(ii) physiological conductance has not been adequately described in terms of variables which influence it, namely rectal temperature, skin temperature and metabolic rate. If physiological conductance is in error then calculations of rectal temperature from the heat balance equation will be incorrect,

(iii) both sweat gland fatigue and hidromeiosis act to suppress sweating after long exposures in the heat, typical in the mining industry. Neither of these effects have been incorporated into a comprehensive sweat rate model. The existence of sweat gland fatigue has never been conclusively proved and has often been confused with hidromeiosis. Although skin wettedness has been included in some "steady state" models of sweat rate, the dynamic way in which it suppresses sweating has never been quantified.

(iv) The modification of heat transfer coefficients by clothing, body posture and body movement have not been comprehensively described (Stewart 1981),

(v) the effects of wearing clothing on the physiology of the heat loss mechanisms have not been investigated.

The above five reasons identify areas of all composite models which require attention. The present study has concentrated on the first three points. The different approaches used to more completely quantify the physiological conductance and sweat rate responses of acclimatized men required to work for long periods in the heat are described below.

2.6.1 Approach adopted for physiological conductance

An experimental approach and empirical model was used to describe the relationship between K, T_{mb} and M. The reasons being;

(i) the sigmoidal shape of K versus T_{mb} is well established in the literature,

(ii) the manner in which M modulates the relationship in (i) has been mathematically investigated in Section 2.4.2 and qualitatively illustrated in Figure 2.8,

(iii) an equation relating K to T_{mb} and M has been experimentally proven for unacclimatized men over a narrow range of response (Stewart 1981).

Extensive experimentation was therefore necessary in order to gather sufficient data to accurately quantify the relationship suggested in Figure 2.8 over a wide range of T_{mb} and M values.

It was estimated that at least six points on each metabolic rate curve were required in order to describe the sigmoidal shape of the curve. Thirty points would therefore have been the minimum number required to describe five metabolic rate intervals. If ten men had been used as experimental subjects, over 18 months of experimentation would have been necessary to establish the average response, an enormous undertaking not within the scope of the present study. Instead, experimentation was carried out in the calorimetric wind tunnel on a single nude acclimatized subject. Detailed measurements were made with a high degree of repeatability and accuracy. The experimental facility, measuring techniques and experimental procedures are discussed in Chapter 3.

As a result of the detailed experimental approach it was possible to postulate the mathematical form of the model and to estimate values of parameters in the model which best fit the data from the one subject. It could be argued that the response of the one subject may have resulted in an incorrect form of the mathematical model of physiological conductance and not just incorrect values of the parameters in the model. The facts that the experimental subject could become acclimatized to hot humid conditions and that he exhibited responses (T_{re}, K and S_r) similar to a group of men being acclimatized at the same time, indicated that his physiological response to work in the heat was not a-typical. There is therefore no reason to suspect that analysis of data collected from one subject would result in an equation which exhibits entirely the wrong characteristic response. Furthermore it is possible to justify the use of a single experimental subject when one considers the following. Future work which must be undertaken in order to predict the average physiological conductance of many men could be greatly simplified as a consequence of having already established the form of the equation. Data need only be collected from a few carefully selected experiments on many men exposed to specific environmental conditions at various levels of exercise. The parameters of the "single man model" could then be determined from a reduced data pool such that the equation would predict average response. The confusing effect of inter-personal differences (Stewart 1981) could be avoided by adopting the method of analysis suggested above. The approach used in the present study would therefore result in a considerable saving in time and effort required for future experimentation.

2.6.2 Approach adopted for sweat rate

The body of literature consulted suggests that sweat rate is purely dependent on body temperatures. However, Wyndham et al. (1966) have demonstrated that sweat rate decreases with time and Nadel and Stolwijk (1973) have included wettedness in such a way that it decreases the drive for sweating. The factors mentioned above have never been combined into one equation. Furthermore, the implications of Stewart's (1981) discussion are that the control of sweat rate should include a number of factors, namely;

(i) a central drive depending on mean body temperature,

(ii) a local stimulating effect as a result of an elevated skin temperature,

(iii) a local skin wettedness effect dependent upon the time history of wettedness,

(iv) a sweat gland fatigue effect which is a consequence of extensive periods of sweat secretion.

The overall function required to describe sweat rate can be expressed mathematically as

$$S_r = f(T_{re}, \bar{T}_s, W(\text{time}), \text{time}) \qquad (2.40)$$

The way in which the variables in the above equation inter-react to control thermoregulatory sweating have been neither mathematically stated nor qualitatively described.

A control engineering approach was adopted in order to piece together the components suggested above into an overall model of thermoregulatory sweating. It was with the specific aim that, by adopting a control engineering approach, the dynamics of the sweat rate response shown in Figure 5.1 could be quantified.

Blocks within the model have been based, where possible, on information in the literature or postulated in terms of equations based on observation during experimentation. In order to demonstrate that, when combined, the blocks would predict actual sweat rate responses, three experimental days' data from the physiological conductance experiment have been modelled. The individual components of the model, method of simulation and parameter optimizations have been described in Chapter 5.

CHAPTER 3

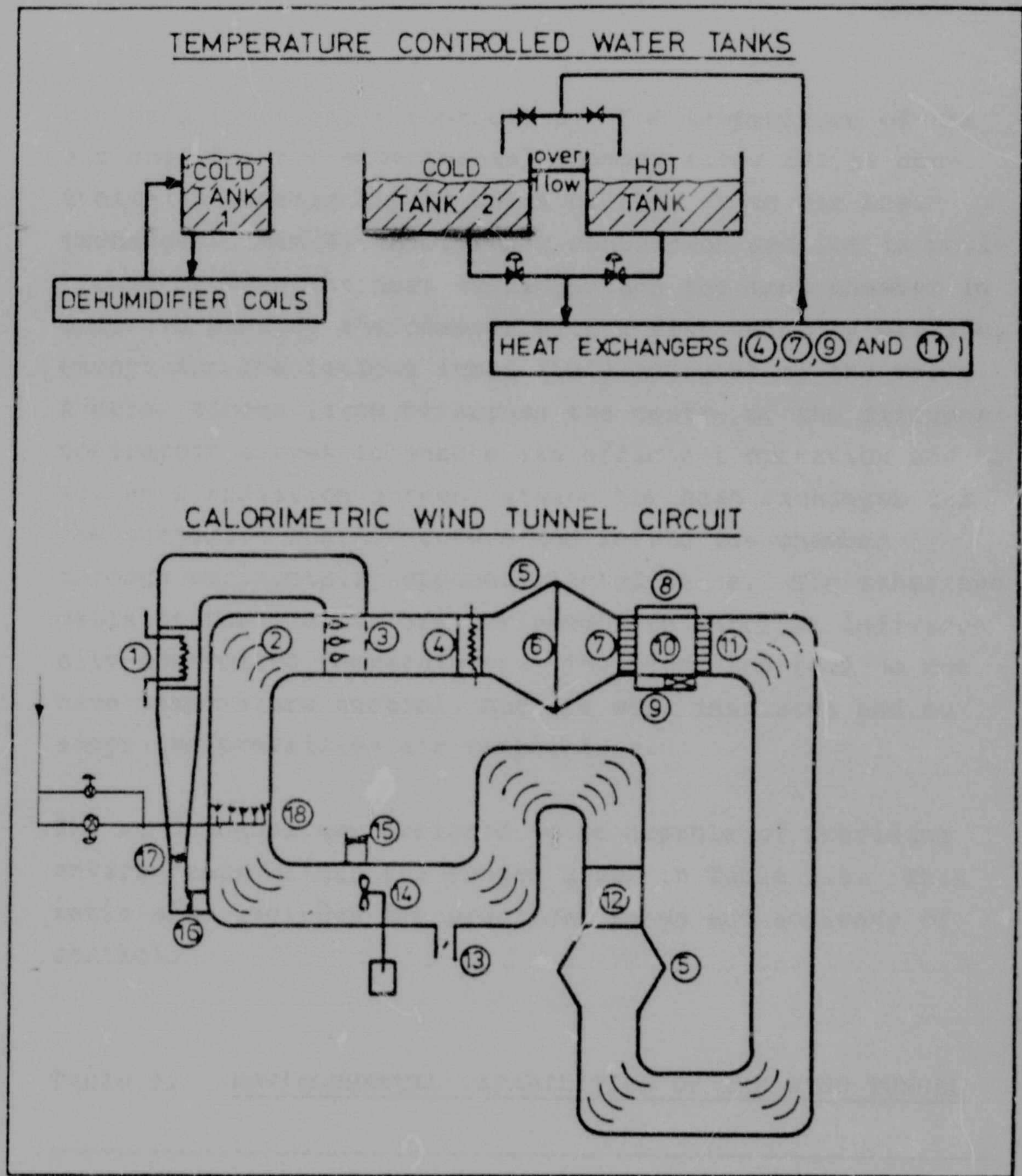
EXPERIMENTATION

All experimentation was carried out in the Calorimetric Wind Tunnel of the Chamber of Mines of South Africa Research Laboratories. Since the equipment and methods described below have been reported in considerable detail elsewhere, the descriptions given have been kept brief, details may however be obtained from the references quoted.

3.1 The Calorimetric Wind Tunnel

The wind tunnel was designed by Grant (1954, 1955, 1956) for the purpose of generating thermal environments which could be accurately controlled. Experimentation on human subjects exposed to these environmental conditions is carried out in either of two 3 x 3 x 3 m test sections. Air flow in the one is horizontal while in the other it is vertical. Transducers and instrumentation for measuring the heat exchange between men and their thermal environment were designed and installed in the horizontal flow chamber (Carroll and Visser 1966 and Hodgson 1974). The calorimetric capabilities of the wind tunnel have been used and described on a number of occasions (Vermeulen 1966, Mitchell 1972 and Atkins 1975).

The main features of the wind tunnel circuit are presented in Figure 3.1. Air is circulated around the tunnel by a large axial fan (item 14) driven by a variable speed motor enabling wind speed to be varied. Steam is injected at a controlled rate through a small and a large control valve. Humidity control is achieved by automatically varying the quantity of steam flowing through the valves.
De-humidification is achieved by passing the air over a set of dehumidifier coils (item 1) located in the bypass circuit. The water temperature in the dehumidifier coils



LEGEND

1	DEHUMIDIFIER COILS	10	CALORIMETRIC TEST CHAMBER
2	CORNER VANES	11	WATER PERFUSED OUTLET GRID
3	DEHUMIDIFIER AIR RETURN	12	VERTICAL FLOW TEST CHAMBER
4	WATER TO AIR HEAT EXCHANGER	13	AIR VENT
5	DIFFUSER-CONTRACTOR SECTION	14	VARIABLE SPEED AXIAL FAN
6	WIRE MESH	15	FRESH AIR FAN
7	WATER PERFUSED INLET GRID	16	BYPASS AIR FAN
8	WATER PERFUSED WALL	17	VARIABLE POSITION LOUVRES
9	WATER PERFUSED WALL & DOOR	18	STEAM INJECTION

Figure 3.1 GENERAL ARRANGEMENT OF THE WIND TUNNEL CIRCUIT

(from Stewart 1981)

can be automatically controlled. The temperature of the air entering the experimental chamber (item 10) is controlled automatically by means of a water to air heat exchanger, item 4. A diffuser-contractor section is positioned between the heat exchanger and the test chamber in order to provide the chamber with a flat velocity profile, except for the regions immediately adjacent to the walls. A metal screen (item 6) across the centre of the diffuser-contractor serves to ensure its efficient operation and to act as a radiation screen between the heat exchanger and the subject. The air enters and leaves the chamber through horizontally opposed slatted walls. The other two walls of the chamber are perfused with water at individually controlled temperatures. The floor and roof do not have temperature control, but are well insulated and so adopt the prevailing air temperature.

The wind tunnel was designed to be capable of providing environments within the ranges given in Table 3.1. This table also includes the practical range and accuracy of control.

Table 3.1 ENVIRONMENTAL CAPABILITIES OF THE WIND TUNNEL

Parameter	Design Range	Practical Range	Accuracy (3 standard deviations over 4 hours)
Air temperature (°C)	5- 55	5-55	$\pm$0,08
Relative humidity (%)	10-100	10-90	$\pm$,25
Wall temperatures (°C)	$T_{db}\pm17$	$T_{db}\pm17$	$\pm$0,08
Wind speed (m/s)	0,1-5,0	0,5-4,5	$\pm$0,1

The experimental subject is required to work on a stepping platform located in the centre of the test section. He occupies less than 0,2 per cent of the total volume of the chamber ensuring that blockage is minimal. Beneath the stepping platform is a dripped sweat collecting pan. During experimentation the pan is covered with oil, any sweat which drips off the subject collects under the oil so that it cannot evaporate and disturb the heat transfer measurements.

The subject's weight is measured by means of a loadcell. The loadcell is positioned under the floor and the column protrudes through a hole in the floor. The subject is required to stand still on two foot plates mounted on either side of the stepping platform. Mass is displayed with a resolution of 5 g in 200 kg.

Expired air samples are collected in a Douglas bag in an adjacent room, through a plastic tube. The subject's metabolic rate is determined from measurement of his ventilation rate, oxygen concentration and carbon dioxide concentration of the expired sample.

3.2 Heat Transfer Measurements

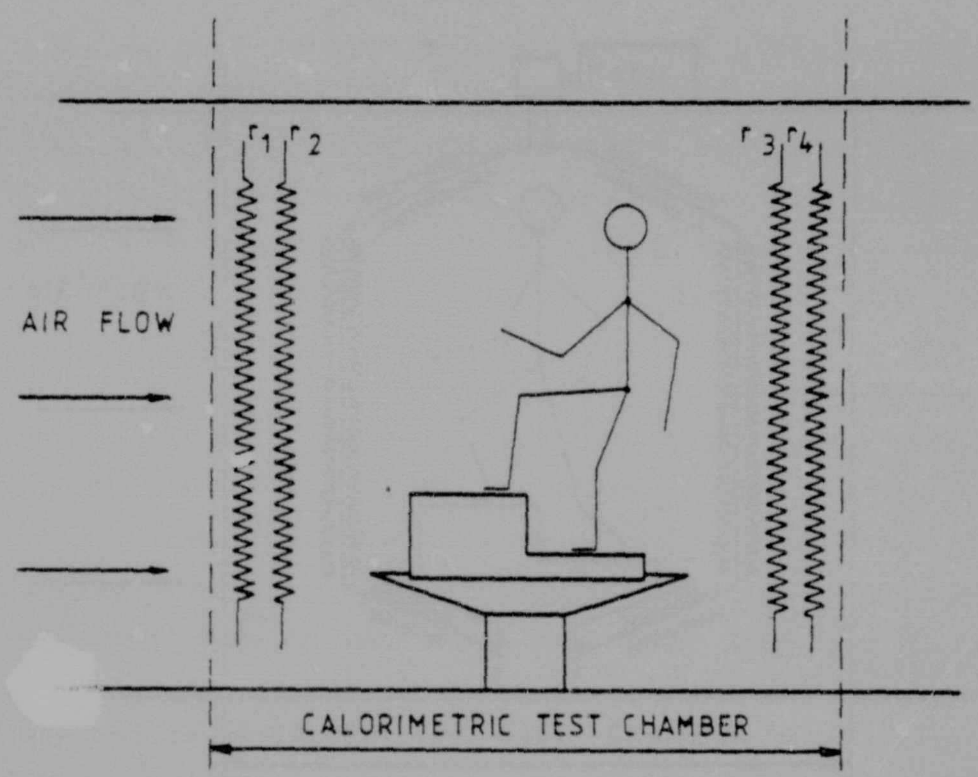
The test chamber is unique in that it permits calorimetric measurements of radiative, convective and evaporative heat exchange measurements on a working man.

Convection

Convective heat transfer between the subject and the air passing over him is determined by measuring the sensible heat gain (or loss) of the air. Carroll and Visser (1966) have developed an extremely sensitive differential thermometer to measure the change in air temperature. The differential thermometer comprises four resistance wire grids, two located upstream and two downstream of the subject. The grids are made from pure nickel wire of diameter 0,1 mm. The four sections of the grid are connected in the opposite arms of a wheatstone bridge circuit. Changes in resistance caused by temperature change are amplified by a strain gauge amplifier and integrated over a selectable period. Convective heat transfer can be determined with an accuracy of better than 5 per cent. A schematic representation of the differential thermometer can be seen in Figure 3.2.

Radiation

Radiant heat exchange between the subject and the walls of the test section is measured using a 4π radiometer. The radiometer encircles the subject except for a small gap above his head and below his feet caused by the drip tray. It consists of an aluminium frame covered by a thin polyethylene sheath. Fine nickel ribbon, 0,25 mm wide by 0,01 mm thick is used to sense infrared radiation. Radiation changes the temperature of the nickel ribbon and consequently its resistance. The ribbon is held in frames, the tension being maintained by hair springs. All frames on each side of the radiometer are connected in series. The ribbon is sprayed with matt black paint after it has been strung. The radiometer revolves around the subject once very minute, mechanically integrating the radiation travelling between the subject and the walls. The arms of the radiometer are connected in a wheatstone bridge configuration. Change in resistance is amplified approximately 10 000 times by a strain gauge amplifier, the output is integrated over a selected period. Radiative heat transfer can be determined with an accuracy of better than 10 per cent. The schematic diagram of the layout of the radiometer can be seen in Figure 3.3.



BRIDGE CONFIGURATION OF DIFFERENTIAL THERMOMETER

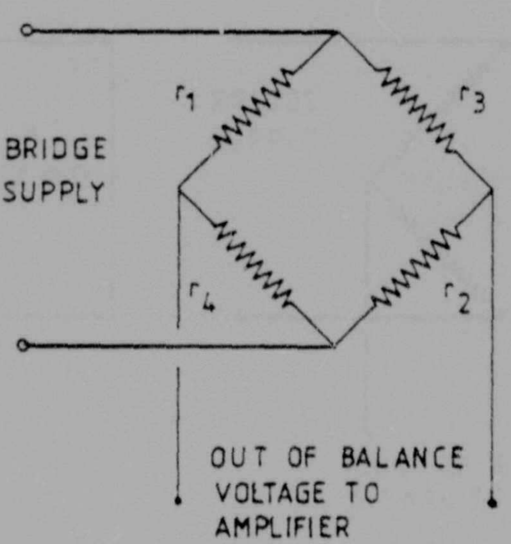
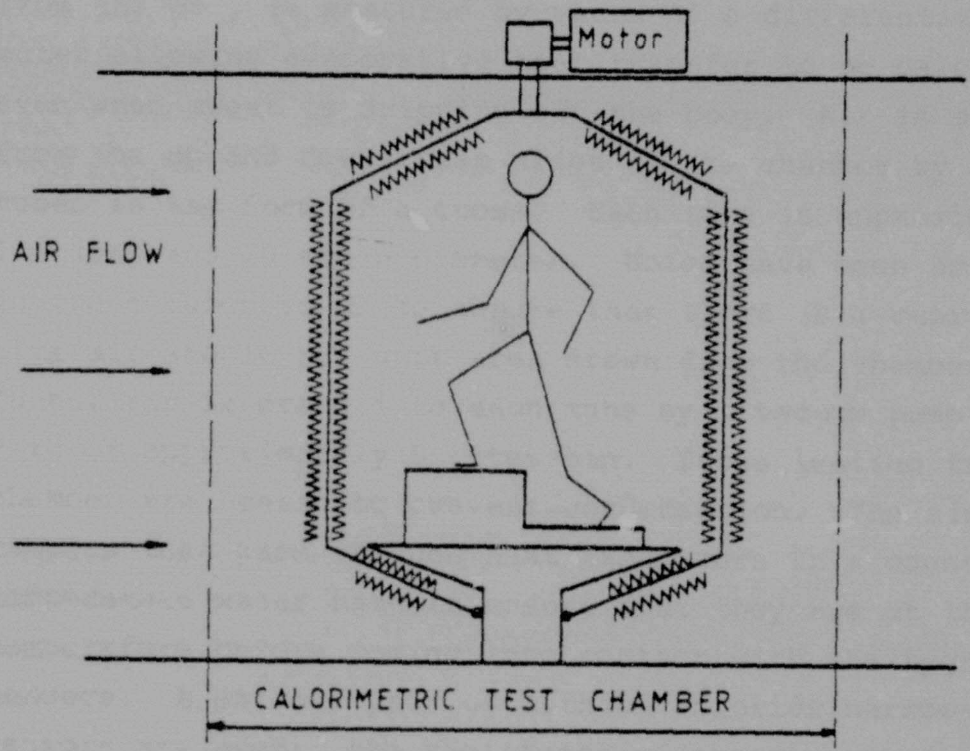


Figure 3.2 <u>SCHEMATIC REPRESENTATION OF THE DIFFERENTIAL THERMOMETER USED FOR THE MEASUREMENT OF CONVECTIVE HEAT TRANSFER</u>



BRIDGE CONFIGURATION OF RADIOMETER

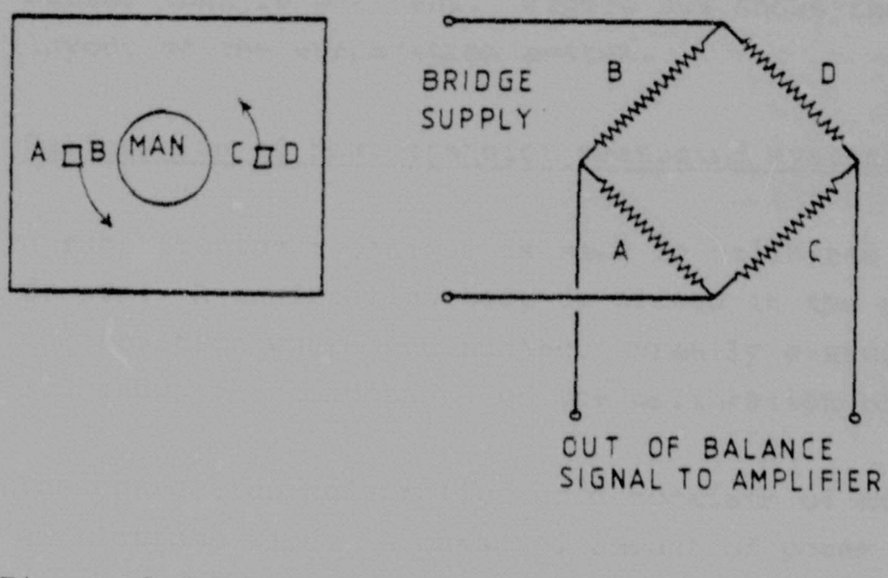


Figure 3.3 SCHEMATIC REPRESENTATION OF THE 4π RADIOMETER

Evaporation

Heat loss due to the latent heat of evaporation of sweat from the body is measured by means of a differential hygrometer allowing evaporative heat transfer to be calculated even when sweat is dripping off the body. Air is sampled from the up and downstream sides of the chamber by two tubes in the form of a cross. Each tube is approximately 1 m long and 10 mm in diameter. Holes have been drilled in these tubes so as to ensure that there is a representative air sample per unit area drawn from the chamber. Tunnel air is drawn into each tube by a vacuum pump at a rate of approximately 5 lites/min. Tubes leading from the chamber are heated to prevent condensation. The air samples then pass through heat exchangers in a constant temperature water bath to ensure that they are at the same temperature before coming into contact with the hygrometer sensors. A matched pair of lithium chloride narrow-range sensors are used; the resistance of the sensors is very sensitive to water vapour content. The differential signal from the transducers is amplified 150 000 times and then integrated over a selectable period of time. Evaporative heat transfer can be measured with an accuracy of better than 10 per cent. Figure 3.4 shows the schematic layout of the evaporation system.

Calibration of heat transfer measuring systems

A substitution technique is used to calibrate the transducers. A calibration body is placed in the chamber in the position where the subject normally exercises. Figure 3.5 shows the components of the calibration body.

The convection calibration grid consists of highly polished nichrome wire. A measured amount of power is supplied to the grid and the corresponding deflection in voltage on the convection strain gauge amplifier is noted. By divid-

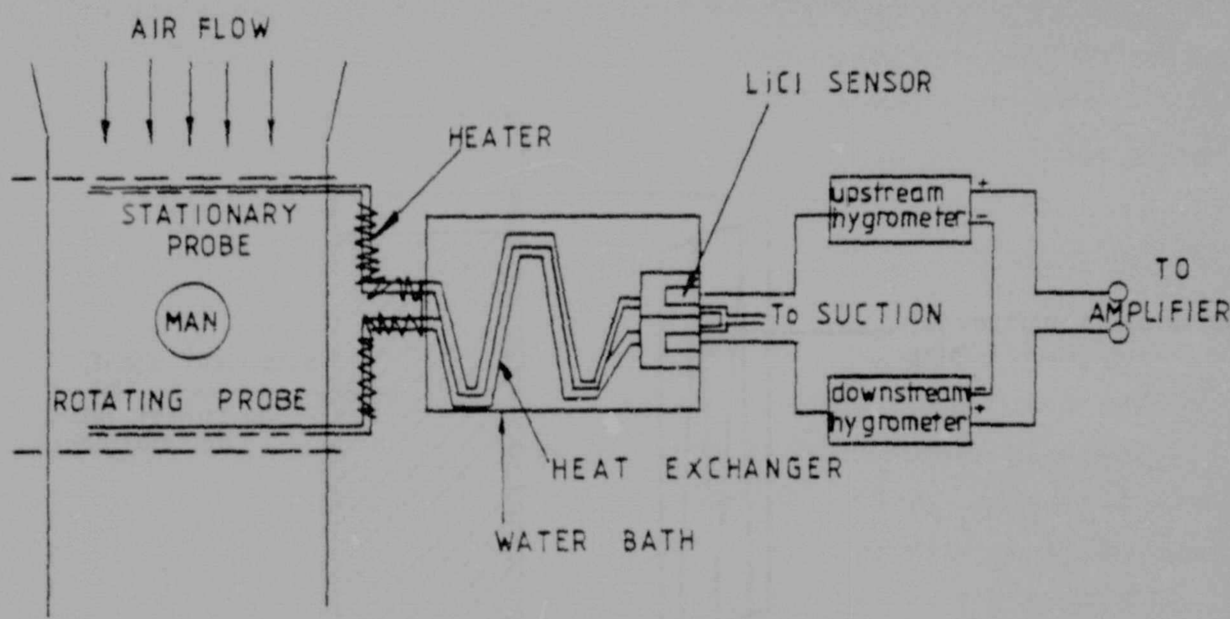


Figure 3.4 SCHEMATIC DIAGRAM OF THE DIFFERENTIAL HYGROMETER

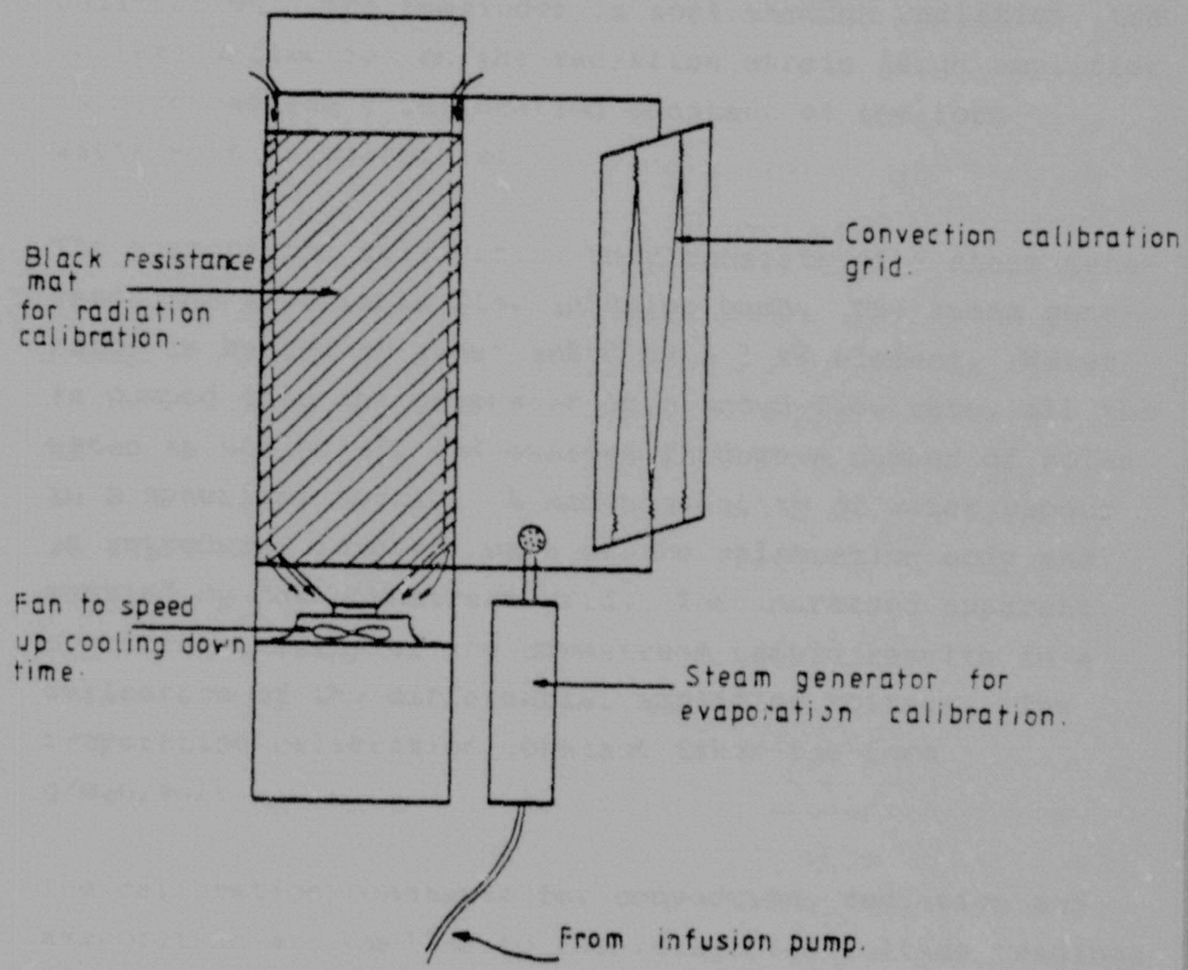


Figure 3.5 SCHEMATIC DIAGRAM OF THE BODY USED FOR HEAT TRANSFER INSTRUMENTATION CALIBRATION.

ing the power by the voltage deflection a calibration constant of the form watts/volt is calculated.

Radiation calibration is performed by supplying a measured amount of power to the matt black heating pads wrapped around the calibration body. About 50 per cent of the power supplied to the pads is lost through convection, but the exact quantity can be calculated from the convection calibration. The remainder is lost through radiation, the voltage deflection on the radiation strain gauge amplifier is recorded and a calibration constant of the form watts/volt is calculated.

The evaporation calibration body consists of a steam generator and a variable flow infusion pump. The steam generator is heated to about 300°C by a 1 kW element. Water is pumped into the generator at a known flow rate, all the water is boiled off and escapes through a number of holes in a spherical nozzle. A known quantity of water vapour is introduced into the wake of the calibration body and sampled by the downstream grid. The increased apparent specific humidity of the downstream sample results in a deflection of the differential amplifier voltage. The evaporation calibration constant takes the form g/min/volt.

The calibration constants for convection, radiation and evaporation are applied to the integrated voltage readings recorded during experimentation so that together with the metabolic rate measurement, a heat balance can be calculated.

3.3 Temperature Measurement

Calibrated copper constantan thermocouples are used to measure all temperatures. Each thermocouple is calibrated against a standard thermometer which can be read accurately to ±0,02°C. A quadratic equation is used to represent the calibration curve. Voltage readings are converted to temperatures with an accuracy of better than ±0,025°C. All reference junctions are maintained at 0°C by an oil filled ice reference bath.

Dry-bulb temperature

The dry-bulb temperature is measured in two ways. Nine 28 gauge thermocouple junctions situated 1 m upstream of the subject, covering the entire cross-sectional area, are connected in parallel to give an average measure of the dry-bulb temperature. A second measurement of dry-bulb temperature is made in a "sampling psychrometer" situated 3 m upstream of the subject. A 30 gauge thermocouple junction has air, sampled across the approximate height of an experimental subject, drawn over it by a fan. The two independent measures of the dry-bulb temperature are always within 0,025°C of one another. The feedback transducer (PT 100 platinum resistance element) used for the automatic dry-bulb control is also situated inside the psychrometer.

Wet-bulb temperature

A single 30 gauge thermocouple junction covered with a tight fitting cotton wick is used to measure the wet-bulb temperature. The thermocouple junction is located inside the sampling psychrometer where a high flow rate of air is maintained. The wick is always kept wet through an automatic water feed mechanism. The water is allowed to equilibrate in a reservoir at the dry-bulb temperature before being supplied to the wick. The wet-bulb PT 100 feedback transducer used for humidity control is also located inside the psychrometer.

Wall, roof and floor temperatures

All four walls, roof and floor temperatures are measured under 25 mm thick polystyrene insulation stuck to the relevant surface. At least two thermocouple junctions are attached to each surface to give the average temperature of that surface.

Mean skin temperature

Six 28 gauge (0,30 mm) thermocouples are used to provide a continuous measurement of mean skin temperature. The thermocouples are held against the skin surface by lightly tensioned elastic threads. The six sites and the area based weighting factors used to calculate mean skin temperature are: arm = 0,3; thigh = 0,2; calf = 0,2; chest = 0,075; abdomen = 0,075 and back = 0,15. The weighting system is similar to the weighting formula proposed by Ramanathan (1964).

In addition to the six-point method of measuring mean skin temperature, at various times during the experiment, skin temperature is measured at 15 sites using a 36 gauge (0,15 mm) thermocouple mounted on a spring loaded probe (Mitchell 1972). A simple average of the 15 temepratures is used to check the six-point determination of mean skin temperature. The two methods were found to differ negligibly.

In all instances lead conduction errors are minimized by ensuring that the lead wires are in contact with the skin for at least 10 mm on either side of the junction. The contact length for the attached thermocouples is usually in excess of 25 mm on either side of the junction.

Rectal temperature

Rectal temperature is continuously monitored using three 30 gauge thermocouple junctions placed in a sterilized plastic sheath. When inserted, the junctions are located 100 mm, 80 mm and 60 mm beyond the anal sphincter. During exercise the rectal temperature probe often begins to slip out. By observing the temperatures of all three junctions, the movement of the probe can be detected and corrected. The temperature recorded 100 mm beyond the anal sphincter is used in the data analysis.

3.4 Automatic Data Acquisition System

All environmental conditions, physiological temperatures and heat transfer measurements are logged automatically every two minutes by a Hewlett Packard data acquisition system. The system consists of a sixty channel scanner linked via the Hewlett Packard Interface Bus to a six digit voltmeter and a series 85 desktop computer. Each two minutes all data is stored on tape and printed on paper. Certain data are plotted to give a visual presentation of important functional relationships.

The scale system is also linked to the computer via a BCD interface bus. The main program is interrupted when the subject's weight is to be measured. A subroutine reads the scale output and stores the information on tape.

All data processing is done after the experiment on a Hewlett Packard 9845A desktop computer.

3.5 Experimentation

The subject

A single male mining recruit was used as an experimental subject. Reasons for using the single subject were given in Section 2.6.1. His physical characteristics are given in Table I.1 in Appendix I. He was willing to participate in the experiment and understood that he was free to withdraw from the experiments at any time.

Acclimatization

Prior to the start of the experimental programme, the subject was acclimatized to exercise in the heat according to the standard eight day procedure (Kok and Strydom 1970). His level of acclimatization was checked periodically during the course of experimentation by comparing his rectal temperature response to that observed on the last day of acclimatization.

Environments and work rates used

In order to ensure that the physiological conductance characteristic could be described over a wide range of mean body temperature driving signals and metabolic rates, an extensive range of environmental temperatures at rest and at four levels of exercise was chosen, and are given in Table 3.2.

Exercise consisted of block stepping at 24 steps per minute at various step heights to achieve the required metabolic rates. Experiments lasted for four hours each day.

During exercise, the wind velocity was set at 0,5 m/s, but during rest, the wind velocity was increased by 0,7 m/s to 1,2 m/s in order to compensate for the wind velocity induced by block stepping (Galimidi et al. 1979).

Routine experimental procedures

The experimental procedure was identical on each day. Experiments were conducted in the mornings of Tuesday to