, as well as accurate temperature indication.

The original humidity controller utilized an electrode boiler to maintain a constant pressure of steam. The detecting element consisted of an adjustable bimetal thermostat surrounded by a wet cotton wick. A fall in wet-bulb temperature caused the thermostat to open a magnetic valve which allowed steam at high pressure (20 lb/sq.in.) to be injected into the air inlet duct; a rise in wet-bulb temperature stopped the injection of steam. This system did not work because (a) the delay in the action of the bimetal thermostat was so great that the air in the chamber became supersaturated before the thermostat responded, and then the air became almost dry before steam was again injected; (b) the sudden opening of the magnetic valve, allowing steam to escape from the boiler, caused a large drop in steam pressure, which initiated oscillations in the pressure control system of the boiler; (c) the hiss of the escaping high-pressure steam was greatly magnified by the metal ducting leading to the chamber, increasing the noise in the chamber to a degree which frightened the experimental animal. This control system was com-

pletely redesigned and indicators added so that the wet-bulb temperature and the absolute humidity of the chamber could be observed. In its final form the controller utilized wet- and dry- bulb thermistors as detecting elements, from which the controlling unit calculated the absolute humidity and acted as a proportional controller to hold the rate of generation of steam (which was injected into the duct at 'zero' pressure) at the level necessary to maintain the desired value of absolute humidity.

The air-temperature control system

The air-temperature control system was redesigned by the present writer and the following system constructed.

The air entering the chamber is heated by five spiral electric heaters placed in a special section of the inlet duct (Fig.1). These heaters are rated at 6 kW, 6 kW, 3 kW, 1 kW and 0.5 kW respectively. The 6 kW and the 3 kW heaters may be switched on or off manually. One of the 6 kW heaters derives its energy from a Variac transformer by means of which the dissipation from this heater may be adjusted continuously from 0 to 6 kW. It is therefore possible to supply heat at a constant rate to the air entering the chamber at any level between 0 and 15 kW, with 3 kW overlap between adjacent ranges. The heat derived from these large heaters is referred to subsequently as 'backing heat'. The two smaller heaters (dissipating 1 and 0.5 kW respectively) are controlled either singly or together by the discontinuous action of the controller;

thus either 0.5, 1, or 1.5 kW may be switched on or off as the air temperature falls below or rises above the desired value.

Fig. 18 is a circuit diagram of the measuring and controlling units. The thermistor Th.1 is a small disc of semiconducting material with a temperature coefficient of resistance of approximately 4%/°C. which is approximately ten times as great as that of most metallic conductors. The present author has shown (Beakley, 1951) that a certain value of fixed resistance placed in series with a thermistor and a source of constant E.M.F. causes the relationship between the temperature of the thermistor and the current flowing through it to be closely linear. Thus by the choice of a suitable value for R4 (Fig. 18) the current through the first winding of the magnetic amplifier M.A.1. varies linearly with the air temperature. The second winding of M.A.1 is almost identical with the first, except that since it is wound rather closer to the bobbin it has a slightly lower resistance. An extra small resistor made of copper wire, R7, is therefore placed in series with this winding and in close proximity with it; this ensures that changes in temperature of the magnetic amplifier cause no difference in resistance between the first winding and the second winding plus R7. The two windings are connected in opposition so that when equal currents are flowing through them the net effect on the flux through the core of the magnetic amplifier is zero. The resistor R6 is identical with R4 and so whenever R5 and the resistance of the ther-

mistor are equal the net input to the magnetic amplifier is zero. R5 is a tapped constantan resistor, the appropriate sections of which may be selected by the 24-way wafer switch S1a, so that the part of R5 in the circuit is exactly equal to the resistance of the thermistor at air temperatures of 15, 16, 18, 20....40, 42, 44, 45°C. S1 is the 'coarse control' for setting the required temperature. In order that the change of current load shall not exert undue influence on the 8 V D.C. supply, the tapped resistor R8 is included in the circuit so that as S1 is adjusted the total current through R5, R8, and Th.1 stays approximately constant under steady working conditions for all settings of S1. The meter M1 is connected across opposite arms of the bridge and so indicates deviation of the actual temperature from the desired value set up on the coarse control S1. This meter, which is a centre-zero instrument, has two ranges selected by the switch S2, maximum deflection representing ±2.5°C. or ± 25°C. respectively. For the more sensitive range the value of R10 is calculated by the method given by Beakley (1951). For the less sensitive range the sensitivity of M1 is reduced to one-tenth by the shunt R12 and the resistor R11 added to restore the total resistance to its normal value. The third winding of the magnetic amplifier passes current which is derived from R1, R2 and R3. This latter potentiometer provides a 'fine control' with a coverage of ± 1.5°C., and is graduated in tenths of a degree. The network also supplies a small bias current to the magnetic amplifier to keep it on the

linear part of its characteristic under normal conditions. The fourth winding of M.A.1 compensates the magnetic amplifier for changes in applied voltage and frequency, so that mains voltage changes of ± 15% and of mains frequency changes of ± 5% produce changes in the control point of less than ± 0.05°C. The non-standard value of the voltage applied to the A.C. windings of M.A.1 (5.2 V) is due to the amplifier having been designed for a nominal voltage of 5V and on test showing the required degree of compensation for input voltages of 4.4 to 6.0 V, which gives a nominal mid-point voltage of 5.2. The transformer supplying this voltage was later designed to give an output voltage of 5.2V at nominal mains input voltage (230V). The fifth winding of M.A.1 provides positive feedback, enabling a stable current gain of approximately 100 to be achieved. The main purpose of the filter network C1, L1, C2, is to prevent the induced voltages from the input winding of M.A.2 from reaching the rectifier M.R.1. The second winding of M.A.2 provides bias, and the third winding positive feedback to give a current gain of 15 to 20. The relay Ry1 requires approximately 10mA to energise it and releases at approximately 5mA. The sensitivity of the whole system is such that a change of 0.05°C. at the thermistor is sufficient to operate the relay. Operation of Ry1 causes the hotwire vacuum switch HVS1 to operate, and this controls either or both the 0.5 and 1 kW heaters, according to the setting of S3 and S4.

The circuits associated with V1 control the movement of the Variac which adjusts the heat dissipated

in one of the 6 kW heaters. The switch S5 allows the choice of a time interval, adjustable in steps over the range 15 to 150 sec. If the time that the small heater stays on or off exceeds this figure the Variac is caused to increase or reduce, respectively, the voltage applied to the 6 kW heater by a fixed amount. Thus under steady-state conditions, when the backing heat is correctly adjusted, the small heater cycles in a regular fashion and the Variac is unaffected, but when thermal demand or power line voltage changes, the duration of the on or off part of the cycle changes and the Variac is automatically adjusted in the correct direction.

The mode of functioning is as follows: Assume Ry1 to be energised at time 0. Ry3 is energised at the same moment. C5 is discharged through R16 and R17 via contact Ry3a. The top of C4 is connected to the anode of V1 via Ry3b, and the bottom of C4 is connected via Ry2a (since the screen of V1 is passing current) to the anode of V2b, to R18 and thence to the grid of V1, and to the selected resistor R19 to 24. C4 therefore starts to charge through R25 and R24; whilst its lower plate is positive it also charges via V2b and to some extent via the grid of V1, although the grid stopper R18 prevents excessive grid current. Since the grid of V1 is thus at approximately cathode potential both screen and anode conduct heavily and so the voltage at the anode is low. C4 continues to charge via R24 to a voltage which is the difference between the anode voltage of V1 and the -15V line. As it does so the voltage at the grid of V1 falls and that at the anode rises. It may be shown that during this period of

Miller action the time taken for the anode voltage to increase by an amount Va is approximately

$$t = \frac{Va}{Vb} \frac{CR}{A} \frac{(1+A)}{} \qquad (1)$$

where Vb is the voltage at the end of R24 remote from the grid (approx. 15V), and A is the steady voltage gain between grid and anode of V1 (which here is in the range 100 to 200). When the voltage at the anode of V1 reaches that at the cathode of V2a (150V) the latter valve conducts, preventing the anode voltage of V1 from rising further and reducing A to zero. The elapsed time from the beginning of the cycle to this occurrence is obtained from equation (1) :-

$$t = \frac{150\ CR}{15} = 10\ CR$$

After the damping of the anode voltage of V1, C4 is left to charge freely via R24. In effect it has applied to it slightly less than 15V in series with R24. The grid cut-off voltage of V1 is approximately -5V and the time taken to reach this point after C4 starts charging freely is of the order of $\frac{1}{2}$ CR. It is apparent that after the anode of V1 reaches 150V the valve is rapidly cut off. The screen current drops rapidly to zero and the relay Ry2 released, discharging C4 via the contact Ry2a and R17, and also isolating C7 from the -15V line. C7 discharges through the selected resistor R26 to 33 and as it does so the grid of V1 rises expontentially at a rate determined by the time constant C7 R26 (or whichever resistor is selected by S6c). When the grid reaches approximately -3V the screen current is sufficient to energise Ry2, and C4 is

again placed between anode and grid of V1, taking the grid to earth potential and assisting the fast action of Ry2. A very short time later C7 has charged via contact Ry2c and R35 to -15V, and the circuit is in its original condition. During the time that Ry2 is released the contact Ry2b applies the neutral 230V mains lead to a capacitor motor which drives the Variac transformer. The other mains lead is connected to the relay contact Ry3c, and according to the state of this relay (i.e. as to whether the chamber is too hot or too cold) is connected to that lead of the motor which decreases or increases respectively the output from the Variac. The time for which the motor runs, i.e. the relative change in voltage output from the Variac, is adjustable from 1 sec. to 3.5 sec. by means of S6.

Should Ry1 stay on for a considerable length of time, the cycling action of V1 described above continues at the interval selected by S5. When Ry1 is released, owing to the chamber having reached the desired temperature, C5 is brought into circuit in place of C4. As long as the alternation of Ry1 continues at time intervals less than the value selected by S5 the anode of V1 can never reach 150V and so Ry2 is not affected.

Other facilities are available with S6, which (a) switch off the motor driving the Variac transformer so that its position is not automatically adjusted, (b) cause the motor to drive the Variac in the direction necessary to increase the voltage output, and (c) cause the motor to decrease the Variac output. Under each

of these conditions the bias on V1 is held at -15V so that the valve does not overheat.

Provision is made for the remote switching of the large heaters so that the mains cables carrying large currents need not be brought to the control cabinet. S8 supplies voltages to the coils of three heavy-duty relays which control the supply to the heaters. These relays were modified from War Surplus equipment and were rewound with 1000 ohm coils to operate at approximately 30mA. The switching arrangement shown in the diagram was found to be the best and most economical method of switching these relays to give steps of 0 kW, 0 to 6 kW (from the Variac), 3 to 9 kW, 6 to 12 kW, and 9 to 15 kW. Each heater has a current transformer placed in its supply line so that the current through any heater may be monitored on a meter M2 in the control cabinet.

The humidity control system

The absolute humidity of a volume of air is the weight of water vapour contained in unit volume of that air. It is conveniently expressed in mg/l. If the volume of air is heated the absolute humidity remains constant, whereas the relative humidity and the wet-bulb temperature change greatly. Further, the amount of water which must be added to a given volume of air to change its absolute humidity from one value to another is proportional to the difference in absolute humidity, independently of temperature, whereas the amount of water vapour added to change the relative humidity or the wet-bulb temperature by a fixed amount varies greatly with

temperature. Thus in a humidity control system utilizing proportional action, the choice of absolute humidity as the controlled physical quantity is far more logical than that of relative humidity or wet-bulb temperature, and simplifies the design of a stable control system.

An examination of the possibilities of using the existing electrode boiler disclosed an elegant control system which is believed to be quite novel. The boiler was equipped with a motor-driven pump to fill it with water, and a magnetic valve to empty it. The principle of operation of such a boiler is that the water acts as an electrolyte, carrying the current between the three electrodes immersed in it. The current, and hence the rate of generation of steam, is proportional to the length of electrode immersed in the water, i.e. to the level of water in the boiler. Included in one of the power leads to the boiler was a current transformer from which was available a voltage proportional to the current taken by the boiler. It was thus possible to oppose this voltage with another voltage and cause the difference, if positive, to operate a relay to cause water to be pumped into the boiler; if negative to let water out of the boiler; and if approximately zero to maintain the status quo. Such a system is in effect a boiler current control system which can hold the boiler current constant at any desired value. It now becomes possible for the desired value of boiler current to be proportionally controlled by the deviation of the absolute humidity from its own desired value, the steam so gen-

erated tending to reduce this deviation to zero. Such a control system consists of two closed loops, the main loop being the humidity control and the subsidiary loop the water-level control for the boiler. Since the air-flow through the chamber and the volume of the chamber are constant, a given rate of injection of steam (or a given boiler current) produces a certain change in the absolute humidity of the air in the chamber. It was calculated from the parameters of the system that, working at nominal mains input voltage, 1A increase in boiler current should increase the absolute humidity of the air in the chamber by 1.6 mg/l.; experimentally it was found that 1A boiler current increased the absolute humidity by 1.50 mg/l.

By the use of electrical instruments to measure humidity, changes in absolute humidity of the air may be converted into electrical changes which are directly comparable with those representing boiler current, and thus with the potential correction to the absolute humidity of the chamber. On this basis it is possible to define a control factor, which is the ratio of the potential correction to the deviation of the absolute humidity. It is well known that a large value of control factor, whilst tending to maintain the deviation very low, gives rise to oscillation in the system. An analysis has been made of the present system to determine the optimum value of control factor for it. It was determined experimentally that (as would be expected from theoretical considerations) the delay in the response of the humidity detecting element, the delay

between an increase in demand of boiler current and the increase in actual rate of generation of steam, and the decay of the absolute humidity of the chamber on stopping the input of a constant flow of steam, were all exponential functions of time. It was found that the time constants of the processes were 1.0 min. for the humidity detecting element, o.2 min. for the boiler, and that the decay time of the chamber was best represented by the product of two exponential functions with time constants of 2.5 and 0.3 min. respectively.

If the system be drawn in the symbolism of electrical engineering as in Fig.19 it is obviously very similar to the circuit of the well-known phase-shift oscillator. For this the conditions required for oscillation are easily calculated. The transfer characteristic of the network (without the feedback represented by the dashed lines) is:

$$\frac{Vo}{Vi} = \frac{A}{(1+j\omega T_1)(1+j\omega T_2)(1+j\omega T_3)(1+j\omega T_4)} \qquad (1)$$

The requirement for stability of such a system with feedback is that $Vo/Vi > -1$ for a phase shift of $(2n-1)\pi$ under conditions of no feedback. The phase shift is $(2n-1)\pi$ when equation (1) contains no imaginary component, i.e. when:

$$-j\omega(T_1+T_2+T_3+T_4) + j\omega^3 (T_1T_2T_3 + T_1T_3T_4 + T_1T_2T_4 + T_2T_3T_4) = 0$$

Substituting the values given earlier:

$$\omega = 1.66 \text{ radians/min.}$$

This corresponds to a period of oscillation of 3.8 min. The ratio of the amplitudes of Vo and Vi is:

$$\frac{|Vo|}{|Vi|} = \frac{A}{\sqrt{\{(1+\omega^2 T_1^2)(1+\omega^2 T_2^2)(1+\omega^2 T_3^2)(1+\omega^2 T_4^2)\}}}$$

Substituting the value of $\omega = 1.66$ from above:

$$\frac{|Vo|}{|Vi|} = \frac{A}{9.5}$$

Thus the system should be stable for gains of less than 9.5. The gain of the amplifier in this system is equivalent to the control factor in a control system, and so in the present humidity controller a value of 8 was chosen for the control factor, giving a factor of safety of approximately 20%. It may be stated here that when the control system was eventually installed and tested, oscillation was found to occur with a control factor of approximately 10 and having a period of 3.4 min.

Whilst comparing the various methods of expressing humidity the author found that values of absolute humidities calculated from published tables (Hodgman, 1945) of relative humidities and wet- and dry- bulb temperatures, and of the variation of the density of saturated steam with temperature, could be plotted graphically in the form of Fig.20. The departure of the calculated points from the family of straight lines is obviously very small. The diagonal line on the graph, corresponding with the points where wet- and dry-bulb temperatures are equal, denotes the condition of saturation. Humidities to the left of and above this line cannot of course be realised, as is shown by the dotting of the extensions of the lines representing humidities from 35 to 50 mg/l.

Fig.20 shows that at any given absolute humidity, a variation in dry-bulb temperature results in a pro-

portional change in wet-bulb temperature. The midpoint of the range of dry-bulb temperatures of interest here is 30°C. Consider now a pair of identical electrical thermometers, over one of which is a wetted wick. Place the dry thermometer in a bridge circuit so that its output at 30°C. is zero, and attenuate the output from the bridge by a factor which is equal to the slope of the line in Fig.20 representing the desired value of absolute humidity. This is the correction for the influence of dry-bulb temperature and must be added to the electrical quantity representing wet-bulb temperature. By subtracting a quantity equivalent to the wet-bulb temperature for the desired absolute humidity at 30°C. dry-bulb temperature an output proportional to the deviation of absolute humidity from its desired value is obtained, Since the absolute humidity lines on Fig.20 are not equally spaced this relationship is not absolutely linear, but over a range of ± 5 mg/l. from any desired value the departure from linearity is less than ± 5% or ± 0.25 mg/l. This principle has been adopted in designing the present absolute humidity control system.

Fig. 21 is the circuit diagram of the humidity controller. The stages up to and including M.A.1 are very similar to the corresponding part of the air temperature controller of Fig.18. There are however two important differences. An extra control winding (no.2) is included in the magnetic amplifier and to this is applied the dry-bulb temperature correction derived from Th.2 and the bridge circuit consisting of R34, R37 and R38. The bridge is designed to be balanced when Th.2

is at 30°C. and the out-of-balance current flowing through winding 2 is designed to be in the correct proportion (as indicated in Fig.20) to the wet-bulb error signal flowing through winding 3. Correct variation of this factor of proportionality is achieved by the variable resistors R35 and R36 which are adjusted by a section of the switch S1 used to select the desired value of absolute humidity. This dry-bulb temperature correction may be switched out of circuit by the switch S3 (b) which enables wet-bulb temperature - as opposed to absolute humidity - to be controlled, although as explained earlier this is less effective.

The output of M.A.1 is developed across R15. Since M.A.1 must work on the linear part of its characteristic a standing current flows through R15 when the currents through the control windings are correctly balanced. The resultant voltage across R15 is cancelled by the bias network R16, R17 so that under balance conditions zero voltage appears between the top of R15 and earth. The resistance of the attenuators R18 and R19 across the output is very large compared with R15 and R17 and so the variation in load on the magnetic amplifier is negligible when they are adjusted. R19 is a stepped attenuator and is adjusted by one section of the switch S1 which is used for setting the required value of absolute humidity. It ensures that the absolute humidity error signal fed to R20 is directly proportional to the actual error and is not a function of the desired value. R18 is a preset control which enables the gain of the system (the value of control factor), to be

adjusted to itw optimum value. The transfer characteristic of this humidity transducer is such that a change in absolute humidity of 1 mg/l. produces an output of 0.5 V, and the equivalance is practically linear over a range of ± 4 mg/l.

The meter M1 is shown in the circuit diagram as measuring only deviation of wet-bulb temperature. In fact S2 is a multiposition switch and may be used to allow M1 to indicate deviation of absolute humidity from its desired value.

The valve V1 serves to match the high impedance output from R19 to the low impedance input windings of M.A.2 and M.A.3. It formerly served a second purpose which has since been discarded. The inclusion of a large-capacity condenser between the anode and grid of V1 results in the effective placing of an integrating circuit of long time constant in the input circuits, and with this it was hoped to achieve increased efficiency of operation by the addition of some integral control action; this proved unsatisfactory and removal of the condenser left the circuit as shown.

The current taken by the electrode boiler is measured by the circuit containing T1 and M.R.7. The original cohtractors' installation included a current transformer in one phase of the 3-phase mains supply to the boiler. When suitably loaded this current transformer gives an output of 1V for each 10A of boiler current. T1 is included in the present circuit to step up this voltage by a factor of 7, so that at 50A boiler current (which is rather greater than the maxi-

mum required in this installation) 35 V (as against the 36 V max. recommended by the makers), are applied to M.R.7. The direct current output from M.R.7 under these conditions varies linearly with boiler current in the range 2 to 50A, but becomes non-linear below 2A. This is, however, below the minimum of 3A which is normally required by the system. Boiler current is indicated on the 5mA meter M2 which is calibrated 0 to 50 A and of which the pointer is offset +1A to give correct indication of boiler current from 2 to 50 A. The relay R3 operates at 4.5mA and opens at 3.5mA. The contact Ry3a is in series with the output from M.A.2 and switches off the pump when boiler current exceeds 45A. The current from M.R.7 also passes through a control winding of each of M.A.2 and M.A.3; through other identical windings in these magnetic amplifiers passes the current from the network consisting of R26, R27 and R28. R27 is used to set the approximate boiler current (within ± 5A) which the given humidity conditions are expected to require. It has an inverse semi-log law and circuit values have been chosen so that the scale on the setting control for boiler current is approximately linear. Control currents flow in opposite directions through the two magnetic amplifiers, so that an increase of (for example) boiler current tends to energise Ry2 and de-energise Ryl. Bias on the magnetic amplifiers is such that when the boiler current is correct neither Ryl nor Ry2 are energised, but a change of 0.5A boiler current operates one or other relay. There is thus a dead zone of 1A in the control of the boiler current. This,

together with the small time delay introduced by the magnetic amplifiers, prevents small and rapid variations in boiler current caused by bubbles of steam at the electrodes from operating the pump or the magnetic valve. It also prevents oscillations caused by the introduction of too much water into the boiler by the pump with subsequent overshoot of the falling water level when the magnetic valve opens. It is possible for the system to run for long periods during which the only control action is the replacement of the water boiled away as steam.

A subsidiary circuit is associated with M.A.2 which ensures that the making of the contacts Rylb and Rylc which operate the pump motor is very rapid. At the moment that Ryl is energised sufficiently to operate the contact Ryla, C4 - which has been charged to 150 V via R32 - is discharged through a winding of M.A.2 and causes rapid action of the relay. C4 is rapidly discharged and does not affect the circuit when the main control currents cause the relay to be released. Override switches S4 and S5 are included so that the pump may be stopped and the magnetic valve opened to empty the boiler rapidly. Metrosil surge suppressors are fitted across the pump motor windings and across the coil of the magnetic valve. The switch S3 enables either wet-bulb temperature, absolute humidity or boiler current to be controlled; independent control of the latter is very useful in allowing the humidity to be changed very rapidly by manual rather than automatic means.

The +300V and -150 V supplies are obtained from

stabilised lines of low impedance output used for other equipment; the +150 V is obtained from a non-stabilised line of similar origin. The 8 V line, which is shared with the dry-bulb temperature controller, is obtained from a magnetic amplifier circuit rather similar to that of Fig.31 but supplying 8V at 40 to 60 mA with a constancy of ± 1%.

Plate 4 is a photograph of part of a chart from an independent wet- and dry- bulb temperature recorder, and shows the degree of control achieved with the system.

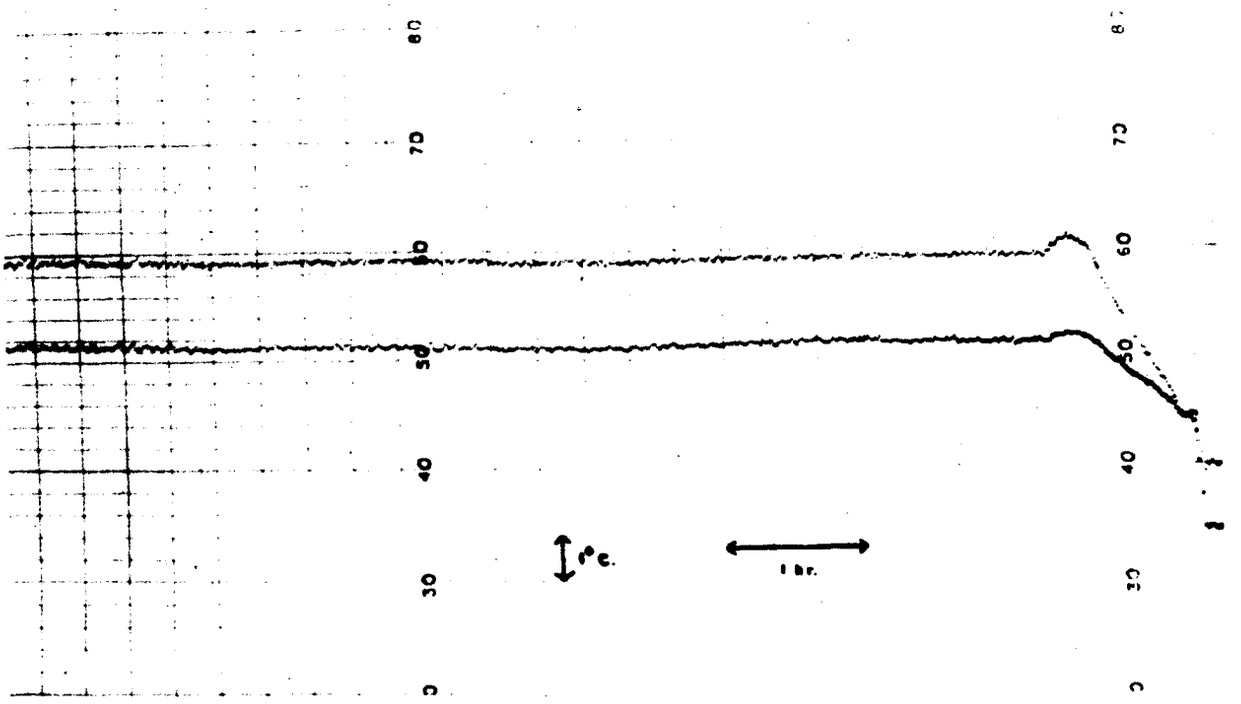

Plate 4. Reproduction of a portion of a chart from a recorder, showing the accuracy of the temperature and humidity control of the psychrometric chamber. The top trace is the dry bulb temperature and the lower trace the wet bulb temperature. The time scale reads from right to left. The air temperature was originally 20°C. and the absolute humidity 15 mg/l.; the controllers were reset to 25°C. and 20 mg/l. and left for a few hours whilst this recording was made. The calibration of the recorder is such that 60 on the chart is 25.2°C. and 40 is 20.2°C.

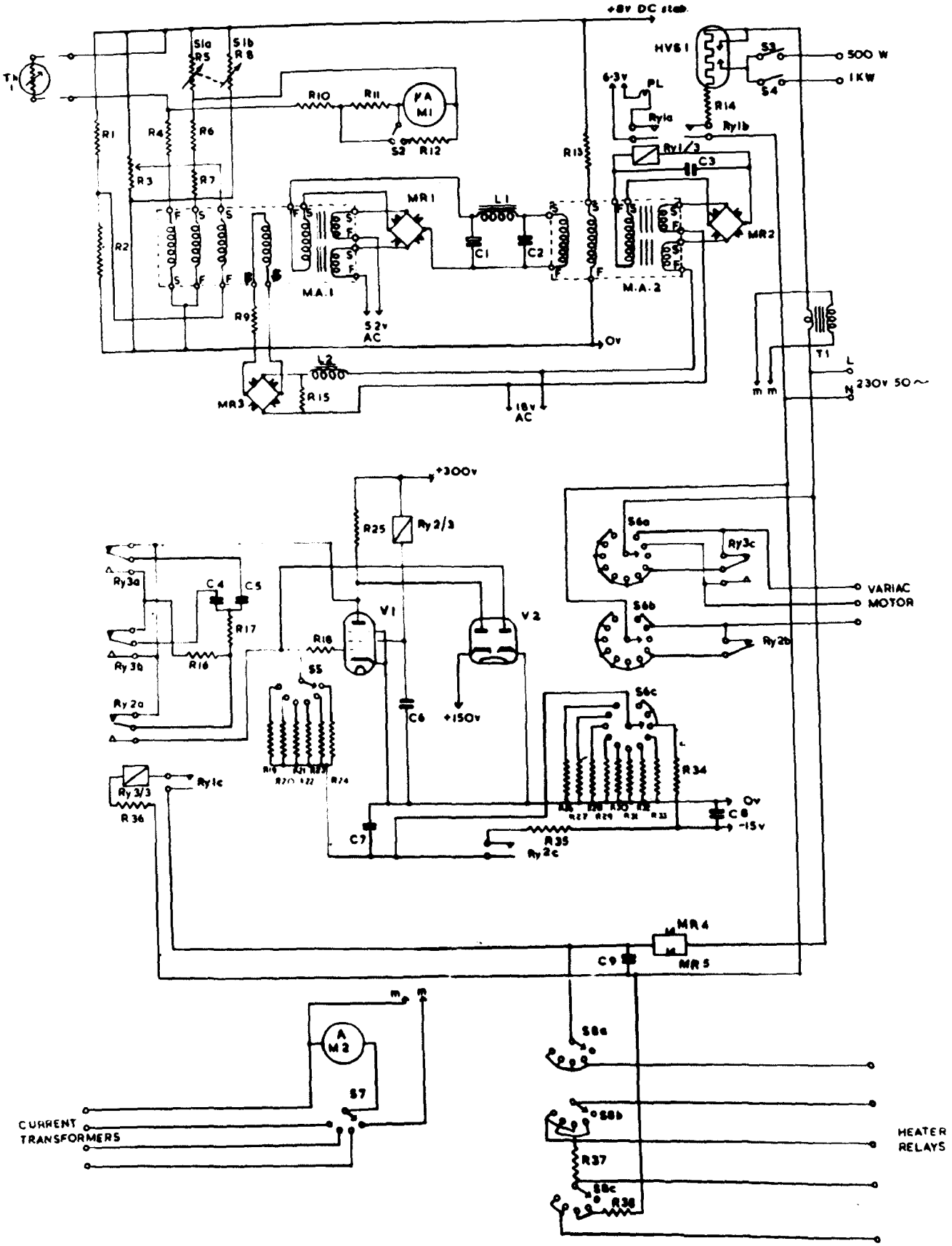

Fig.18. Circuit diagram of the air-temperature control unit used in the psychrometric chamber.

Key to Fig. 18

R1	13K	1%	HS
R2	6.8K	1%	HS
R3	2.5K	WW Pot	
R4	414Ω	0.1%	Const
R5	2463Ω	0.1%	tapped Const
R6	53Ω	1%	Copper
R7	414Ω	0.1%	Const
R8	See last column.		
R9	8.4K	1%	HS
R10	11.6K	1%	HS
R11	3.9K	1%	HS
R12	490Ω	1%	HS
R13	2.9K	2%	HS
R14	10K	5%	WW (7W)
R15	590Ω	1%	HS
R16	100Ω	20%	
R17	2.2K	20%	
R18	100K	20%	
R19	3.3M	5%	
R20	2.2M	5%	
R21	1.5M	5%	
R22	1M	5%	
R23	680K	5%	
R24	470K	5%	
R25	47K	10%	(2W)
R26	3.3M	10%	
R27	2.2M	10%	
R28	1.5M	10%	
R29	1M	10%	
R30	680K	10%	
R31	470K	10%	
R32	390K	10%	
R33	270K	10%	
R34	220K	20%	
R35	4.7K	20%	
R36	20K	10%	(5W)
R37	1K	10%	(3W)
R38	1K	10%	(3W)
L1	2H	10Ω	10mA
L2	5H	30Ω	50mA

C1	25μF	12V
C2	25μF	12V
C3	50μF	25V
C4	4μF	600V paper
C5	4μF	600V paper
C6	4μF	450V
C7	2μF	350V paper
C8	50μF	25V
C9	8μF	450V
V1	EF50	
V2	EB34	
MR1	S.T.C.	B7
MR2	S.T.C.	B7
MR3	S.T.C.	B7
MR4	S.T.C.	H18-26-1RW
MR5	S.T.C.	H18-26-1RW
M1	12½-0-12½ μA	4440Ω Calibrated 2.5-0-2.5
M2	0-5mA A.C. M.C. rect.	Calibrated 0-30 A
Ry1/3	P.O.	1000Ω 3M (5A)
Ry2/3	P.O.	20K 1B,1M,1C0
Ry3/3	P.O.	3K 300
S1	Oak type G 24way 2wafer	
S2	Single pole changeover	
S3	250V 10A	on-off
S4	250V 10A	on-off
S5	Oak type H 6way 1pole	
S6	Oak type H 11way 3wafer B.B.M.	
S7	Oak type H 4way 1pole	
S8	Oak type H 5way 3wafer B.B.M.	
M.A.1	See next column.	
M.A.2	See next column.	
Th.1	S.T.C. thermistor type K2361/120	

R8

For S1 set to	15-22°C.	2K 5%
	24-28°C.	2.7K 5%
	30-34°C.	4K 10%
	35-38°C.	8K 10%
	40-45°C.	Infinite.

M.A.1

Cores. 2. Each 91 stampings 0.005" Mumetal size 226E

A.C.Windings. On each core 200 turns 30 SWG

Feedback and control windings.

a.	210 turns	30 SWG	(no.5 in text)
b.	400	40	4
c.	400	40	3
d.	2500	40	2
e.	2500	40	1

M.A.2

Cores. 2. Each 91 stampings 0.005" Mumetal size 226E

A.C.Windings. On each core 600 turns 40 SWG

Feedback and control windings.

a.	630 turns	40 SWG	
b.	4500	44	
c.	1000	38	

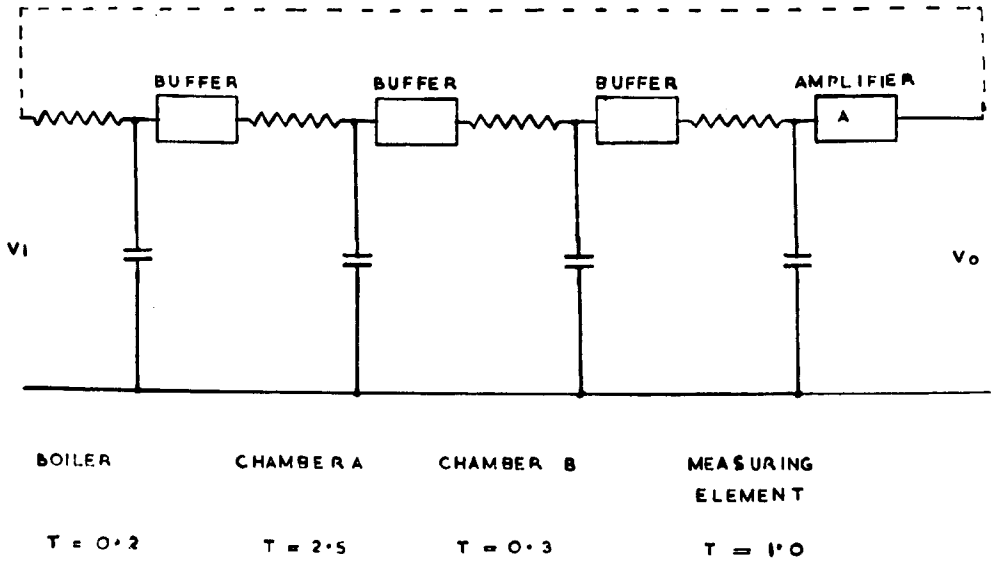

Fig. 19. Diagram showing the similarity of the humidity control system of the psychrometric chamber to an electronic phase-shift oscillator.

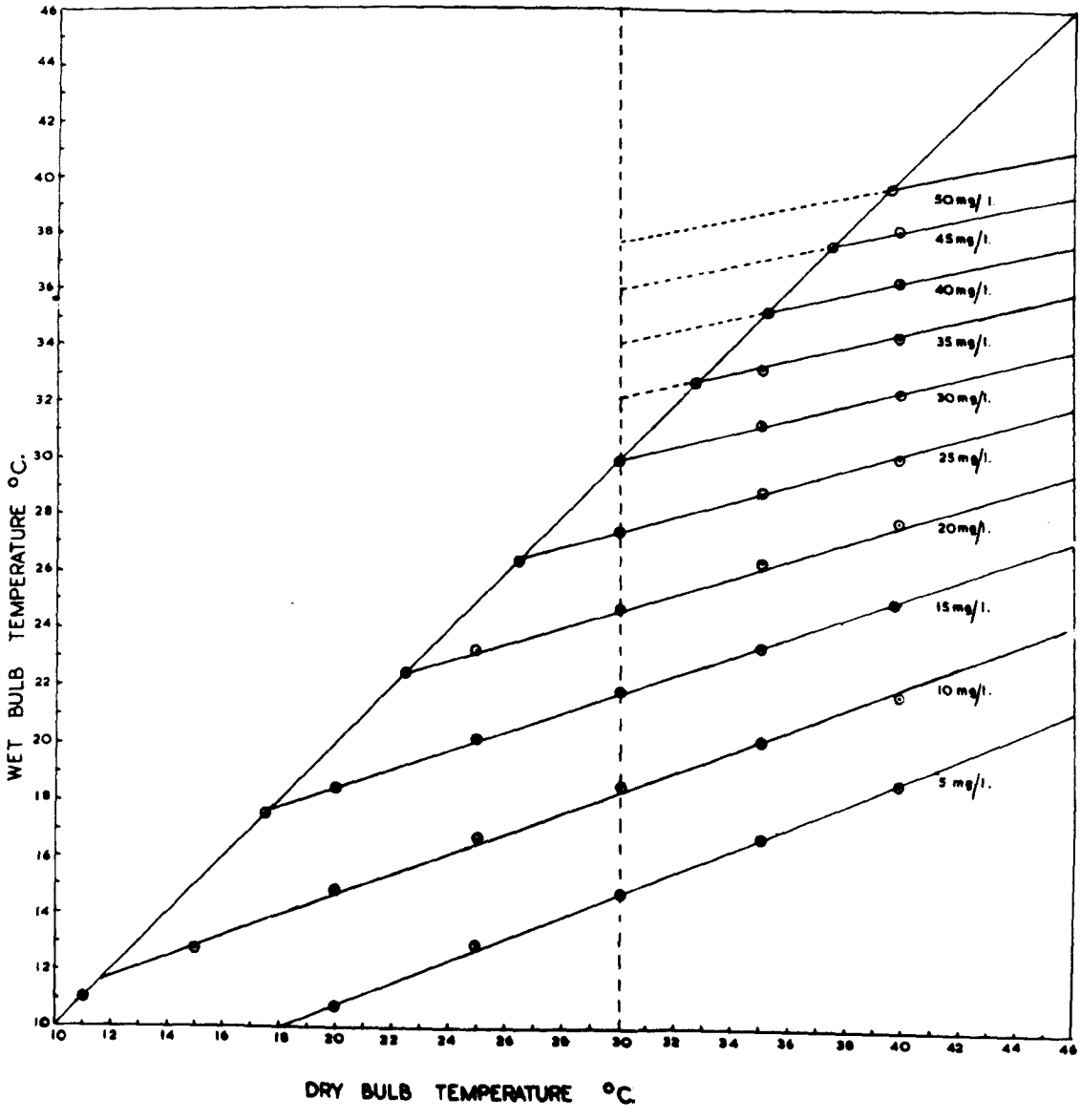

Fig.20. The relationship between absolute humidity and wet- and dry- bulb temperatures. The points on this graph were calculated from the tables of 'Relative Humidity from Wet- and Dry- Bulb Thermometers' and of 'Properties of Saturated Steam (Density)' collected by Hodgman (1945).

Key to Fig. 21

R1	3.3K	1% HS
R2	7.2K	1% HS
R3	1.8K	1% HS
R4	2.5K	WW pot
R5	570 ω	0.1% const
R6	2463 ω	0.1% const tapped to match thermistor
R7	See last column	
R8	570 ω	0.1% const
R9	30 ω	2% copper
R10	8.2K	1% HS
R11	590 ω	1% HS
R12	12K	2% HS
R13	3.9K	2% HS
R14	490 ω	2% HS
R15	1K	2% HS
R16	56K	1% HS
R17	1.5K	1% HS
R18	100K	WW pot
R19	See last column	
R20	1M	10%
R21	33K	2% HS (1W)
R22	750 ω	5% HS
R23	500 ω	WW Pot
R24	33K	5% HS (2W)
R25	39K	5% HS (2W)
R26	2.7K	1% HS
R27	2.5K	WW pot (Law ISL)
R28	540 ω	1% HS
R29	10K	10%
R30	10K	10%
R31	25K	1% HS
R32	330K	10%
R33	1M	20%
R34	1680 ω	0.1% const
R35	See last column	
R36	See last column	
R37	1680 ω	0.1% const
R38	1252 ω	0.1% const
R39	1.2K	2% HS
C1	50μF	25V
C2	50μF	25V
C3	50μF	25V
C4	2μF	350V
C5	8μF	350V

MR1	S.T.C. B7
MR2	S.T.C. B7
MR3	S.T.C. B7
MR4	S.T.C. B7
MR5	S.T.C. B7
MR6	S.T.C. B45-1-1FW
R5,6,8,12	specially matched to Th1
R34,35,36,37,38	specially matched to Th2
Th1	S.T.C. thermistor type K2361/120
Th2	S.T.C. thermistor type K2361/120
Ry1	PO 1000 ω/2M,1CO
Ry2	PO 1000 ω/2M
Ry3	PO 2000 ω/1B
PL1	Miniature neon
P12	6V 0.06A
L1	5H 30ω 50mA
T1	1:7 step-up
M1	12.5-0-12.5 μA MC 4430 ω Calibrated 2.5-0-2.5
M2	0-5 mA DC MC Calibrated 0-50 A
S1	Oak type G 2lway 5wafer
S2	Oak type H 11way 2wafer
S3	Oak type H 3way 2pole
S4	Toggle on-off
S5	Toggle on-off
V1	EF50

T°C.	AH mg/l	R6 (ω)	R7 (ω)	R19*	R35 (ω)	R36 (ω)
15	5	2643	2200	9	∞	0
16		2349	"	"	"	"
18		2136	"	8	"	"
18.5	10	2086	"	"	3900	47
20		1946	"	7	"	"
22	15	1776	"	"	"	"
24		1621	2700	6	"	"
25	20	1548	"	"	1800	82
26		1481	"	5	"	"
27.5	25	1385	"	"	"	"
28		1355	"	4	"	"
30	30	1242	3900	"	1000	150
32	35	1139	"	3	"	"
34	40	1045	"	2	680	180
35		1001	8200	1	"	"
36	45	960	"	"	"	"
37.7	50	895	"	0	470	220
38		884	"	"	"	"
40	60	815	∞	"	270	270
42		752	"	"	"	"
44		694	"	"	"	"
45		664	"	"	"	"
Tolerances		0.1%	5%	-	5%	5%

*R19 consists of a 41K 2% HS resistor in series with nine 6.8K 2% HS resistors, one end of the 41K resistor being earthed The numbers in this column refer to the tappigg point with reference to the number of 6.8K resistors between the required point and R18.

M.A.1

Cores 2. Each 91 stampings 0.005" Mumetal type 226E.

A.C.windings. 600 turns, 40 SWG each core.

Feedback and control windings, over both cores together:-

a.	630 T	40 SWG	(winding 7 in fig.)
b.	60	40	6
c.	1200	44	5
d.	2000	40	4
e.	2000	40	3
f.	2000	40	2
g.	320	44	1

M.A.2 M.A.3 each:-

Cores 2. Each 91 stampings 0.005" Mumetal type 226E

A.C.windings. 720 turns, 38 SWG each core.

Feedback and control windings, over both cores together:-

a.	756	T	38	SWG
b.	72		38	(not used)
c.	720		40	
d.	1440		40	
e.	1440		40	
f.	2160		40	
g.	1440		44	(only in M.A.2)

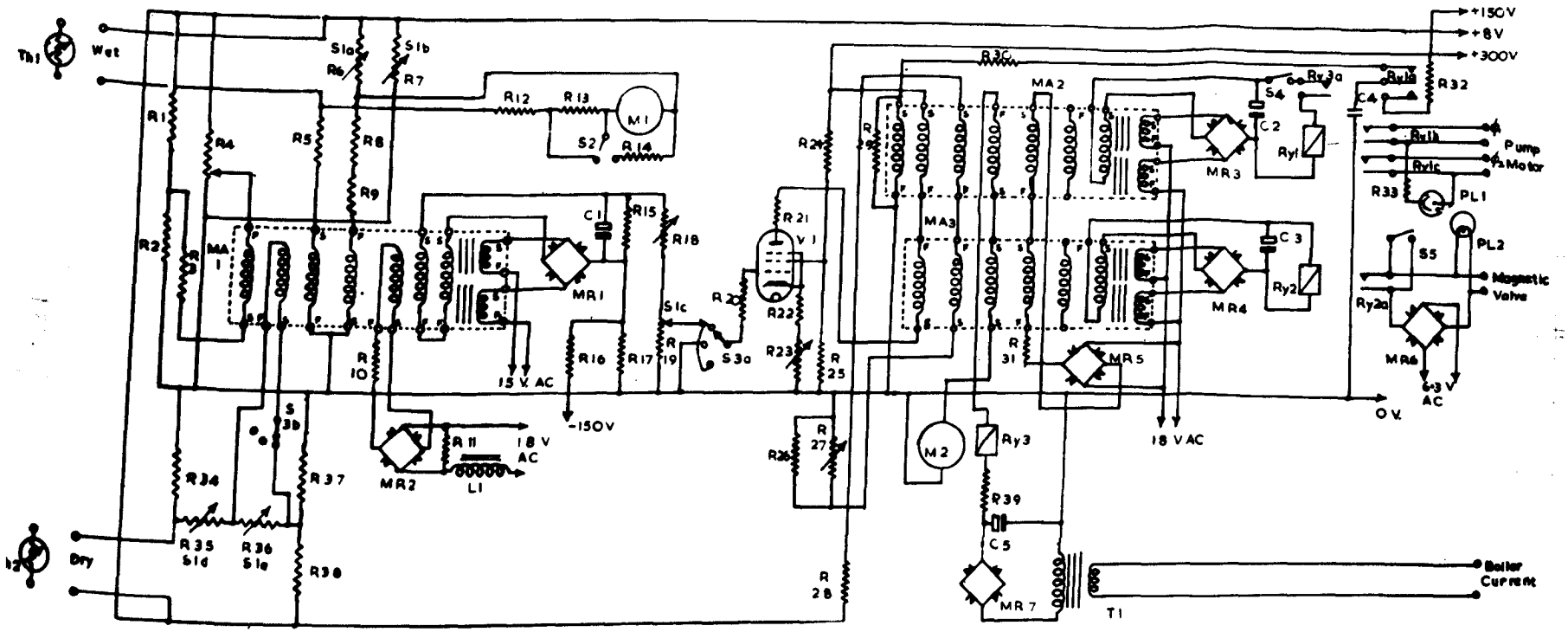

Fig. 21. Circuit diagram of the humidity control unit used in the psychrometric chamber.

Chapter 9

The Measurement of Temperature

Thermometers

Many papers, reviews and books have been written on the measurement of temperature. Of these, the most convenient collection is a series of papers read at a Symposium held in 1939, published under the auspices of the American Institute of Physics. In it liquid-in-glass thermometers were discussed by Busse (1941), thermo-electric thermometers by Roeser (1941), resistance thermometers by Mueller (1941), and other aspects of temperature measurement by Scott (1941) and by Roeser & Wensel (1941). In other publications Bedford & Warner (1934), Murlin (1939) and Elder (1941) have reviewed methods of measuring skin temperature. Aldrich (1928) and Hardy (1939) have described radiometers for the measurement of surface temperatures but for various reasons these radiometers are unsuitable for universal application. Findlay (1950) has reviewed the measurement of temperature in environmental physiology, and Prouty & Hardy (1950) have reviewed the subject of temperature measurement for biological purposes. Powell (1935), Ewell (1941) and Lorenzen (1941) have discussed the measurement of environmental dry- and wet- bulb temperature, whilst Vernon (1934) and Bedford (1946) have described the use of globe thermometers for measuring the mean temperature of the surroundings, combining the air and wall temperatures into one figure.

The accuracy of the methods used to measure temperature is of fundamental importance in studies of the effect of heat on animals. In the experimental procedures dealt with in this thesis, where the temperatures of a large number of objects of different kinds have to be read in rapid succession, the chief requirements of the temperature measuring system are:-

(a) All readings must be presented at one central position.

(b) The calibration of the thermometer scale must be directly in degrees centigrade; i.e. it must be unnecessary to convert any reading of arbitrary units into degrees.

(c) The temperature-sensitive element must be capable of being fixed to the skin without affecting heat loss or blood circulation. It must be capable also of accurately measuring surface temperature or air temperature, and of being used as a rectal thermometer.

(d) The accuracy of the system must be within $\pm$ 0.1°C.

(e) The range of temperature over which accuracy must be maintained is 15 to 45°C.

(f) In order to be unaffected by the conditions in a badly-ventilated observation room the instrument must hold its accuracy at ambient temperatures of between 12 and 30°C. under conditions of rapidly changing temperature.

(g) All temperature-sensitive elements must have identical characteristics to obviate the necessity for a large number of individual calibrations.

(h) The temperature-sensitive elements must be either very robust, or else cheap and easily made and replaced.

(i) The complete temperature measuring system must be simple to use, quick in response, and require the absolute minimum of adjustment.

The device which most nearly satisfies these conditions is the thermocouple or thermoelectric thermometer. The major difficulties inherent in its use are:-

(a) A very sensitive indicating instrument is required.

(b) A reference junction must be provided.

(c) Stray thermoelectric and electrolytic potentials may cause errops.

(d) A potentiometric method, or some adaptation of it, must be used when high accuracy is required.

(e) Inhomogeneities in wiring must be avoided.

A more comprehensive list of the possible sources of error is given in a number of papers by White (1914a, 1914b, 1933) who has also devised a rapid method for detecting inhomogeneities in long samples of constantan wire.

The temperature measuring system developed by the present writer for these studies overcomes all these difficulties and is described in the following pages.

<u>The Thermoelectric Thermometer used in the present studies</u>

Fig.22 is a schematic diagram of the thermometer. G is a self-contained reflecting galvanometer whose sensitivity is approximately 2 cm/microamp and resistance

25 ohms. RJ is a special reference junction, described later, the effective temperature of which is maintained constant to within ± 0.05°C. of a chosen value although its actual temperature may vary between the limits 10 to 30°C. A switch is incorporated so that the effective temperature may be set to 20.0, 30.0 or 40.0°C. The thermocouples are of 40 S.W.G. copper and constantan wire, and since the resistance of the required length of this gauge of wire is prohibitively great a 'compensating lead' of 28 S.W.G. wires of similar materials is used. Switching from one couple to another is performed with specially designed switches, which prevent the introduction of spurious E.M.F.s. Close tolerances of length (and hence of resistance) are held on all thermocouples and leads so that they do not vary more than ± 0.5 ohms from a nominal value. The galvanometer as purchased was calibrated in centimetres, with minor divisions at 2 mm intervals, and with a centre zero on a curved scale. That part of the scale between the limits -5cm and +5cm is in this application read as degrees C. to be added to the effective temperature of the reference junction. The meter deflection being linear to within 1%, the temperature may be read on it (assuming the temperature-E.M.F. characteristic of the thermocouple to be linear) to 0.05°C. over a range of 15 to 45°C. It will be shown later that the overall long-term error of this system is less than 0.1°C.

The Galvanometer

The galvanometer used in the instrument is a Cambridge Spot Galvanometer of nominal resistance 20 ohms. When used in series with a resistance of about 60 ohms it is effectively a microvoltmeter of sensitivity approximately 1 cm/40 microvolts. Of three galvanometers of this type tested, all were linear to within 1% over a deflexion range of -5 to +5 cm., but one in particular was outstandingly good, being absolutely linear to within the accuracy of observation (i.e. ± 0.5 microvolt, ± 0.3 mm.) over a range -6 cm. to +7 cm. It was expected that the galvanometer would show a temperature coefficient of voltage sensitivity and preparations were made to compensate for this, but over a range of ambient temperature from 13 to 35°C. the temperature coefficient was found to be zero. However, a slight drift of the galvanometer zero, amounting to 2 mm. over the above ambient temperature range was apparent. Also, a drift of 2 mm. was found to occur during the first hour after switching on the galvanometer lamp, presumably due to the differential heating effect of this lamp on the internal leads.

In order to allow a zero adjustment of the meter to be made occasionally, a switch has been incorporated which disconnects the thermocouple circuits from the meter and substitutes a manganin resistor of the same resistance.

The total resistance of the circuit in series with the galvanometer is such that the meter is slightly overdamped, allowing a reading to be taken within 3 to 4 sec. of the application of an E.M.F.

The Thermocouples and Leads

There is practically no choice of materials for the thermocouples. The short life obtained under the conditions of the physiological experiments, and their comparatively low sensitivities rule out the precious metals. The high sensitivities available with such metals as tellurium are negated by their high resistivity and great variability. The choice really lies between copper-constantan and iron-constantan; and whilst the linearity and sensitivity of the latter combination are rather better than those of the former, the lack of resistance to corrosion and the comparatively high electrical resistivity and temperature coefficient of resistivity of iron make this material inferior to copper.

Eggert (1946) and others, have shown that the conduction of heat along a thermocouple wire to or from the surface of a body may lead to appreciable errors in the measurement of its temperature unless thin wires are used. Further, the heating effect of radiation is greater with thicker wires and their flexibility is low. Consequently the thermocouples are made of 40 S.W.G. copper and constantan wires insulated and twisted together. The resistance of this combination is approximately 13 ohms/ft. and it is possible to use 1 ft. of this with 25 ft. of the lead wire without reducing the voltage sensitivity of the instrument below the required figure.

The thermoelectric sensitivities of the 40 and 28 S.W.G. pairs of wires must be very well matched for good accuracy. If the measuring junction and the joint between this and the leads differ in temperature by 20°C.,

and the sensitivities of the two pairs of wires differ by 1% the magnitude of the error so introduced is 0.2°C. Manufacturers of constantan wire for thermocouples quote a tolerance of ± 2½% in sensitivity between batches of wire. It is thus virtually impossible to find two samples of wire which under the above conditions produce an error of less than 0.05°C., i.e. are matched to within 0.25%.

Measurements were made on a number of available samples of constantan wire to determine the temperature-E.M.F. characteristics of the wires, which included samples from three different manufacturers. The method adopted was to use one batch of wire as standard, determining accurately (±1.0 microvolt, ±0.05°C.) the characteristic of this batch against copper, and using as a temperature standard a mercury-in-glass thermometer corrected by the N.P.L. All other samples of constantan wire were measured against this standard batch, thus obviating the necessity for such extreme care in determining the actual temperature at which comparisons were made. Table 44 shows the results of these comparisons. It is immediately obvious from this table that the three manufacturers have produced some samples (nos. 1,2,3,5) very nearly though not exactly similar to each other; these samples have the same characteristics as those given in the International Critical Tables (1926). It is also apparent that the thicker wires fall naturally into a group of one small range of sensitivities, and that the 40 S.W.G. wires, with one exception, comprise another group of rather higher sensitivity than the

former. This observation suggested that the differences might be caused in the drawing process in the manufacture of the wire, when strains may have been developed in the thinner wire which might be removed by annealing.

A 3 ft. length of 40 S.W.G. enamelled constantan wire was held horizontally under very slight tension in air in a draught-free enclosure. Alternating current from the mains was passed through the wire via a Variac transformer and ammeter. Different pieces of wire were subjected to different currents for different periods of time. The middle portion of each of the treated lengths of wire were compared with the untreated. The differences in sensitivity between each differently treated length of wire and the original are tabulated in Table 45. It can be seen from the results that it is possible to reduce the sensitivity of constantan thermocouple wire by heating it. In this particular case a certain sample could be brought to the required sensitivity by passing 1.45 A of alternating current for 155 sec.

Five similar lengths of wire were given this treatment and each was found to have a sensitivity within 1 microvolt/30°C. of the standard in the range 15 to 45°C. The characteristics of these pieces of wire were measured at intervals over a period of three months and no further changes could be observed. It was concluded that this method could be used to produce 40 S.W.G. wire of characteristics identical with those of the thicker lead wire over the required range of temperature.

It was later proved that the original assumption of the change being due to a process of annealing was incorrect. Heating the wire in an atmosphere of coal gas produced little change in its temperature-E.M.F. characteristics. Further, a sample which had been brought to the required condition by heating in air was returned to its original condition by sandpapering. It is probable that the effect is due to the formation at the surface of the wire of a thin layer of oxide of one or both of the constituent metals. However, this does not affect the applicability of the method in producing a thermocouple of the required characteristics.

In making the complete thermocouple the treated constantan wire is dipped in a commercial varnish (Hymeg 4a); heated to 100°C. for 1 hr; twisted together with 40 S.W.G. double silk covered copper wire; one end of each wire is cleaned by scraping for a length of 1 to 2 mm; the ends are twisted and soldered and varnished overall and again baked. The couple is adjusted for resistance, checked for insulation, and when required for use soldered to the lead wires and the joint insulated with plastic paint (R.A.Brand; Adhesive type 1) and tape.

After this work had been completed it was found possible to select from new stock two reels of 40 S.W.G. constantan wire, equal lengths of which in parallel gave less than 2 microvolts against the lead wire used in this installation at all temperatures from 0 to 50°C. This pair twisted together has since been used in making the couples.

The Reference Junction

The basic circuit of the reference junction is shown in Fig.23. It consists of a resistance thermometer of sensitivity identical with that of the thermocouple but connected in opposition with it, so that any change in their mutual ambient temperature produces zero electrical effect. The basic principles of this system have been in use for some time in commercial instruments but except for a generalised description by Miller (1951) the author has found no details of the finer points in the literature.

In view of the dearth of information on the subject, and in particular of details of the accuracies obtainable with such a system, a new and independent design of reference junction has been carried out.

Semiconductor materials for use as resistance thermometers (thermistors) have become commercially available during the past few years. These have a temperature coefficient of resistance of approximately 0.04/°C., which is ten times that of the metals normally used in resistance thermometry. Certain types of these thermistors are highly stable, and over a fairly wide range of temperature (greater than 30°) their resistance/temperature relationship is accurately described by the equation:

$$R_T = A \exp(b/T) \qquad (1)$$

where R_T is the resistance of the thermistor at the Absolute temperature T, and A and b are constants depending on the size and material of the thermistor.

The author (Beakley, 1951) has shown that it is possible to design thermistor thermometers of a high degree of linearity over a fairly wide temperature range (e.g. the maximum departure from linearity over a range of 20°C. may be kept as low as $\pm 0.03°$ with proper design).

In a circuit such as Fig.24 optimum linearity is obtained when:

$$r = \frac{b - 2T_o}{b + 2T_o} R_o \qquad (2)$$

when R_o is the resistance of the thermistor at the mid-point T_o of the working temperature range.

Departure from linearity (ϵ_{max}) over a range of temperature between the limits $T_o - h_o$ and $T_o + h_o$ is given by the equation:

$$\epsilon_{max} = 0.03 h_o^3 \quad b^2/T_o^4 \qquad (3)$$

The sensitivity (dI/dT) of such a thermometer is given by:

$$dI/dT = \frac{E(b + 2T_o)^2}{4 T_o^2 b R_o} \left(1 - \frac{h_o^2 b^2}{12 T_o^4}\right) \qquad (4)$$

where E is the applied E.M.F. across the thermistor and series resistor r.

In view of the high temperature coefficient of the thermistor material high voltage sensitivity is obtainable for low current consumption at low applied E.M.F.

In the reference junction of Fig.23 the resistance r is divided in two. $r_1 + r_2$ is made equal to r, and r_2 is chosen to provide the required temperature

coefficient of voltage across itself. Thus if dV/dT is the sensitivity of the thermocouple material over the required range:

$$dV/dT = r_2\, dI/dT$$

$$= \frac{r_2\, E(b+2T_o)^2}{4T_o^2 bR_o} \left(1-\frac{h_o^2 b^2}{12T_o^4}\right) \qquad (5)$$

thus defining r_2, the other parameters being fixed or known.

The voltage across r_2 produced by the standing current must be cancelled in a bridge network. Thus r_3 is made identical with r_2, and r_4 added to balance the bridge at any required temperature. Since r_2 and r_3 are of the order of $2\frac{1}{2}$ ohms each the total resistance introduced into the thermocouple circuit need be of the order of only 5 ohms. r_2, r_3 and r_4 are made of constantan wire, which besides having negligible temperature coefficient resistivity is of the same material as the thermocouple wire and so does not introduce spurious E.M.F.s into the measuring circuit. The resistance of the thermistor is in the region of 2000 ohms and an energising source of 2 or 2.6 volts need supply only 1 or 2 milliamps to the network for efficient operation. r_4 may be made variable, or as is done in the present instance, consist of any number of resistors selected by a switch so that the temperature at which the bridge is balanced - or what is the same thing, the 'effective temperature' (T_E) of the reference junction - may be easily and accurately varied at will.

Fig. 25 shows the error introduced at various ambient temperatures by a particular reference junction used in these studies.

Table 46 shows the extent to which the temperature/E.M.F. characteristic of copper-constantan thermocouples is non-linear, but that departure from linearity in the range of approximately 10°C. to 30°C. is usually negligible. The comparatively large error beyond 30°C. in the characteristic of the reference junction of Fig. 25 is mainly due to this curvature in the thermocouple characteristic.

When measuring temperatures in the range 15 to 45°C. allowance must be made in the measuring circuit for the curvature of the thermocouple characteristic. In the present installation this has been done by dividing the total range of the instrument into three subsidiary ranges, each of 10°(5° on either side of the effective temperature of the reference junction); over any one of these ranges departure from linearity is very small. The sensitivity of the galvanometer is changed for each subsidiary range by using an extra section of the switch which selects the effective temperature of the reference junction to add extra resistance in series with the galvanometer on the 30 and 40°C. ranges.

The constancy of the E.M.F. of the supply to the bridge is of great importance. Errors introduced into the system by variations in the applied E.M.F. may be separated into two distinct categories:

(a) Effect on thermistor sensitivity

The temperature coefficient of the voltage appearing across r_2 is directly proportional to the applied E.M.F. (E). Thus for each 1% change (ΔE) in the applied E.M.F. there is a corresponding change in compensation. If T_o is the midpoint of the range of compensation, then at an ambient temperature of $T_o \pm h$ an error of $\pm h\Delta E/E$ is introduced; i.e. for an ambient temperature 10° below the midpoint of the compensated range, an error of 0.1° for each 1% variation of applied E.M.F. exists.

(b) Effect on offset temperature

The offset temperature is directly proportional to the applied E.M.F. Thus if T_1 is the effective temperature of the reference junction an error equal to $(T_1-T_o)\Delta E/E$ is introduced by a change ΔE in the applied E.M.F.

The total effect due to (a) and (b) is:

$$= (T_1+T_A-2T_o)\Delta E/E$$

where T_A is the ambient temperature. In the instrument as used here the maximum value of the term in the brackets is 30°, and therefore in order to hold the error below 0.03° it is necessary to maintain the applied E.M.F. constant to within $\pm 0.1\%$, which for a source of 2 volts is $\pm$ 2 millivolts. The total variation in the current of the whole bridge is approximately 0.8 milliamps under extremes of working conditions. Thus the output impedance of the source must be kept below approximately 5 ohms for the $\pm$ 0.4 milliamps change of load to produce less than $\pm$ 2 millivolts change in the applied E.M.F.

Two different methods of providing a constant E.M.F. for the bridge have been developed. The first, using special dry batteries as the source has been in use previous to and during the physiological experiments described in Part I of this thesis. The second, a mains-operated unit, was developed later, needs less attention and maintainance, and makes possible the simplification of the earlier circuits.

(1) The battery-operated unit. Ordinary dry Leclanche cells ('flashlamp batteries') were deemed unsuitable for this application since on discharge their voltage falls continuously from the nominal 1.5 volts to 1.2 volts. In recent years a new type of dry cell has become available, an example of which is the Kalium cell manufactured by Messrs Vidor Ltd. This cell uses mercuric oxide as depolariser, and its discharge curve is characterized by an initial small fall followed by a long plateau of constant E.M.F. and finally a sharp fall. The nominal E.M.F. of these cells is 1.35 volts. The internal resistance is 2 to 3 ohms and does not change appreciably with discharge. Data supplied by the manufacturer gives the temperature coefficient of E.M.F. of these cells as 0.5 mV/°C. from -40 to 17°C. and zero from 17 to 40°C.

A discharge test was made on 3 Kalium cells, their E.M.F. at a continuous discharge current of 3 mA being measured with a potentiometer with an accuracy of 0.1 mV. The measurements were made twice daily under ordinary laboratory conditions, the ambient temperature being normally about 17°C. but ranging from 10 to 22°C.

Fig. 26 shows the discharge curve so obtained.

When these cells are used as a source of comparatively constant E.M.F. it is necessary to age them before use by drawing 3 mA for 48 hr. or longer to bring the working level down to the plateau region. This plateau varies in height from 1.33 V to 1.30 V/cell, but for any given cell varies by less than 10 mV or $\pm 0.4\%$ approximately during the working life of the cell.

Adjustment of the voltage applied to the bridge in the reference junction cannot be made by means of a series variable resistor since a total source impedance of only 5 ohms is allowable (see p.178), and this is completely taken up by the internal resistance of the two cells required to give 2.6 V. Consequently, in the present instrument sensitivity rather than voltage is adjusted. Fig.27 shows the basis of this method. The resistor r_5 between r_2 and r_3 is effectively a pair of resistors each of resistance $r_5/2$ ohms and in parallel with r_2 or r_3. In order to compensate for a change ΔE in E, r_2 must take the new value r_{2a}. Then:

$$\frac{r_{2a}}{r_2} = \frac{E}{E+\Delta E}$$

$$r_{2a} = \frac{r_2 r_5}{r_5+2r_2}$$

Combining these:

$$r_5 = 2r_2 E/\Delta E$$

By making $r_2=r_3$ the adjustment of sensitivity is the same on either side of the bridge.

Thus the bridge circuit is designed for the lowest probable value of applied E.M.F. (2.600V) and one of a number of resistors r_5 whose resistance is calculated from the last equation, is switched into circuit for other values of applied E.M.F. It is necessary to provide an indication of when the system is correctly adjusted. There are no points within the bridge network between which a suitable voltage may be compared with a standard. In order to facilitate adjustment the expedient has been adopted of connecting a voltage divider across the battery, the ratio of which is adjusted in uniform steps by another section of the switch which adjusts the sensitivity of the bridge. Provision is made for using the galvanometer to indicate when the output from the voltage divider is equal to the E.M.F. of a Weston standard cell. Each switch position is associated with a known value of E and the appropriate value of r_5 is inserted across the bridge at each step. In view of the required accuracy of setting (0.1% or 2mV approx.) and the comparatively wide range of applied E.M.F.s (2.60 to 2.70 V) at least 50 discrete steps in the adjustment must be provided. This is most economically performed by using two sets of resistors r_{51} and r_{52} respectively, one of which affects the second decimal place of the sensitivity factor, and the other the third decimal place. The various resistors r_{51} are selected by a ten-position switch, and the resistors r_{52} by a five-position switch. For less strigent requirements of accuracy the second switch could be omitted. Table 47 gives the ratios

of the various resistances r_{51} and r_{52} to the resistance r_2.

Fig. 28 is the complete circuit diagram of this reference junction. The switch S_2 has the three positions OFF, NORMAL, SET. In the first position the battery is disconnected and the manganin resistor r_{10} connected across the galvanometer. The resistance of r_{10} is the same as the total resistance of the circuit normally in series with the galvanometer, and allows adjustment of the galvanometer zero to be made. In the second position of the switch the battery is applied to the instrument and the galvanometer included in the reference junction and thermocouple circuit. The third position of the switch S_2 places the galvanometer in series with the standard cell, W.S.C., and the resistor r_8 which forms part of the voltage dividing network across the battery. Adjustment of S_3 and S_4 then brings the galvanometer to the null point and at the same time inserts the appropriate value of r_5 across the bridge. The switch S_1 gives the choice of 20, 30 or 40°C. as the effective temperature of the reference junction by selecting the appropriate r_4 to balance the bridge-thermocouple circuit at these temperatures. At the same time the appropriate resistance (r_9) to provide correct galvanometer sensitivity is inserted in series with the galvanometer. The resistances r_2 and r_3 are made as one centre-tapped resistor of constantan wire. This is wired into the circuit in such a way that the constantan thermocouple leads and resistors form a network of homogeneous material (except for the solder used in

connecting them) and that the high tolerances on the resistances of r_2 and r_3 are maintained within this network; i.e. the small but appreciable resistance of the main current-carrying leads is placed in the part of the circuit associated with r_1 and S_1.

(2) The mains-operated unit. A later version of the reference junction has been developed which retains the principles of that of Fig.28 but does not include the switches S_3 and S_4 and their associated resistors. The improvement has been made by substituting a highly-stable mains operated source of E.M.F. for the rather variable battery. This new source maintains its output voltage constant to within o.1% and has negligible output impedance. Fig.29 shows the degree of constancy of voltage obtained with variations in mains voltage and load of the source of E.M.F. as eventually developed.

The basis of the method is to use a magnetic amplifier as a D.C. impedance transformer between a source of voltage of high stability and high impedance, and the low impedance output terminals. At first, attempts were made to develop a circuit as in Fig.30 using non-linear resistances (Metrosil), but commercially available components of this type lose their non-linear characteristics at applied E.M.F.s below about 25V. Non-linear elements such as thermistors and copper oxide or selenium rectifier elements were tried but found to be either unsuitable for the low voltages required or insufficiently stable to give a constancy of o.1%.

The circuit finally adopted is that shown in Fig.31. Although perfectly satisfactory as regards constancy of output, it is inefficient and rather complex and large. The reference voltage is obtained from V_2 which is a highly-stable gas-filled diode type 85A2 through which is maintained an almost constant current of 5 mA by the buffering stabilising tube V_1. Benson (1951) has found some variation ($\pm$0.2%) in the long term stability of the 85A2, but no variation approaching 0.1% has been found in the present instrument, over approx. 1900 hr. of use after the first 10 hr. The reference voltage is reduced to 2.6V approx. and the magnetic amplifier compares this voltage with its own output, feedback being in such a direction as to tend to bring this difference to zero. The positive feedback supplied by self-excitation of the magnetic amplifier is such that a current gain of approximately 500 is obtained and a compensating winding is included to cancel the effects of variations in mains voltage. A voltage divider across the output terminals provides a voltage which may be compared directly with the E.M.F. of a Weston standard cell for monitoring purposes. Preset coarse and fine controls are provided for adjustment of the voltage output. Since the unit operates best at current drains of between 5 and 8 mA (see Fig.29) a variable resistor RV2 is connected across the output so that the total output current of the unit may be set to lie in some region between these limits. After the initial setting up of this unit no further adjustment has been found necessary over long periods of constant use.

Selector Switches

The complete thermometric installation contains approximately 50 thermocouples whose functions are divided as follows:

a. rectal thermometers,
b. environmental thermometers,
c. wall, floor and ceiling thermometers, and
d. skin thermometers.

Each group of thermometers is wired to its own switch or switches (see Fig.22) each of which may be selected for reading by a master switch. If a common circuit be included in any parts of the wiring, stray E.M.F.s developed by or induced in any one section, or leakages between any sections, might affect the others. In order to prevent this both copper and constantan leads are switched. In an earlier installation laboratory-type switches with all-copper contacts and rotating leaves were used, but spurious E.M.F.s were generated at the points where the constantan leads were joined to the copper terminals. No source of supply of switches with constantan contacts could be found, and so a special type of construction was developed.

The British N.S.F. Co. sell small kits of component parts for making up their type H wafer switches. The wafers in these switches are approximately 1 mm. thick, and the switch contacts of silver-plated spring brass are normally riveted around the periphery of one face of the wafer. The modification here adopted was to rivet a contact on either side of the wafer, the contacts directly facing each other and the soldering tags

lying parallel and spaced 1 mm. apart by the thickness of the wafer. The switch rotor then connects these two together as required. The closeness and parallelism of the soldering tags ensures that individuals of any one pair are at the same temperature, and that the thermal E.M.F.s generated at the constantan-terminal junctions are equal and hence cancel each other.

Tests made on switches of this type, by blowing hot air at about 60°C. across the switch, produced an error - apart from a few seconds after first applying the air stream - of less than 0.1°C. With standard switches such a test produced 3 to 4° error.

The overall errors of the system

The theoretical errors of the system are as follows:-

Cause	Magnitude (°C.)
1. Non-uniformity of leads	Less than 0.01 when wire is selected
2. Reference junction compensation	± 0.03
3. Tolerance on length of thermocouples and their leads	± 0.02
4. Variations in applied E.M.F.	± 0.03
5. Difference between characteristics of thermocouples and leads	Negligible when wires are correctly matched
6. Non-linearity of galvanometer in terms of temperature	± 0.02
7. Thermal E.M.F.s at switch contacts etc.	± 0.02
8. Drift of galvanometer zero	Negligible if checked hourly
9. Stray E.M.F.s due to leakage	Negligible if good insulation of leads and thermocouples is maintained

The total error as enumerated above is ± 0.13°C. maximum, but since all sources of error are independent of each other the probability of the error exceeding 0.1°C. is exceedingly small. The root of the sum of the squares of the errors is ±0.06°C. The system has been frequently checked by immersing thermocouples in water at various temperatures and comparing the readings with a mercury thermometer; on all occasions the error was found to be less than 0.1°C.

Adaptation of the measuring elements to their different functions

1. Air temperature. This is measured directly by one of the 40 S.W.G. couples hanging in the air. Since the wall temperature is at worst only 2 or 3° different from the air temperature, and since the wire is so thin, no shielding from radiation is necessary.

2. Wet bulb temperature. This is usually measured in the outlet duct of the chamber where an air speed greater than 3 m/sec. is available over a short distance. The 40 S.W.G. couple is threaded into a small cotton wick kept moist with distilled water. The corresponding dry bulb temperature from which the humidity is calculated is measured at a point a few cm. distant.

3. Wall temperature. This is measured at a number of points by 40 S.W.G. couples stuck to the surface with adhesive cellulose tape.

4. Rectal temperature. This is measured by inserting a 40 S.W.G. thermocouple into a length of polythene tubing 7 mm. in diameter and 20 cm. long, with one end

moulded on to a small copper dome to which the end of the thermocouple is attached. The polythene tubing (which was originally the dielectric in a concentric 80 ohm R.F. cable) is bent to fit the groove between the tail and rump of the animal. On insertion into the rectum it stays in place and usually need be adjusted only after defaecation.

5. Skin temperature. This is measured by sticking the tip of a 40 S.W.G. thermocouple to the skin at the base of the hairs by means of a small pellet of latex dissolved in light petroleum. The consistency of the adhesive at the time of application is rather critical, but in the semi-solid state it sets in a few seconds. The thermocouple runs along the surface of the skin, below the hairs, for a few cm. and is fastened to the hairs - leaving some slack - to take the strain off the tip.

Summary

A temperature measuring installation of versatile performance and with an overall error of less than ± 0.1°C. has been constructed and described. In order to fulfil a rigid specification certain elaborations have been made, the need for which has often been overlooked in other installations. The two worst difficulties encountered have been (a) the wide tolerances which manufacturers allow between batches of constantan wire, and (b) the lack of a source of electric current at a stability of voltage approaching that of a standard cell.

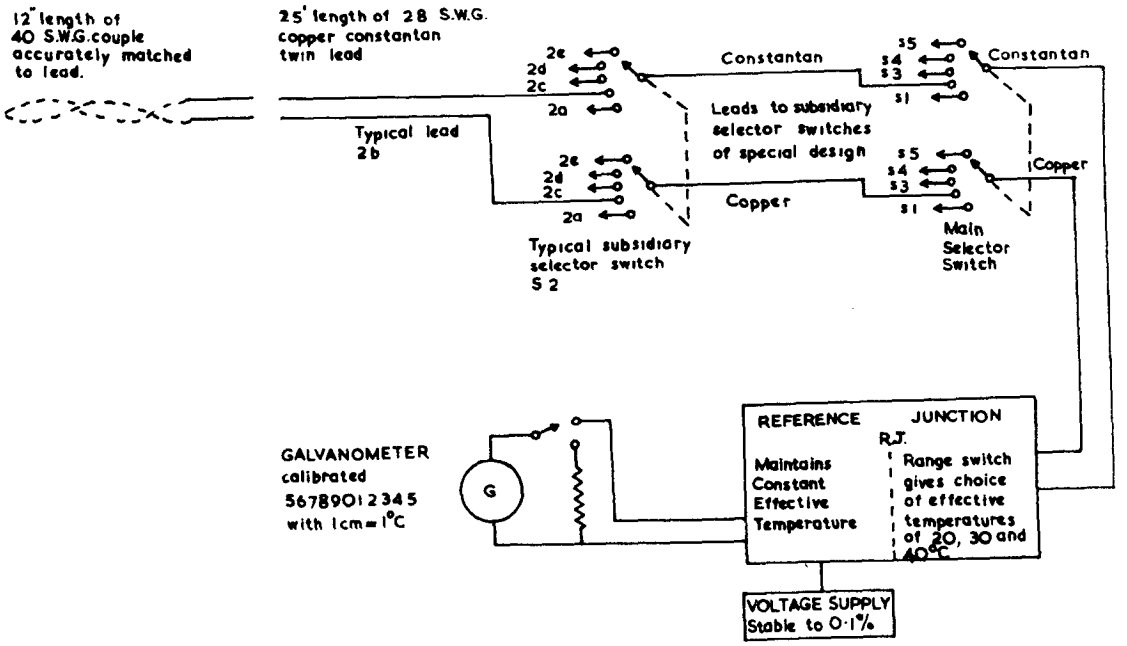

Fig. 22. Block schematic diagram of the psychrometric chamber temperature measuring installation.

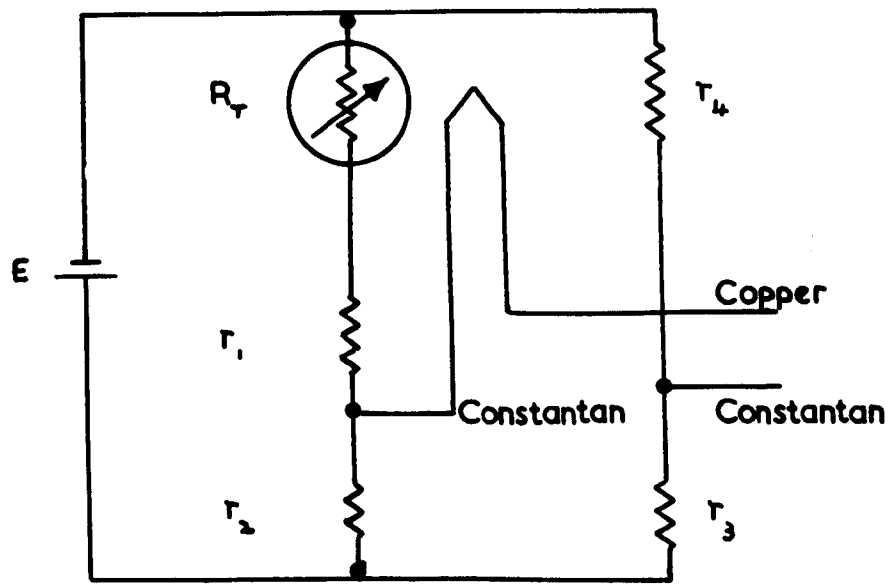

Fig. 23. Basic circuit of Reference Junction. For explanation of symbols see p. 175.

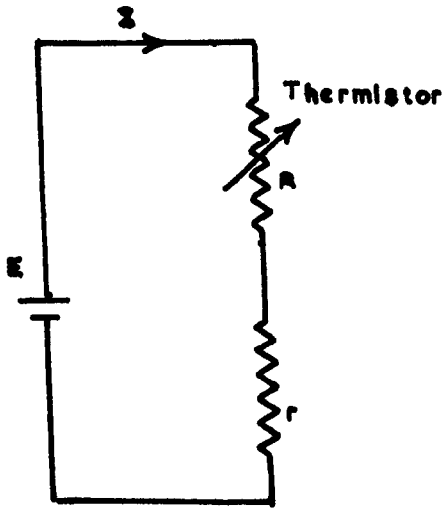

Fig. 24. Diagram defining the network discussed on p.175.

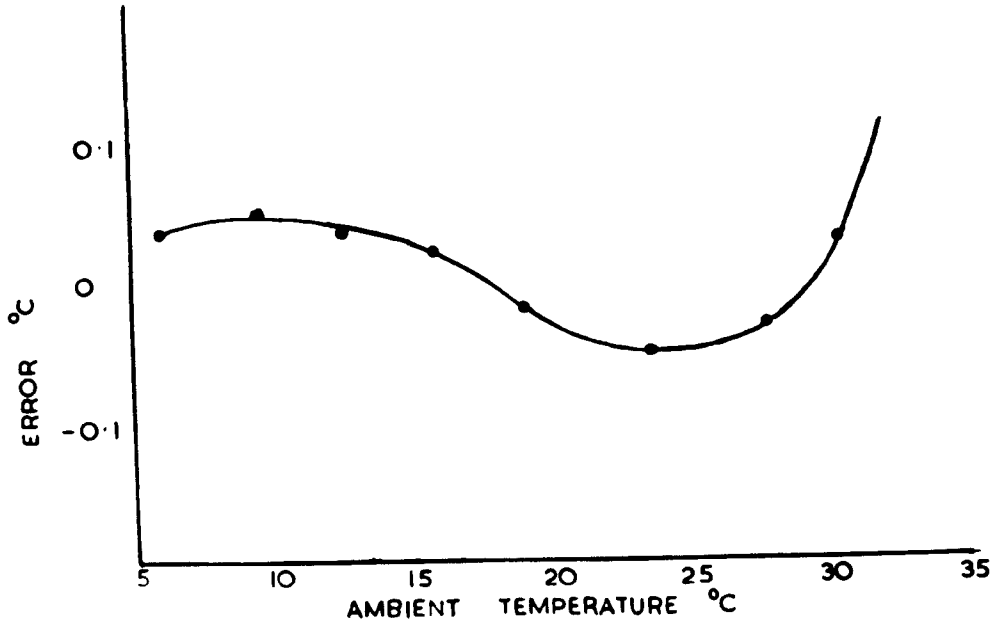

Fig. 25. The error introduced by a reference junction at different ambient temperatures. This particular reference junction was used for most of the temperature measurements made on calves in the present experiments.

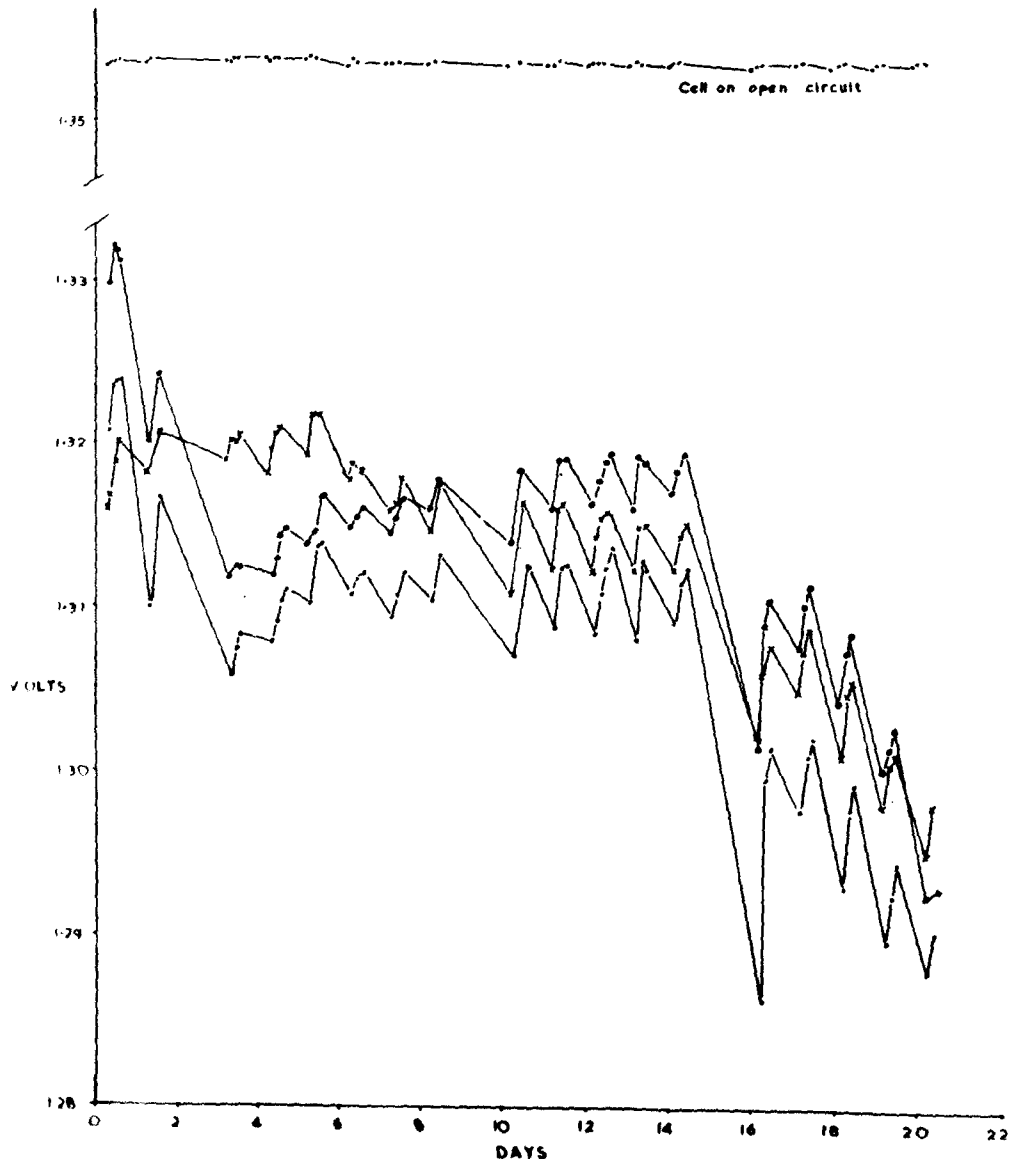

Fig. 26. The variation of the E.M.F.s of three Kalium cells supplying 3mA continuously, and of one Kalium cell on open circuit.

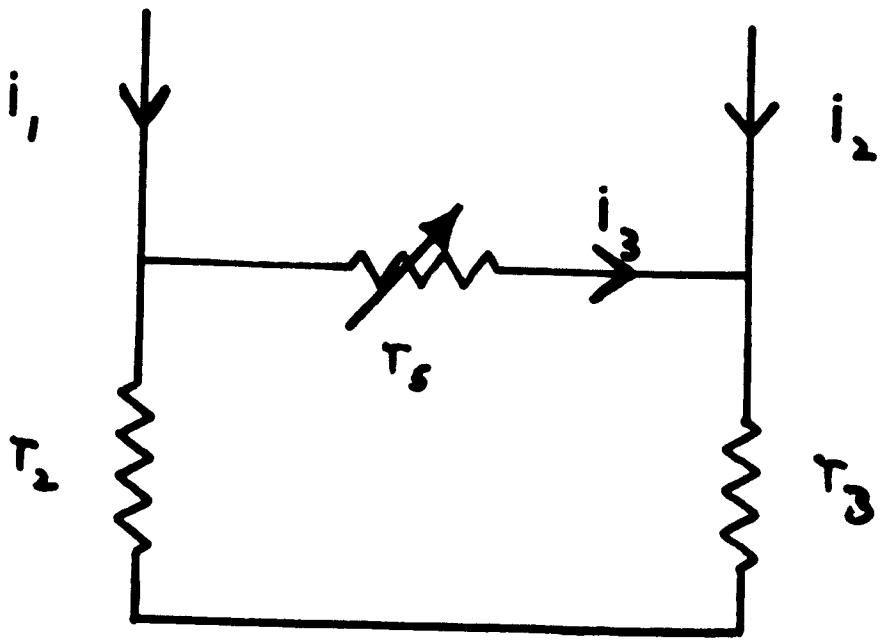

Fig. 27. Diagram defining the network discussed on p. 180.

Key to Fig. 28

R S.T.C. Thermistor type F2311/300

r1, r2, r3, r4a, r4b, r9a, r9b, r10 - see text.

r51, r52 - see Table 47.

r61 180Ω tapped at 20Ω intervals ± 0.5%

r62 16Ω tapped at 4Ω intervals ± 5%

r7 3162Ω ± 0.1%

r8 2037Ω ± 0.1%

E 2 Kalium cells type V0106 in series.

S1 Oak type H 3 way 2 pole

S2 Oak type H 3 way 3 pole 2 wafer B.B.M.

S3 Oak type K 10 way 2 pole 2 wafer

S4 Oak type H 5 way 2 pole 2 wafer

Table 48 gives the values of the special resistors incorporated in one particular reference junction.

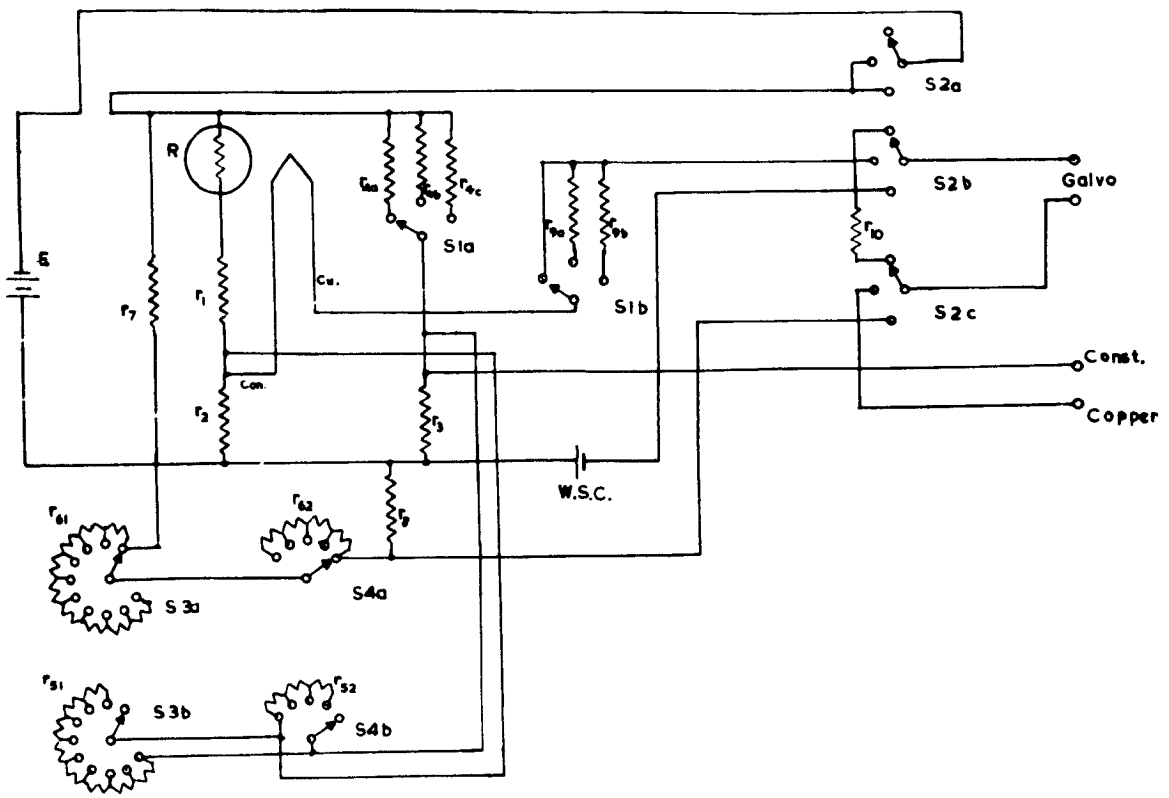

Fig. 28. Circuit diagram of the battery-operated reference junction described on p.179.

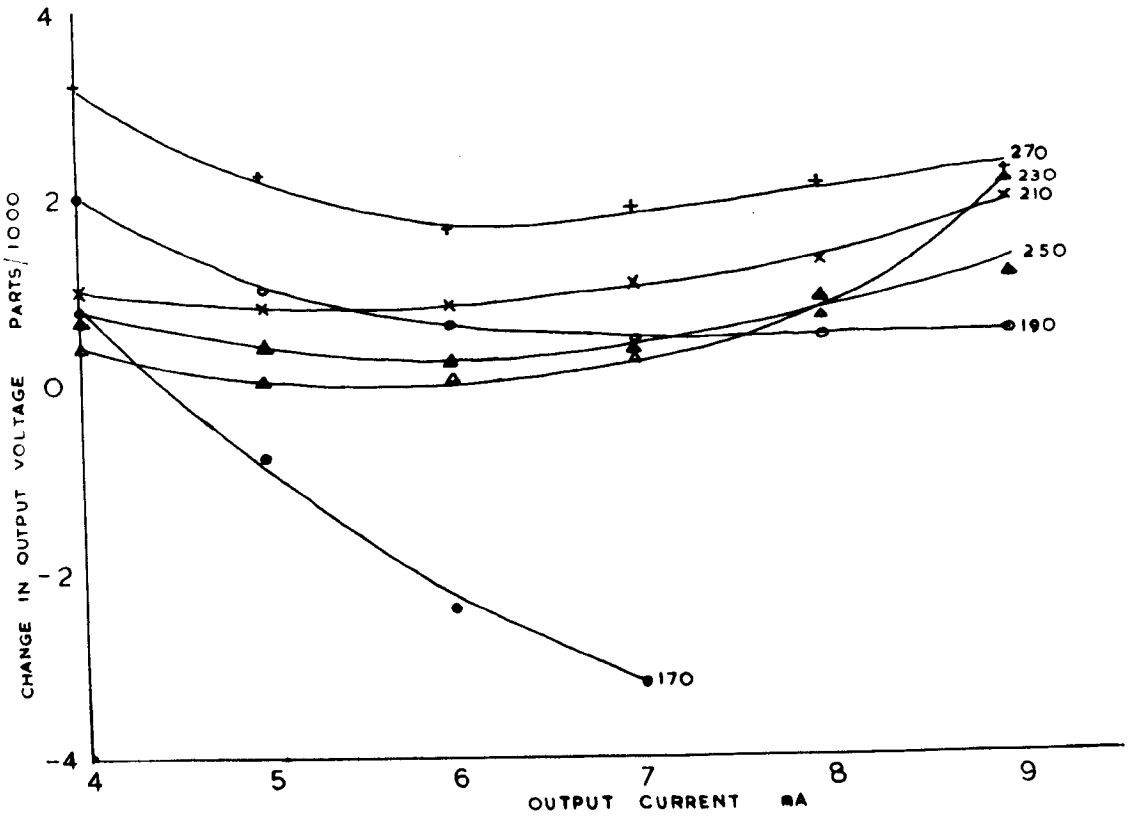

Fig. 29. The variation of the E.M.F. of the constant voltage supply of Fig.31 with mains voltage and with current load. The numbers at the right of each curve are A.C. mains R.M.S. voltages.

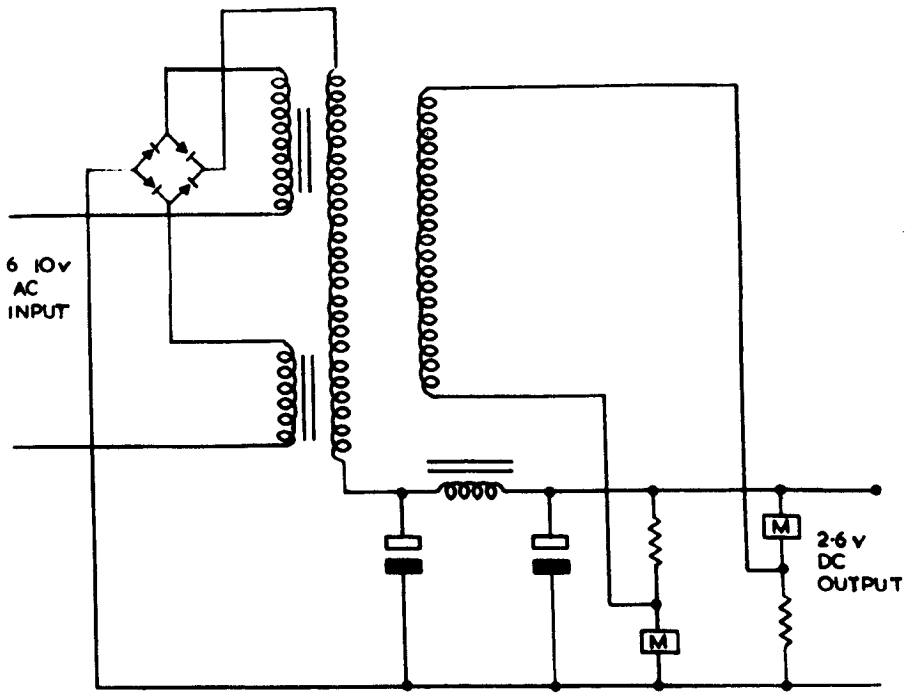

Fig. 30. Desirable circuit of stabilised voltage supply. This design is not realizable, since no suitable commercial non-linear resistance M is available.

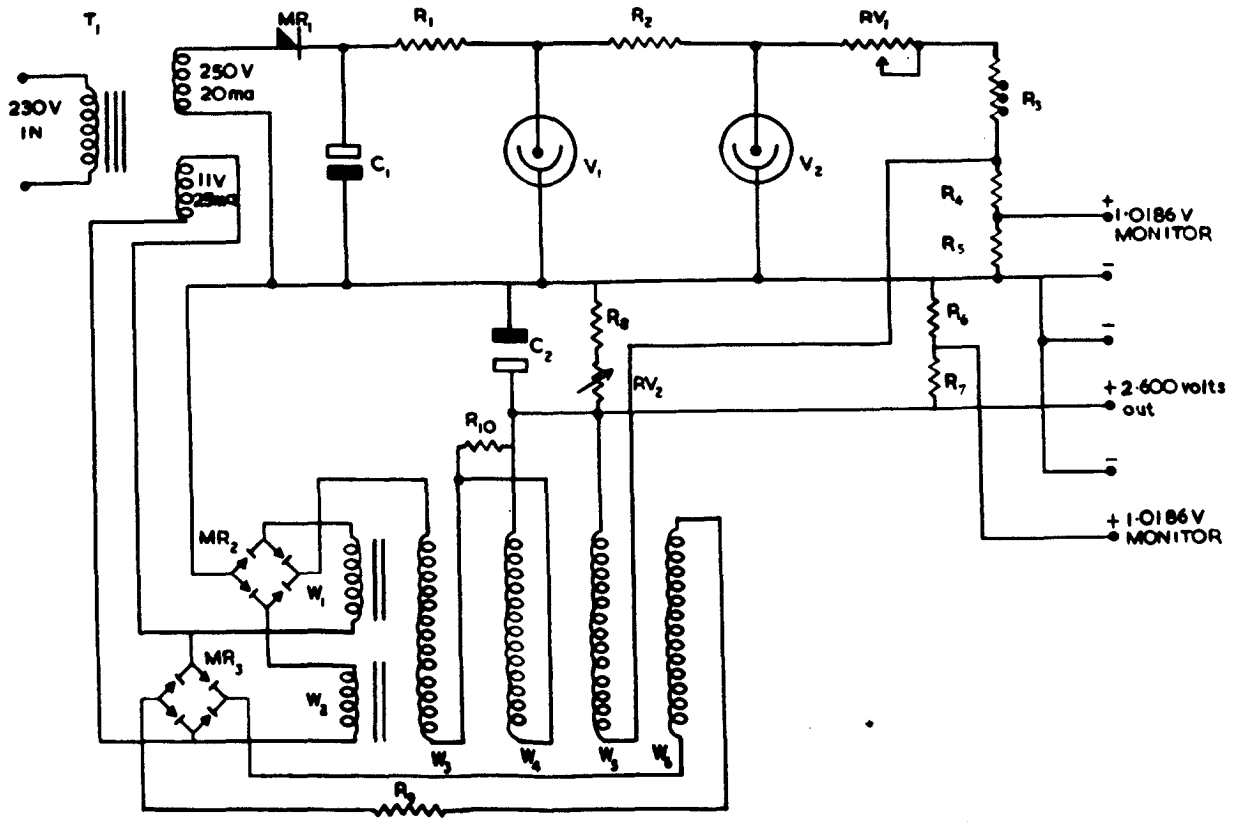

Fig. 31. Circuit diagram of stabilised voltage supply. The output voltage remains constant to within ±0.1% for variations of mains voltage of ±15% and output currents of 5 to 8 mA.

R1	10K 5% 5w W.W.
R2	10K 5% 5w W.W.
R3	26K+5x400Ω tapped const
R4	527.2Ω 0.05% const
R5	339.5Ω 0.05% const
R6	1.0186K 0.05% const
R7	1.5814K 0.05% const
R8	220Ω 10%
R9	4.7K 2% HS
R10	0.6Ω approx.
RV1	500Ω W.W,
RV2	2.5K W.W.
C1	16μF 450v
C2	100μF 12v
V1	QS150/15
V2	85A2
MR1	Selenium 280v 30mA
MR2	S.T.C. B6
MR3	S.T.C. B7

Magnetic Amplifier

Cores 2. Each 91 stampings 0.005" Mumetal size 226E.

Windings

W_1	400 T	36 SWG
W_2	"	"
W_3	420 T	38 SWG
W_4	40 T	38 SWG
W_5	400 T	38 SWG
W_6	4400 T	38 SWG

Table 44. The thermoelectric characteristics against copper, of some samples of constantan wire of different gauges and from different manufacturers

Sample no.	Gauge S.W.G.	Manufac-turer	0°C.	10°C.	20°C.	30°C.	40°C.	50°C.
0*	-	-	0	389	787	1194	1610	2034
1	28	A	0	392	788	1196	1610	2034
2	28	A	0	-	787	-	1609	-
3	25	B	0	-	783	1194	1611	-
4	25	B	0	389	783	1187	1602	-
5	25	C	0	388	789	1195	1611	-
6	40	A	0	-	795	-	1625	-
7	40	A	0	-	794	-	1627	-
8	40	A	0	-	818	-	1675	-
9	40	A	0	-	797	-	1629	-
10	40	A	0	-	775	-	1582	-
11	40	B	0	-	792	-	1622	-

* Figures from the International Critical Tables.

The entries in the table are the microvolts output when one copper-constantan junction is at 0°C. and the other is at the temperature given at the head of the column.

Table 45. The change in the thermoelectric characteristics of a sample of 40 S.W.G. constantan wire after heating with an electric current

Current Amp.	Duration Min.	Change μV/°C.
1.20	2.0	0.03
1.30	2.0	0.08
1.40	2.0	0.33
1.50	2.0	1.45
1.60	2.0	2.50
0	0	0
1.50	1.0	0.13
1.50	2.0	1.48
1.50	3.0	1.80

Table 46. The thermoelectric sensitivity and departure from linearity of two different samples of constantan wire (against copper) about different initial temperatures

Sample no.	T_o	α	β	γ	e_5	e_{10}
1	10	39.35	0.0358	0.00055	0.01	0.05
	20	40.23	0.0522	0.00055	0.02	0.07
	30	41.44	0.0686	0.00055	0.02	0.09
	40	42.98	0.0850	0.00055	0.02	0.10
4	10	39.08	0.0216	0.00069	0.01	0.03
	20	39.85	0.0360	0.00069	0.02	0.06
	30	41.03	0.0514	0.00069	0.02	0.07
	40	42.60	0.0648	0.00069	0.02	0.08

T_o, α, β, γ, are constants in the equation

$$E(T_o + h) = \alpha_o + \alpha h + \beta h^2 + \gamma h^3$$

where T_o is the initial temperature in °C. and h is the departure from T_o α is in μV/°C., β is in μV/°C.^{2}, and γ is in μV/°C.^{3}

e_5 and e_{10} are the maximum values of the errors introduced by assuming the thermocouple characteristics to be linear about T_o for $-5<h<+5$ and $-10<h<+10$ respectively. The entries in the columns beneath e_5 and e_{10} are in °C.

Table 47. Values of resistance, relative to r_2, to provide correct sensitivities for various voltages applied to the reference junction

Applied E.M.F. Volts	r_{51}/r_2	Third decimal place of E.M.F.	r_{52}/r_2
2,60	∞	0	∞
2.61	520	2	2600
2.62	260	4	1300
2.63	173	6	870
2.64	130	8	650
2.65	104		
2.66	86.7		
2.67	74.3		
2.68	65.0		
2.69	57.8		

Table 48. Design sheet for a particular reference junction

E	given	2.600	volts
T_o	decided	295	°K *
h_o	decided	10	°C
T_{Ea}	decided	293	°K *
T_{Eb}	decided	303	°K *
T_{Ec}	decided	313	°K *
dv/dt	measured	40.25	μV/°C
R_o	measured	1950	ohms
b	measured	3291	°K
r	calculated **	1356	ohms
r_2	calculated ***	2.324	ohms
r_3	$= r_2$	2.324	ohms
r_{4a}	adjusted to give required T_E	3502	ohms
r_{4b}	adjusted to give required T_E	2835	ohms
r_{4c}	adjusted to give required T_E	2394	ohms
r_{9a}		2.3	ohms
r_{9b}		5.5	ohms
r_{10}		56	ohms

* °K are taken to be °C + 273

** Equation 2 p.175 of text.

*** Equation 5 p.176 of text.

For explanation of the symbols see p.p. 174-183.

Chapter 10

The Cardiotachometer

Earlier workers (Horton, 1938; Henry, 1938) have described methods of measuring heart rate based on electrocardiography. Their instruments have been used in studies on humans, for which purpose they have proved very satisfactory. It was found at an early stage in the present work that major difficulties existed in the use of such instruments in the psychrometric chamber. It was found with the calves that (1) the amplitude of the waveforms appearing on the surface of the calves were in general much smaller than those for humans, (2) under the conditions of these experiments it was impossible satisfactorily to insulate the animals from comparatively large stray fields of electrical mains leakage current which existed in the chamber owing to the proximity of heavy electrical equipment, and (3) the animals very frequently moved their heads, legs and tails, and twitched their skins, developing large muscle potentials which completely masked the cardiac potentials. It was therefore decided that in the new design of instrument, as well as a direct meter display of heart rate it would be necessary to provide a permanent record of each individual heart beat which would be suitable for counting at some other time. It was later found that frequent monitoring of the apparatus was necessary as potentials coinciding with the respirations of the animal could be confused by the tachometer with cardiac potentials. It was also noticed that considerable DC potentials were

developed between the electrodes when in place on the animal, and that under these circumstances AC coupling between the electrodes and the amplifier was necessary.

The cardiotachometer was therefore designed to embody the following features:-

(1) An amplifier with a noise level below 10 μV and with a gain of approximately 500, 000 so that an input of 100 μV could produce a 1 cm. deflection on a monitoring cathode-ray tube.

(2) A coarse gain control with 10dB steps and a fine gain control giving continuous adjustment from 0 to 15dB.

(3) A choice of coupling time constants between stages, ranging from 0.02 sec. to 4 sec. The smaller values enable the peaked R wave to undergo optimum amplification, and also reduce the blocking time due to very large potentials charging the coupling condenser via the grid of the following valve. The highest value provides adequate coupling when the amplifier is used as an electrocardiograph.

(4) Effective means of eliminating or considerably reducing 50 cycle mains interference.

(5) A monitoring 1½" cathode-ray tube and time-base for it.

(6) Provision for the output from the amplifier to be directly coupled to an external oscillograph whose trace may be photographed to provide a permanent electrocardiographic record when required.

(7) A triggering circuit which is triggered once by each heart beat.

(8) A meter to read heart rate directly.

(9) A means of generating a pulse from each heart beat of sufficient power to operate an electromagnetic marker for writing on a kymograph.

(10) Generators of 1 sec. and 5 sec. marker pulses whose timing accuracy and stability are much better than 1%, having an output of sufficient power to operate an electromagnetic marker for writing on a kymograph.

Fig.31 is a circuit diagram of the instrument. V1 and V2 are aged and matched and form a balanced input amplifier, the common cathode load of which is V3. R11 provides negative current feedback to V3 and so its output impedance is large (250K approx.). Further feedback of the amplified in-phase component of the input signal is effected via the common cathode load of V4 and V5, and the resistor R23, further raising the output impedance of V3, (and hence the rejection ratio of the complete circuit) to a very high value. V4 and V5 are directly coupled to V1 and V2 and the feedback via R23 also serves to hold constant the mean anode voltage of V1 and V2 so that V4 and V5 are always working on the linear portions of their characteristics even though the mean input voltage to V1 and V2 changes, or the valve characteristics or supply voltages change. R10 allows the standing anode voltages of V1 and V2 to be adjusted to equality; R3 allows the balance of the inputs to V1 and V2 to be adjusted for optimum rejection of in-phase input voltages. S2 is a gain control giving attenuation steps of 10dB, and R19 gives continuously variable adjustment of atten-

uation from 0 to 15dB. S1 gives a choice of AC or DC coupling from the electrodes and provides a calibrating pulse of 1mV amplitude and 1 sec. repetition rate.

V4 and V5 are condenser-coupled to the cathode-followers V6. S3 allows the time constants of the coupling network to be varied from 0.02 sec. to 4 sec. R31 serves as a shift control for the anode voltages of the following stages.

V6 matches the high impedance outputs from V4 and V5 to the low impedance inputs of the Twin-T filter networks consisting of R33/35 C13/15 and R36/38 C16/18. These provide a practically infinite attenuation at a frequency of 50 c.p.s. but very little attenuation at frequencies on either side of it. S4 allows these filters to be placed in or out of circuit and may be used to reverse the polarity of the signals fed to V7 and V8.

V7 is another balanced amplifier and provides a symmetrical input to the vertical deflector plates of the monitoring cathode-ray tube V22. It also provides the signal to operate the triggering circuits of V9 etc.

V8 is a cathode-follower providing an output at approximately earth potential for an external oscilloscope on whose screen may be photographed the electrocardiac waveforms. R42 is an amplitude control and also allows the polarity of the outgoing waveform to be reversed.

V9a is an isolating stage between the amplifier and the triggering circuits. In the absence of an input signal its grid is biassed to -32V; V10a is conducting, its grid being clamped at 15V by the diode V18b;

The network consisting of R55, R53 and R48 holds the cathode of V9a close to -32V. Thus positive-going pulses applied to the grid of V9a appear at its cathode, and so at the grid of V9b. V9b and V10a together form a triggering circuit such that when the cathode voltage of V9a approaches 0 (i.e. when a signal of approximately 30V is applied to the grid of V9a) the cathode voltage of V10a falls from 15V to 0V. At the moment of triggering the grid voltage of V10a is driven negative with respect to its normal voltage by an amount equal to the potential difference between the cathode of V17a and the anode of V18a, i.e. 200V. It then rises exponentially towards +100V as C22 charges via R54, with time constant R54C22. As its grid reaches approximately 0V, V10a starts to conduct and positive feedback via C21 produces a cumulative action which causes a rapid increase of grid voltage of V10a after this point has been reached. V18 clamps the grid voltage at 15V when the cycle is complete. Thus there appears at the cathode of V10a a negative-going pulse of duration 0.2 sec. and amplitude 15V, whose stability is very nearly independent of valve characteristics. During the pulse, i.e. when V10a is not conducting, the cathode of V9a rises to +15V and so isolates the triggering circuits from all input voltages to V9a of amplitude less than 45V; the duration of the output pulse is thus not affected by input pulses which may occur within 0.2 sec. of a pulse which triggers the circuit. The output pulse from V10a passes to the cathode-follower V10b which provides sufficient power to drive a pen attached to a modified high-speed relay,

and produce a mark corresponding with each heart beat on a kymograph.

The valve-voltmeter V11 measures the mean voltage at the cathode of V10a, which is a linear function of heart rate. R67 and C24, with Miller feedback on V11, provide a time constant of integration of approximately 15 sec., and C23 passes the residual impulses at the grid of V11b to the grid of V11a so that a steady meter deflection (with a waver of less than 1 beat/min) is obtained. M1 has two ranges, 0-100 and 0-250 beats/min., the desired range being selected with S5. R61 allows for the setting of the zero of the meter.

V12 serves as a low impedance source of +100V.

V13 is in a phantastron circuit. From its anode is obtained a sawtooth waveform to provide a time-base for the monitor tube V22. The phantastron is triggered at the suppressor grid of V22 by the output pulse from V10. The rate of fall of anode voltage is determined by C25, R74 and the voltage at the junction of R66 and R73. This latter voltage is determined by the voltage at the anode of V11b and hence is a linear function of the heart rate. By careful desigh it has been found possible to make the timebase speed vary linearly with heart rate over a range of 40 to 250 beats/min. The timebase lasts for approximately 1½ heartbeats so that a complete cycle of the cardiac wave-form is always visible independently of heart rate and without the necessity for adjustment. The circuit triggers on every second beat. The cathode-ray tube has a long afterglow screen and so waveforms at very

low rates may easily be observed. Spot flyback is suppressed in the c.r.t. by means of the negative-going pulse from the screen-grid of V13, the time constant of C33R111 being sufficiently large to hold the grid of V22 negative during the flyback; the diode V23 prevents the grid from going positive on the trailing edge of the blackout pulse.

V14 is a multivibrator giving timing pulses at 1 sec. intervals. In such a multivibrator each triode acts merely as a switch, in one position of which the top of C27 (or C28) is connected to the 100V line via the diode V21, and in the other position it is connected to the 300V line via R91 (or R87). Thus C27 alternately discharges via V21b and R86, and charges to 300V via R91 and the grid-cathode current of V14b to earth. Switching is performed during the discharge part of the cycle, i.e. when the grid voltage of the triode rises above cut-off. Since the grid- cathode voltage for cut-off for the 6SL7 is -6V at an anode voltage of 300V, switching occurs when the voltage across R86 is 106V, i.e. approximately one third of the voltage to which C27 was charged. The output from this multivibrator is developed across R88 and R89. During the part of the cycle when V14a conducts, this valve passes 1mA anode current. During the early stages of this part of the cycle the grid current of V14a also passes through R88 and R89 and this is initially 0.8mA falling to zero in approximately 0.2 sec. The voltage waveform at the cathode of V14a is thus an initial rise to 18V, falling exponentially in approximately 0.2 sec. to 10V at which

level it stays until 0.5 sec. after the initial rise. This is followed by a fall to 0V lasting 0.5 sec. The whole cycle is continuously repeated with a period of 1 sec. ±1%. In practice it has been found that over 12 months no error approaching 0.4% could be detected whenever the rate was checked with a stopwatch.

A similar but attenuated waveform appears across R89 and this is further attenuated to 1mV initial peak to make a calibrating pulse available on S1.

The output from the cathode of V14a is taken to the cathode-follower V16b from which is available sufficient power to actuate an electromagnetic time marker on the kymograph.

V15 provides a 5 sec. marker pulse by counting down the 1 sec. pulses from V14. V16a is the cathode-follower to supply 5 sec. pulses for the kymograph time marker.

The instrument derives its power from a standard power pack delivering 440V D.C. unstabilised, 300V D.C. stabilised, -150V D.C. stabilised, and -500V D.C. unstabilised. Valve heater supplies are derived from a constant voltage transformer.

This instrument has proved to be very efficient in 'reading through' interference of all types, and although on occasion the meter indication has been in error due to severe interference, it has been possible to detect on the monitor that error exists and revert to the kymograph record from which sufficiently long periods of interference-free traces are available for accurate counting.

Key to Fig. 32

R1	4.7K	20%		
R2	4.7K	20%		
R3	100K	pot		
R4	10 ~	2%	HS	
R5	10K	5%	HS	
R6	300K	1%	HS	2W
R7	100K	2%	HS	1W
R8	300K	1%	HS	2W
R9	56K	2%	HS	1W
R10	250 ~	pot		
R11	27K	2%	HS	1W
R12	6.8K	2%	HS	
R13	22K	2%	HS	
R14	68K	2%	HS	
R15	330K	2%	HS	
R16	300K	1%	HS	2W
R17	330K	2%	HS	1W
R18	300K	1%	HS	2W
R19	25K	pot		
R20	22K	2%	HS	
R21	22K	2%	HS	
R22	150K	2%	HS	
R23	1M	2%	HS	
R24	330K	2%	HS	
R25	1M	10%		
R26	1M	10%		
R27	220K	10%		
R28	220K	10%		
R29	27K	10%		
R30	27K	10%		
R31	50K	pot		
R32	470K	10%		
R33	91K	1%	HS	
R34	91K	1%	HS	
R35	40.5K	1%	HS	
R36	91K	1%	HS	
R37	91K	1%	HS	
R38	40.5K	1%	HS	
R39	300K	5%		1W
R40	300K	5%		1W
R41	150K	10%		1W
R42	50K	pot		
R43	10K	5%		
R44	10K	5%		
R45	82K	10%		
R46	1M	20%		
R47	2.2M	20%		
R48	470K	2%	HS	
R49	100K	20%		
R50	33K	2%	HS	
R51	120K	2%	HS	
R52	330K	10%		
R53	680K	2%	HS	
R54	3.3M	2%	HS	
R55	120K	2%	HS	1W
R56	56K	10%		
R57	680K	20%		
R58	15K	2%	HS	
R59	47K	10%		
R60	39K	1%	HS	
R61	200 ~	pot		
R62	6.8K	1%	HS	
R63	1M	10%		
R64	120K	1%	HS	
R65	180K	1%	HS	
R66	2.2M	1%	HS	
R67	1.5M	10%		
R68	18K	1%	HS	
R69	18K	1%	HS	
R70	1K approx.		HS*	
R71	1K	5%	HS	
R72	47K approx.		HS*	
R73	3.3M	1%	HS	
R74	2.2M	5%	HS	
R75	680K	1%	HS	
R76	330K	1%	HS	
R77	18K	5%		
R78	18K	5%		
R79	56K	5%		1W
R80	6.8K	5%		
R81	4.7K	5%		
R82	1M	10%		
R83	220K	20%		
R84	820K	10%		
R85	10K	10%		
R86	2.2M	1%	HS	2W
R87	330K	2%	HS	
R88	10K	2%	HS	
R89	110 ~	2%	HS	
R90	1.8K	2%	HS	

*Selected to suit M1

R91	330K	2%	HS
R92	2.2M	approx. HS 2W**	
R93	4.7K	20%	
R94	1M	10%	
R95	330K	5%	HS
R96	100K	5%	HS
R97	6.8M	1%	HS
R98	15K	10%	
R99	3.3M	2%	HS
R100	2.2M	2%	HS
R101	1M	20%	
R102	100K	20%	
R103	1M	20%	
R105	100K	20%	
R106	2.2K	20%	
R107	2.2K	20%	
R108	470K	20%	
R109	200K	pot	
R110	100K	20%	
R111	1M	20%	

**Selected to give 1 sec. period.

C1	4µF	
C2	4µF	
C3	8µF	450V
C4	100pF	
C5	4µF	600V
C6	0.5µF	
C7	0.1µF	
C8	0.02µF	
C9	4µF	600V
C10	0.5µF	
C11	0.1µF	
C12	0.02µF	
C13	0.0350µF	0.5% mica
C14	0.0350µF	0.5% mica
C15	0.0700µF	0.5% mica
C16	0.0350µF	0.5% mica
C17	0.0350µF	0.5% mica
C18	0.0700µF	0.5% mica
C19	100pF	
C20	0.05µF	1000V
C21	0.05µF	1% mica
C22	0.0654µF	0.5% mica
C23	2µF	600V
C24	2µF	600V
C25	0.035µF	0.5% mica
C26	0.01µF	
C27	0.205µF	0.5% mica
C28	0.205µF	0.5% mica
C29	0.5µF	5% 600V
C30	0.1µF	
C31	0.1µF	
C32	0.1µF	
C33	0.1µF	1000V

S1	Oak type H 2p3w
S2	Oak type H 1p5w
S3	Oak type H 2p4w
S4	Oak type H 2p4w
S5	Oak type H 11w2wafer

V1	EF37a
V2	EF37a
V3	EF37a
V4	EF37a
V5	EF37a
V6	6SL7
V7	6SL7
V8	6SL7
V9	6SL7
V10	6SL7
V11	ECC35
V12	EF50
V13	6F32
V14	6SL7
V15	6SL7
V16	6SL7
V17	EB91
V18	EB91
V19	EB91
V20	EB91
V21	EB91
V22	E4103/M/4
V23	D1

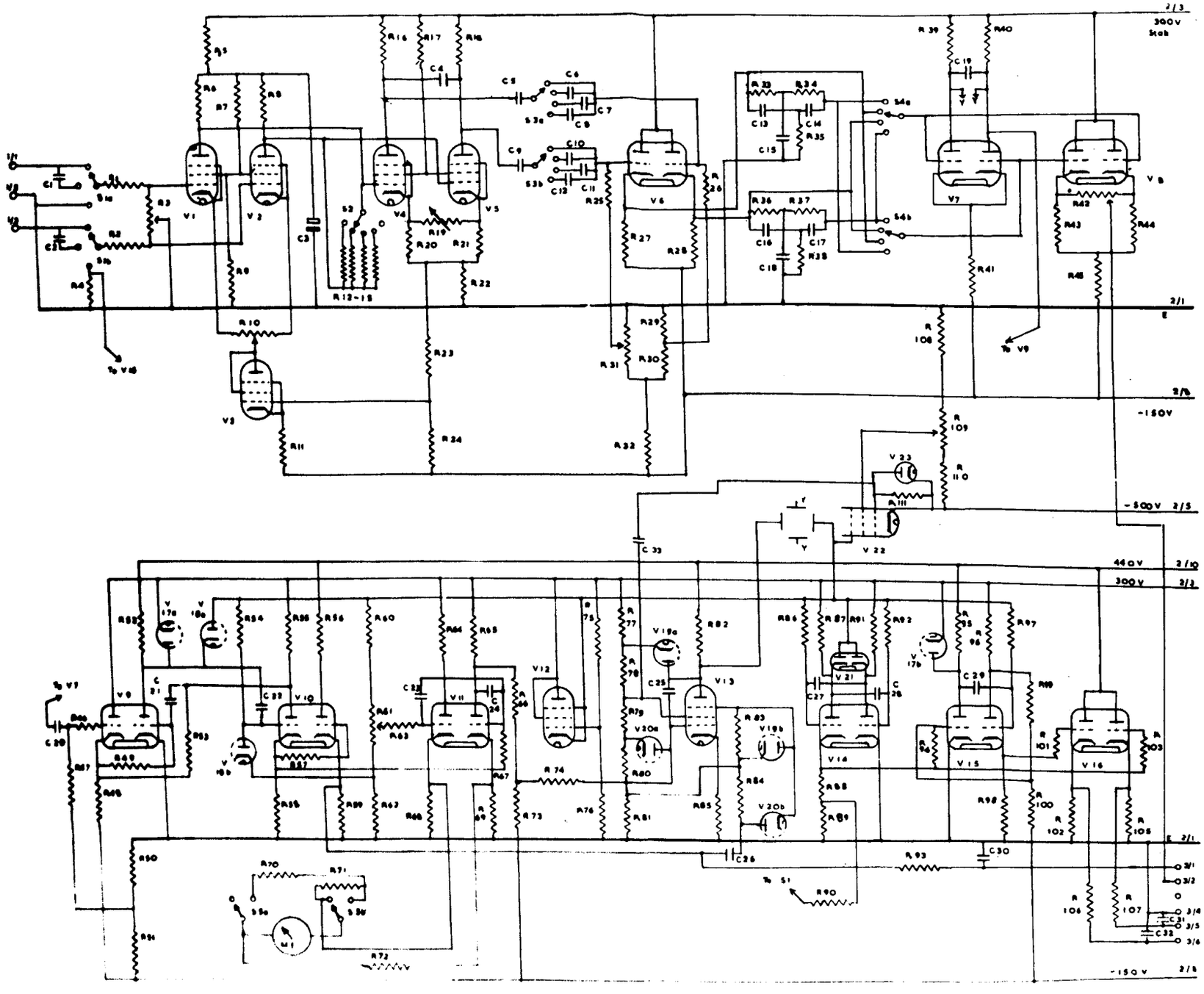

Fig. 32. Circuit diagram of Cardiotachometer.

Chapter 11

Summary to Part II

In order to prepare for a large programme of investigations into thermoregulation in the bovine, and to perform the experiments which are described in Part I of this thesis, a large amount of technical preparation was necessary. A psychrometric chamber was built by a commercial firm of ventilating engineers, but after testing it the author was obliged to design and develope control systems to maintain the air temperature at any desired level between 15°C. and 45°C. with an accuracy of ± 0.2°C., and the absolute humidity constant at any level between 5 and 55 mg/l. with an accuracy of ±1 mg/l. These were satisfactorily completed, with the exception that neither physical quantity can be reduced below the value prevailing outside, since no refrigeration is provided.

Thermistors and magnetic amplifiers are used in the control systems, and special techniques have been developed by means of which absolute humidity is directly controlled by wet- and dry-bulb thermometers.

A number of special thermometric techniques were developed by the author, and a multipoint thermocouple thermometer was designed, in which a number of difficulties, enhanced by the high degree of accuracy required and by the environmental conditions within the psychrometric chamber and observation room, were overcome. This thermometric installation is capable of measuring

temperatures from 12°C. to 48°C., with an accuracy of ± 0.1°C. between 15°C. and 45°C. The author designed a special reference junction which maintains its effective temperature constant to within ± 0.05°C. although its actual temperature, or the ambient temperature may vary between 10°C. and 30°C. Two versions of this reference junction are described, one of which is battery-operated and the other is mains-operated.

It was found that the thermoelectric powers of the constantan wires used in the thermocouples and their leads were so different from batch to batch that no thin (40 S.W.G.) wire could be obtained which satisfactorily matched the thicker lead wire. Consequently a method was developed by the author by means of which the power of the thin wire could be accurately and reproducibly reduced to be sufficiently close to that of the lead wire, and which retained its new value for a long time.

In order to select for reading any one of a large number of thermocouples it was found advisable to switch both copper and constantan leads. Under the conditions of use in the observation room, where large temperature gradients exist, and large variations of ambient temperature with time frequently occur, commercial switches were found to be unsuitable since unwanted thermoelectric forces could be generated at the switch terminals. Consequently the author devised modifications to wafer-type switches which reduced such errors to negligible proportions.

Finally a cardiotachometer designed by the author is described, which enables the heart rate of experimental animals to be measured and recorded rapidly, remotely and accurately.

Without the special techniques and apparatus described in Part II the experiments of Part I would not have been possible.

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