FALCONER, S.M. 1984. *A laboratory and performance evaluation of clothing assemblies which incorporate sliver-knit fabrics*. Robert Gordon's Institute of Technology, MPhil thesis. Hosted on OpenAIR [online]. Available from: https://doi.org/10.48526/rgu-wt-1993206

A laboratory and performance evaluation of clothing assemblies which incorporate sliver-knit fabrics.

FALCONER, S.M.

1984

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A LABORATORY AND PERFORMANCE EVALUATION OF CLOTHING ASSEMBLIES WHICH INCORPORATE SLIVER-KNIT FABRICS

SHEENA M FALCONER BA

This thesis is submitted in partial fulfilment of the requirements for the Degree of Master of Philosophy of the Council for National and Academic Awards.

The research was conducted at Robert Gordon's Institute of Technology, Aberdeen and the Department of Textile Industries, University of Leeds and in collaboration with the Institute of Environmental and Offshore Medicine, University of Aberdeen.

November 1984

ACKNOWLEDGEMENTS

I should like to thank Dr R Bennett my Director of Studies and Dr J H Keighley, and Dr I M Light for their assistance, guidance and encouragement with this project.

I am grateful for having had the opportunity to work with colleagues in the Department of Textile Industries, University of Leeds and Institute of Environmental and Offshore Medicine, University of Aberdeen and thank Prof Grosberg of Leeds and Prof Norman of Aberdeen for allowing me access to their facilities.

I am greatly indebted to all the subjects who participated in the wearer trials presented in this thesis. Without their tremendous cooperation, motivation and enthusiasm, in the hostile experimental conditions, the experiments would not have been possible.

I should like to thank Mountain Equipment, Glossop and W L Gore & Associates (UK) Ltd, Livingston for supplying fabrics and to Prof F MacIntosh and staff of his School of Electronic and Electrical Engineering, Robert Gordon's Institute of Technology for building experimental apparatus.

My thanks are also due to Mr M G Gibson for the statistical analysis, Mr W Black for photography and Mrs Jean Cumming for typing this thesis.

Finally I would like to acknowledge the support and encouragement of many friends and colleagues and in particular Alex A Falconer, husband and friend.

A LABORATORY AND PERFORMANCE EVALUATION OF CLOTHING ASSEMBLIES WHICH INCORPORATE SLIVER-KNIT FABRICS

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ABSTRACT

The physiological factors relating to temperature control in man and the effect of a cold environment are reviewed and outlined.

The properties of fibres and fabrics as they relate to thermal insulation within a clothing assembly are considered and moisture vapour retention and transmission within the assembly and the relationship to clothing insulation are discussed in detail. The results of laboratory tests on a number of outer fabrics and insulators are presented, analysed and discussed.

On the basis of experimental work one sliver-knit pile insulator and three outer fabrics were selected to be used in wearer trials. The determination of performance in wear of anorak type jackets under cold conditions is described and the physiological trials, weighing techniques and comfort questionnaire used are discussed and the findings analysed. Some correlation was found between moisture vapour transmission experiments on fabrics and the performance during wearer trials. The comfort scores represent the subjects' feelings and correlate reasonably with the garments warmth, dryness and soft handle as identified in the laboratory trials. It appears that bench trials on fabrics followed by wearer trials accompanied by a questionnaire would give a reasonable appraisal of garment performance and acceptability in use. The physiological monitoring which was conducted in these trials would not be absolutely necessary in evaluations of this type.

The outer fabrics which had moisture vapour transmission properties performed best in the trials, but the number of subjects studied and the duration of the trials limit the conclusions which can be drawn.

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CHAPTER I

INTRODUCTION

1.0 General Introduction

The purpose of clothing is predominantly as a protective microclimate which maintains the thermal balance between body heat generated and that lost to or gained from the environment, and also as a physical barrier to environmental exposure which will cause bodily damage.

Although it is perfectly feasible to measure the insulation properties of fabrics and fabric assemblies, the relationship between this and their performance in practice depends on many additional factors, viz. closeness of fit, type of fastening and environmental conditions. Clothing designed as a functional protective system will encompass both safety and comfort factors as essential elements. However, this introduces a further sphere of difficulty in analysis, namely the difficulty of determining what comfort is and how it is to be measured.

It is obvious that comfort is a subjective concept and will relate to the individual as well as the garment. The influences of psychological and environmental factors, and the individual's physiological state as well as the physical properties of the assembly will all have an effect. The real test of a clothing assembly, particularly one intended primarily for protection in a severe environment, is surely that it maintains the individual's temperature at a normal level and that comfort is experienced at all levels of activity.

This concept immediately introduces the necessity of reconciling opposing demands. It is clear that thicker material provides greater insulation but also, however, renders the assembly less mobile.

Water resistance may also be judged to be a necessary property and this also adds complications since traditional water resistant treatments normally reduce the flexibility of the fabric and prevent or inhibit the removal of moisture from the skin, which has further implications for comfort. There are therefore many factors of relevance in this area, some of which are capable of objective measurement and others which are not.

Factors of relevance might be:-

a) physiological parameters

b) physical properties of fabrics and assemblies

c) design and fit of the clothing assembly

d) environmental conditions, eg. temperature and air movement

e) activity levels and the state of mind of the individual at any specific time.

The aim of this study is to investigate the effectiveness of various fabrics used as outers in anorak type jackets when combined with a single insulator as the inner. Thus the insulator in all cases will be a sliver-knit pile fabric which has been chosen on the basis of a preliminary investigation designed to establish optimum performance. This investigation is described.

While six commonly used outer fabrics were investigated in the laboratory, only three were chosen to be made into garments for use in the wearer trials to make the time spent on this aspect of the study more manageable. Laboratory investigations were carried out under standard conditions and also in conditions simulating wear at near-zero and sub-zero temperatures. These investigations were intended to determine the performance characteristics necessary for a garment to be effective in cold, wet conditions.

The three outers chosen for further testing were selected on the basis of their performance in the waterproofing and moisture vapour transmission laboratory tests. When constructed, the garments were shaped identically and the techniques used were as close as the individual fabrics permitted.

The garments were then subjected to assessment of thermal and comfort properties by means of two sets of wearer trials (ie at rest and exercise) in a cold chamber. Any correlation between fabric performance in the laboratory and the wearer trials was noted.

A preliminary background discussion on the physiological factors relating to temperature control in man is presented in Chapter II. The properties of fibres and fabrics, as they relate to thermal insulation within a clothing assembly, are then discussed. (Chapter III). Moisture retention and transmission within an assembly and their relationship to clothing insulation are also reviewed. (Chapter IV). The tests carried out in these areas were undertaken in order to select a single insulator, and three outers for further evaluation in wearer trial investigations. Chapter V reviews the complexities involved in determining comfort in clothing (Spencer Smith 1977).

Details of the experimental methods and the materials used are given in Chapter VI while the results and some discussion are contained in Chapter VII. Since the results gained have a direct bearing on decisions taken in relation to further work, the laboratory conclusions are summarised in Chapter VI. The results and discussion of the wearer trials are contained in Chapter VIII and in particular the relationship between the objective laboratory and physiological measurement studies and the degree of comfort expressed by the experimental subjects is examined.

CHAPTER II

PHYSIOLOGICAL ASPECTS OF MAN IN THE COLD

2.0 Tropical Origin of Man

The phrase "Man is a tropical animal" was used in Charles Darwin's original hypothesis (1906), but remained a theoretical concept until archaeological and paleontological evidence to substantiate it came to light from findings in Africa later in the century. Homo Sapiens, a direct descendant of the African hominids through Homo Erectus, possesses physiological characteristics advantageous to tropical dwellers. The skin, which is man's boundary layer with his environment, exhibits certain properties which are valuable for living in warm regions. The ability to sweat facilitates a high rate of heat loss so that thermal balance can be maintained and clearly the maximum evaporative cooling effect is achieved from a skin that is virtually devoid of hair.

The concept of critical temperature, i.e. the lowest air temperature at which an animal can maintain body temperature without increasing its metabolic rate from the resting level, has been investigated in many animal species. (Schalander 1955). This critical temperature has been considered as a fundamental index of the overall thermal adaption of an animal. Erikson, et al (1956) showed that the critical temperature of the naked Caucasian male of normal indoor habitation was approximately 26°C. Below this temperature, heat production increases approximately in proportion to the body to air temperature difference and man responds as a tropical animal under these conditions. When man, who is accustomed to living in a temperate climate, is repeatedly or continuously exposed to a hot environment, he rapidly develops a greatly increased capacity to withstand heat stress and this adaption is accompanied by demonstrable physiological changes. (Macpherson 1958). However, when transferred from a temperate to a cold or even Arctic environment, this increased tolerance and adaption does not occur and to survive successfully he must use his intellect.

Man, even in temperate climates, is often in an environment which can impose severe thermal demands upon his physiological mechanisms. Most homeothermic animals maintain a constant internal body temperature which is higher than that of the external environment. In colder latitudes the temperature gradient is so great that the main problem becomes one of preventing heat loss and therefore the development of a barrier in the form of clothing becomes necessary.

2.1 Physiology

Many factors associated with human physiology are relevant to the design of any clothing system. Heat transfer mechanisms, the state of individual acclimatisation, environmental conditions, work rate and the type of fabric used in the clothing assembly, all affect the comfort and perhaps the survival of the wearer.

2.1.1 Thermoregulation

The metabolic generation of heat and the control mechanisms of the body which maintain deep body and skin temperatures at approximately constant levels are known as the thermoregulation system. It is generally accepted that when considering thermoregulation in man, two areas should be investigated together. These areas are the CORE, which consists of the heart, lungs, brain, organs of the abdominal cavity and their associated blood circulatory systems, and where the temperature varies only within narrow limits. The other area is the SHELL, which is the layer between the core and the skin surface. In this area, the peripheral tissues can be subjected to wider temperature variation than the core without detriment to health. Wide variations in skin temperatures are to be found between the finger, hand, foot and torso of any individual. The core, or deep body temperature is a factor of vital importance to organs such as the brain, and maintenance of this temperature at or near $37^{o}C$ is essential for the satisfactory continuation of normal body functions. The maintenance of a relatively constant core temperature, even in the presence of wide variations of thermal stress, has been proposed as evidence for the existence of a regulatory system for internal body temperature of the negative feedback type, incorporating proportional control. (Open University 1979). The essential feature of the core control system is the work rate and it is independent of the environment whereas skin temperature depends on the environment. (Neilsen & Neilsen 1965). The core temperature being considerably higher than that of the normal environment allows heat loss to act as an additional regulation mechanism so that steady heat production can take place regardless of any variation in external temperature.

Stolwijk (1970) suggested that the thermo-regulation process can be divided into three regions:

a) sweating

b) shivering

c) vasomotor activity.

Information drawn from the skin receptors and the central temperature receptors (the anterior hypothalamus or heat loss centre) suggests that two distinct systems operate. The peripheral temperature controlling system is the first line of defence and the central temperature controlling system is the second. The primary responses are effected via changes in vasomotor activity. When a change in environmental temperature is detected by the skin receptors, the controlling system responds by constricting the blood vessels, thus reducing the blood supply to the extremities and so conserving the core temperature. If, however, the vasomotor adjustments are inadequate, the thermal equilibrium of the core will be upset causing the hypothalamus to initiate more drastic thermogenic responses.

2.1.2 Thermogenesis

2.1.2 Thermogenesis - Metabolic Heat Production

Metabolic processes are the sole source of heat production and can be classified as either obligatory or regulatory. (Carlson & Hsieh 1974). Obligatory heat production refers to the heat liberated when food is utilised by the biochemical processes of the body to maintain life. The resting human body produces approximately 70W from oxidative metabolism and heat production at a high level of activity is some 6 to 10 times greater than this and is an essential parameter to consider when designing clothing for a specific situation. When activity and heat production span a wide range, the design of the clothing as a heat loss control mechanism clearly becomes much more difficult.

Regulatory heat production refers to the heat produced in response to the controlling system of the skin receptors, hypothalamus and spinal cord. In man, the peripheral and central cold receptors in the skin seem to be most important factors in the human defence against cold. This mechanism can raise the metabolic rate only slightly compared to the increase which may occur by increasing muscular activity or by shivering.

2.1.3 Shivering

The other mechanisms which increase heat production operate by increasing skeletal muscular activity by voluntary or involuntary action. Man can maintain and increase his metabolic rate and heat production by 2 to 5 times the resting value by shivering. This mechanism is initiated by the posterior hypothalamus. Shivering is a co-ordinated movement of voluntary skeletal muscle under involuntary nervous control and is induced around 35°C core temperature at the early stages of hypothermia. However, the body temperature cannot be maintained by this mechanism if the ambient temperature continues to descend. The efficiency of shivering in terms of body heat maintenance is only 11%. (Horvath et al 1956). This is thought to be because there is an increase in the body to environment heat transfer co-efficient caused by increased blood circulation to skeletal muscles near the body surface and increased convective heat loss caused by body action. Shivering, however, has been shown to prevent hypothermia, despite a drop of 25°C in the environmental temperature. (Hervey 1973). Clinical observation suggests that effective shivering can be diminished by lack of oxygen at high altitude, which is a relevant consideration when engineering clothing assemblies for mountaineers, skiers etc. After several weeks of exposure to cold, shivering is replaced by non-shivering thermogenesis, which is more efficient in the maintenance of body temperature.

2.1.4 Non-Shivering Thermogenesis

This term relates to the ability of an organism to elevate its metabolic rate without exhibiting outward signs of shivering, until a certain threshold is reached. This method of heat production is more efficient than shivering, due to the lack of convection and because maximum tissue insulation is not impaired. Many small animals generate extra heat using brown adipose tissue but the ability in man to produce additional heat by this means without shivering originally appeared to be restricted to infants. (Hay 1974). However, further studies in Canada, Cambridge and Queen Elizabeth College, University of London in 1980 suggested that brown fat cells are relevant to heat production in adult humans. Non-shivering thermogenesis and shivering are additive in their contribution to the total production of body heat.

2.1.5 Hypothermia

When the rate of heat loss is greater than the rate of heat production the body temperature will fall and a state of hypothermia is said to have been achieved when the deep body temperature falls to 35°C and below. The significant temperatures are as follows:

a Core Temperatures - Stages of Hypothermia

a) Core Temperatures - Stages of Hypothermia

35.5°C - 34.5°C	The fall in central body temperature induces the physiological responses of vasoconstriction and shivering. Personality change.
34°C	Tissue metabolism is progressively increased. Shivering activity usually ceased. Mental confusion.
33°C	Heart rate and respiratory rate depressed. Unconsciousness. Physiological mechanisms of heat conservation are inactive and heat is lost passively.
27°C	Heart failure.

Hypothermia can be either induced or accidental. Induced hypothermia is associated with controlled body cooling and lowering of body temperature, often linked with muscle relaxation to prevent involuntary shivering, and conducted under clinical conditions. This type of surgical hypothermia was initiated in the 1930's and much of today's information stems from this work. This research played a vital part in enabling cardiac and brain surgery to be carried out when other methods of anaesthesia were impractical.

Accidental hypothermia is a hazard to which anyone undertaking activities in a cold environment is exposed. Chronic hypothermia occurs in the elderly, alcoholics and drug abuse victims. The lowest recorded body temperature (18°C) and subsequent recovery, was measured in a young woman (commonly known as Chicago Nell), who had lain in an alcoholic stupor for 11 hours in a temperature in the region of -30°C. The patient was rewarmed slowly, consciousness returning after 10 hours when rectal temperature reached 28°C. The largest number of hypothermia cases occur among the elderly in their own homes who, for reasons of financial constraint, cut heating and food intake to a minimum, and this, combined with the deteriorating efficiency of the thermo-regulatory and blood circulation systems, puts them at great risk.

2.1.6 Sweating

The two elements involved in this thermo-regulatory mechanism and defence against heat stress are:

a) insensible perspiration

b) sweat or perspiration

Insensible perspiration is a diffuse evaporation which occurs when water oozes through the blood vessels of the dermis by transudation, to pass into the space between the cells of the epidermis. This evaporation increases with a rise in the skin or ambient temperature, but decreases as relative humidity rises at temperatures over 18°C. Insensible perspiration stops at an air temperature around 26.5°C.

The active sweat mechanism involves two types of glands:

a) Apocrine - predominate in animals, but are very sparse in humans. They serve very little purpose and are commonly accepted as showing the superior human position in evolutionary history.

b) Eccrine - these are distributed all over the human body and emit a water secretion known as perspiration.

Women tend to sweat less than men at a given deep body temperature, (Fox et al 1969), and if heavy sweating takes place the sweat rate is found to decline as the presence of moisture on the skin inhibits local sweat secretion; recovery of this mechanism is rapid if the skin is dried, this is known as hidromeiosis (Kerslake 1972). The secretion of sweat is a means of eliminating heat energy from the body in a hot environment or where vigorous exercise is taking place. The quantity of heat lost by this means depends on:

a) the rate of fluid secretion

b) the capacity of the environment to remove water vapour (relative humidity in the air and air movement)

c) the barrier set up by the clothing assembly.

The sweat rate is controlled by the anterior hypothalamus which incudes control mechanisms of vasodilation and sweating.

Work rate determines rectal temperature; rectal temperature and skin temperature together determine sweat rate; therefore thermal sensation signals from the skin are able to modify the sweating response.

Up to 2 litres of sweat or more may be produced in one hour by individuals acclimatised to work vigorously in heat. At an ambient temperature of approximately 26°C, with a relative humidity over 80%, evaporation becomes impeded and the skin becomes covered with droplets of sweat. However, in tropical conditions of 37°C to 52°C, with low relative humidity of 5 to 25% evaporation is very rapid especially when little or no clothing is worn. A clothing system obviously acts as a barrier to evaporation and is an additional complication in the regulation of heat exchange.

2.1.7 Skin Temperature

Skin temperature should be an excellent indicator of thermal stress. However, the difficulty of making the necessary measurements discourage the use of skin temperature as a definitive measure of thermal stress. The skin temperature measurements were used in the wearer trials and are discussed in Chapter VIII. The effects of local skin temperatures are summarised below:-

36°C - 35°C	Upper limits of thermal comfort at rest.
34°C - 33°C	Most comfortable at rest.
35°C - 30°C	Zone of comfort at exercise.
25°C	Uncomfortably cold.
5°C	Numbness.
Zero and below	Frostbite.

2.1.8 Physiological Insulation

It has been established that various mechanisms control heat loss or gain. Thermal conductance, or the rate of heat transfer from core to skin is very variable in man and circadian rhythm can act as a governor. Total conductance, core to air, is maximal in the late afternoon and minimal soon after midnight.

Changes in the thermal conductivity of subcutaneous tissue are controlled by the blood flow and therefore affect the insulation values of various tissues. Blood flow to the brain remains constant and therefore there is not much variation in heat transfer and insulation values of the head and neck do not change with environmental temperature of the overall thermal state of the body. Froesce and Burton (1957) showed that in still air at -4°C, heat loss from the head is about 35W and established that this region is important when heat is to be conserved. Muscle and the subcutaneous fat layer provide effective insulation and Keatings (1969) studied this in cold water immersion trials. He showed that thin people lost heat more quickly than subjects with skin fold thickness of 20mm. The fat layer tends only to be relevant as insulation prior to the onset of shivering.

2.2 Thermal Balance

The living body produces heat at all times and this is transferred to the environment. Thermophysiology involves identifying and studying the physiological measurements related to heat exchange and is an essential element of any consideration of a clothing system. Analysis of the factors involved in heat exchange are defined in the following equation:

The equation for heat balance can be written:

$$M - W = R + C + E + K + S$$

where

M = metabolic heat production

R = radiative heat exchange

C = convective heat exchange

E = evaporative heat exchange

K = conductive heat exchange

W = external work performed

S = heat storage.

For man at rest, W = 0, and the equation may thus be re-arranged:

$$M - S = E + R + C + K$$

Heat balance exists when heat storage is zero and this is the state the body strives to maintain. Heat from the body must pass through the tissues before it is lost to the environment and to maintain equilibrium, the heat lost must be equal to the heat generated. It is necessary to consider heat transfer in two systems:

a) skin to environment

b) tissue to skin.

The physical laws governing heat loss from the human body are generally the same as those governing heat loss from any hot object. Measurements of the human body are complicated and vary from person to person. However, this variation is much less if examined in terms of heat loss per unit surface area.

Four mechanisms of heat transfer are recognised as follows:

a) radiation

b) conduction

c) convection

d) evaporation

Heat is lost by conduction, convection and radiation only when environmental temperature is lower than the body temperature and evaporative losses occur only when the moisture vapour pressure present in the ambient air is less than that of the skin surface. Conduction, convection and radiative heat exchange mechanisms function at different proportional rates in different environmental conditions. (Burton and Edholm 1955).

2.2.1 Avenues of Heat Exchange

A) Skin to Environment

a Radiative Heat Exchange (R)

Thermal emission by radiation occurs in all bodies with a temperature above zero. The phenomenon of thermal radiation forms part of the electro-magnetic spectrum. The exchange of heat by radiation between two objects is not affected by air temperature or air movement but depends upon the surface temperature of the two objects or more precisely is proportional to the differences of the fourth power of the surface temperature.

The temperature differences are not the only factors but the characteristics of the surfaces will affect emissivity and reflection.

When radiation impinges on matter it may be totally or partially reflected, transmitted through it or absorbed by it. A body which absorbs all the radiant energy of whatever frequency incident upon it is called a "black body" and it is an established fact that the better the absorber of radiant heat a surface is, the better emitter it is also. Therefore a "black body" absorbs and emits total radiant heat for the given temperature. The clothed human body behaves as "a black body". The net heat loss by radiation depends on the differences between the surface temperature of the body and the temperature of its surroundings. In the case of the clothed human, the radiation emitted from the clothing surface depends on the surface temperature of the fabric which in turn depends on the rate of heat transfer through that clothing. Radiation emitted by the skin will be absorbed almost totally, for the majority of clothing assemblies, by the water vapour and fibres present so that there will be no fundamental direct loss by radiation except where the skin is left uncovered, such as head, face and hands. In reality, in cold environments, where man is nearly totally clothed, radiation heat losses will be minimal and not significant and heat losses by other processes take precedence.

b Conductive Heat Exchange (K)

The first of the modes of heat transfer relating to the presence of matter and temperature difference is conduction. The physical principle here is that heat flows from the hot to the cold regions until the temperatures equalise. The actual mechanism is complex. It is partly due to the impact of adjacent molecules vibrating about their mean positions, thus contributing to the redistribution of energy throughout the mass and partly due to internal radiation.

This is usually classified as an unimportant avenue of heat loss in man's normal environment where surface contact is small. However, in situations of contact with extremely hot or cold surfaces e.g. sleeping in sub-zero temperatures this mechanism becomes more important. In this study direct heat loss from the body by conduction is of minor importance but of major importance when examining the clothing assembly. Materials with low thermal conductivity offer a higher resistance to the conduction of heat through the assembly.

Still air has a very low thermal conductivity and its inclusion between the body and between layers of clothing will benefit thermal insulation. The thermal resistance of the surrounding atmosphere also acts as an additional stagnant air or boundary layer in the series and is relevant to any calculations. Thermal conductivity of textiles will be discussed more fully later.

c Convective Heat Exchange (C)

Convection requires the physical movement of fluid (air) past the body to carry away heat. Heat is lost to the boundary layer around the body by conduction, and then the warmed air molecules rise due to their lowered density and are replaced by cooler air molecules. Air which has been warmed by the body is removed and the heat with it. This process is known as 'Natural convection'. The human body continually produces a flow of warmed air which moves upward and can be detected 1 metre above the head. The strength of the flow is proportional to the temperature difference between the surface and the air. Increase in convection heat loss occurs with movement of limbs

TABLE 2.0

WINDCHILL CHART

As wind has an important effect on the temperature it is most advisable to use a tent or bivouac shelter when sleeping in cold weather or at high altitude in windy weather.

Estimated windspeed in MPH	ACTUAL THERMOMETER READING (°F)											
	50	40	30	20	10	0	-10	-20	-30	-40	-50	-60
	EQUIVALENT TEMPERATURE (°F)											
calm	50	40	30	20	10	0	-10	-20	-30	-40	-50	-60
5	48	37	27	16	6	-5	-15	-26	-36	-47	-57	-68
10	40	28	16	4	-9	-21	-33	-46	-46	-58	-83	-95
15	36	22	9	-5	-18	-36	-45	-58	-72	-85	-99	-113
20	32	18	4	-10	-25	-39	-53	-67	-82	-96	-110	-124
25	30	16	0	-15	-29	-44	-59	-74	-88	-104	-118	-133
30	29	13	-2	-18	-33	-48	-63	-79	-94	-109	-125	-140
35	27	11	-4	-20	-35	-49	-67	-82	-98	-113	-129	-145
40	26	10	-6	-21	-37	-53	-69	-85	-100	-116	-132	-148
(windspeeds greater than 40 mph have little additional effect	LITTLE DANGER (for properly clothed person)				INCREASING DANGER			GREAT DANGER				
					Danger from freezing of exposed flesh							

This chart has been prepared so you can adhere it to some part of equipment that you use constantly e.g. inside rucksack flap, first aid kit, jacket etc.

IMPORTANT ALWAYS KEEP THIS CHART HANDY, DON'T BE CAUGHT OUT.

TABLE 2.0

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	EQUIVALENT TEMPERATURE (°F)											
calm	50	40	30	20	10	0	-10	-20	-30	-40	-50	-60
5	48	37	27	16	6	-5	-15	-26	-36	-47	-57	-68
10	40	28	16	4	-9	-21	-33	-46	-46	-58	-83	-95
15	36	22	9	-5	-18	-36	-45	-58	-72	-85	-99	-113
20	32	18	4	-10	-25	-39	-53	-67	-82	-96	-110	-124
25	30	16	0	-15	-29	-44	-59	-74	-88	-104	-118	-133
30	29	13	-2	-18	-33	-48	-63	-79	-94	-109	-125	-140
35	27	11	-4	-20	-35	-49	-67	-82	-98	-113	-129	-145
40	26	10	-6	-21	-37	-53	-69	-85	-100	-116	-132	-148
(windspeeds greater than 40 mph have little additional effect	LITTLE DANGER (for properly clothed person)				INCREASING DANGER			GREAT DANGER				
					Danger from freezing of exposed flesh							

This chart has been prepared so you can adhere it to some part of equipment that you use constantly e.g. inside rucksack flap, first aid kit, jacket etc.

IMPORTANT ALWAYS KEEP THIS CHART HANDY, DON'T BE CAUGHT OUT.

even in conditions of no overall air movement (Gagge et al 1967). Atmospheric pressure and the use of heliox gases also affect the value of the heat coefficient. However wind speed movement causes greater heat losses.

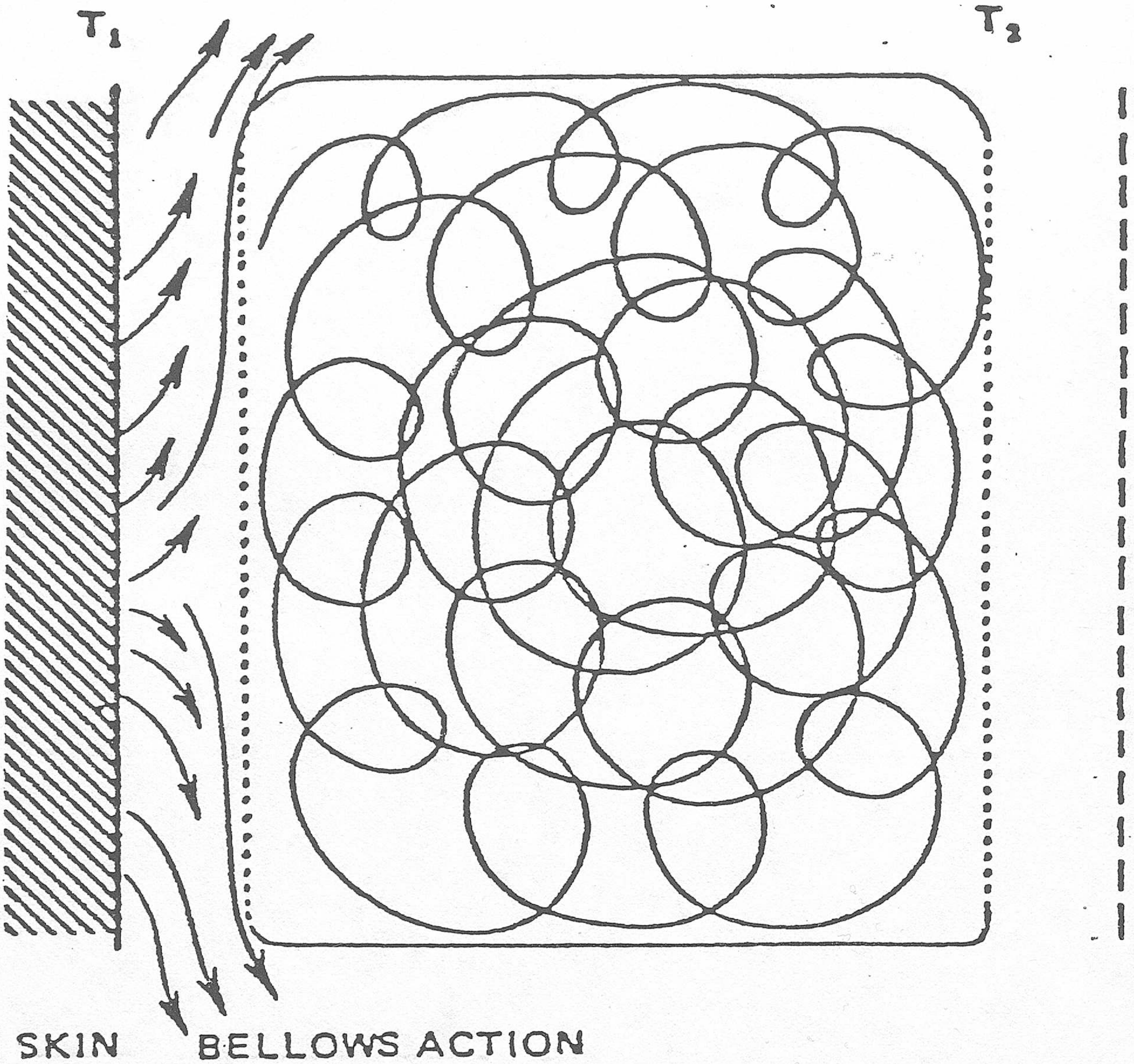
i Forced Convection

In most cases air is never still and the faster the air movement over the body, the thinner the stagnant air layer becomes, and thus the removal of heat becomes greater. The rate of heat loss by convection is further complicated by irregular motion of the body or by turbulent motion of the air. The work done by Clark et al (1977) in connection with convective heat losses caused by helicopter down draught found that the convective transfer coefficients were double that expected using Kerslake's (1972) formula. In very cold weather the dominant factors affecting heat loss from a person are air speed and air temperature. Increased air velocities accelerate heat loss by disturbance of the boundary layer, and also of the still air contained within the assembly. Larose (1947), Breckenridge & Woodcock (1950) and Pugh (1969) showed that in high wind velocities it was advantageous to employ an outer fabric with as low an air permeability as possible in order to limit heat loss.

ii Windchill

The concept of windchill is an attempt to correlate air speed and air temperature in a simplified way, the most frequently used index being that devised by Siple and Passel (1945). This was derived from work done in Antarctica and was initially based on the time taken to express the rate of cooling of a surface at 33^{O}C skin temperature. This WINDCHILL INDEX did not take clothing into account but it is useful as a predictor of the effect of cold wind on exposed bare flesh. The index has serious disadvantages if used to predict heat loss from a clothed body, but it is useful to describe the severity of winter conditions, although its use in cold, wet conditions is not

FIGURE 2.0 The Bellows Action of a garment incorporating insulation encased in inner and outer fabrics.



appropriate. A more realistic model of heat exchange was devised by Steadman (1971). For any given air temperature and windspeed it is possible to calculate the windchill experienced by an uncovered object at +30°C and therefore the quantity of clothing insulation required. Smithson and Balwin's work (1978) on monitoring windchill in British mountain conditions has shown that clothing thickness must be increased in relation to wind velocity and rise in altitude. (TABLE 2:0). The effect of water has received much consideration, but as yet no effective measure of the cooling power of the environment has been developed which takes dampness into account in addition to wind and temperature. Water is a better conductor than air by a factor of 25 and the insulative value of a clothing assembly is largely determined by the amount of still air which it can trap in its interstices. The thorough wetting of a conventional clothing assembly and the replacement of air by water will have the effect of reducing its insulative value to 10% of its control value.

iii Bellows Action

'Chimney' ventilation occurs through openings in the clothing assembly, particularly at the neck, with the convection current by-passing the clothing. This loss is accentuated by body movements (including breathing) when air is forced out by movements of one layer or another, known as bellows action. Figure 2.0. This effect will be discussed further under 'Insulation'.

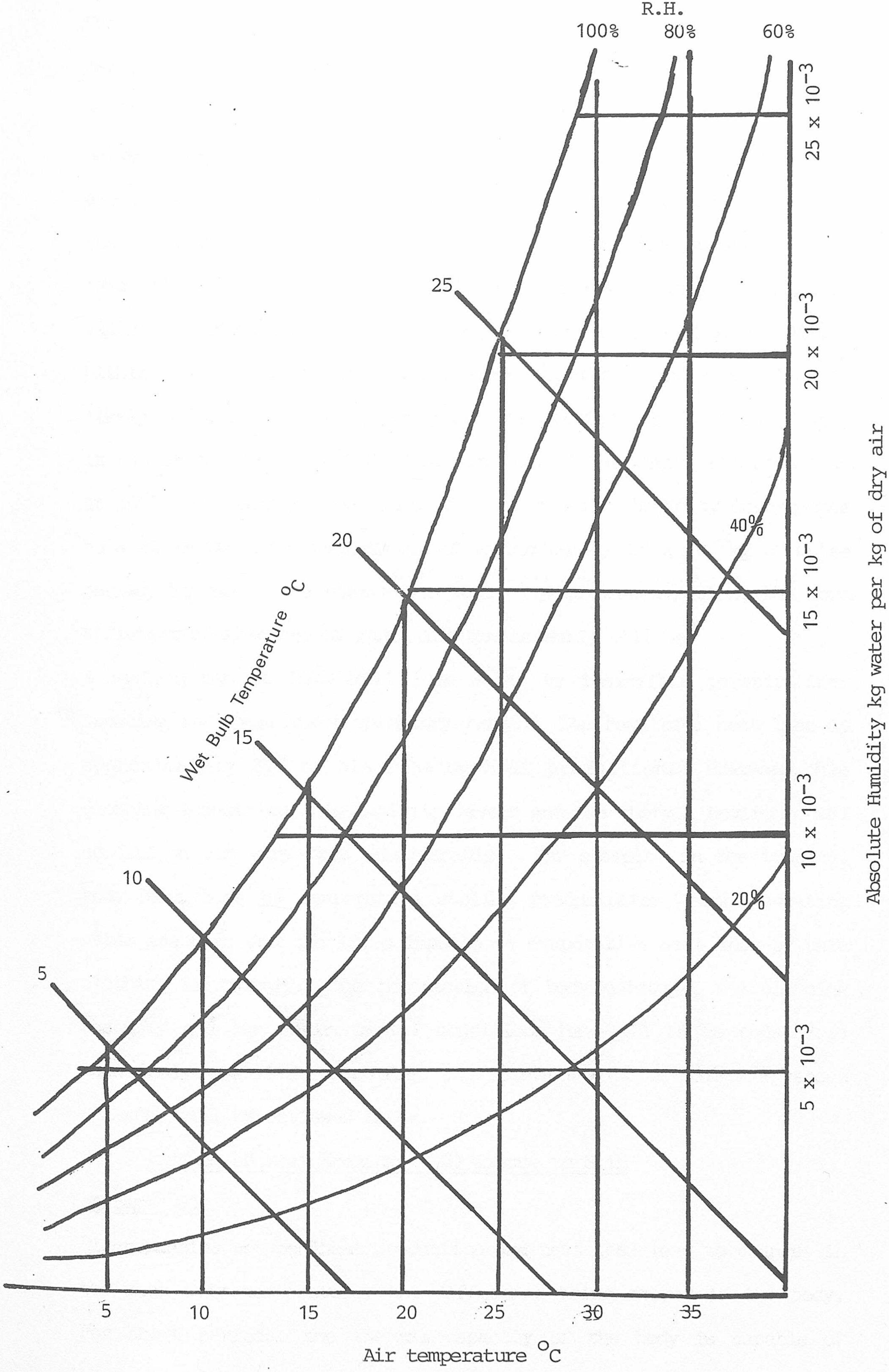
d Evaporative Heat Exchange (E)

Energy is required when liquid changes to the vapour phase and is known as the latent heat of vaporisation. Evaporation of moisture (sweat) absorbs body heat and cooling therefore takes place. The heat of evaporation of sweat is that of water, i.e.

$$\pi = 2.45 \times 10^6 J/kg.$$

Raising the ambient relative humidity decreases the amount of body heat that can be dissipated by the evaporation of body moisture.

FIGURE 2.1 Psychrometric Chart



The rate of evaporation from a wet surface to the ambient air is determined not by the difference in relative humidity between the surface and the air, but by the difference in water vapour pressure between them. The higher the ambient temperature, the greater the amount of moisture needed to saturate the air, therefore the greater the saturation water vapour pressure. The Psychrometric Chart (Fig.2:1) shows that at 20°C and 65% relative humidity, the water vapour concentration is 10×10^{-3}kg water content per kg of dry air. Within a clothing assembly after exercise, the relative humidity is likely to be high, and depending on construction and duration of use, it can be as high as 70% to 80%. In Fig.2:1 the chart indicates that at 35°C (skin temperature) this level of relative humidity corresponds to a water vapour concentration of approximately 25×10^{-3}kg of water per kg dry air. The higher the water vapour concentration, the more efficient an absorber of radiation the assembly will be.

A resting man at 20°C will lose water by insensible perspiration, sweating and from his respiratory tract. The resultant heat loss is approximately 25% of his resting heat production. However, his clothing insulation, his activity levels and the thermal environmental conditions can vary this considerably. For example, in the tropics, body heat loss by evaporative cooling predominates, since sweating rates are high and the limit imposed on evaporative heat loss by thin clothing is minimal. The interaction of body moisture, the clothing assembly and the environmental conditions have all to be considered when analysing clothing comfort and relevant work on moisture vapour transfer will be reviewed later.

2.2.2 Avenues of Heat Exchange - B) Tissue to Skin

a Storage (S)

Discrepancies between heat production and heat loss lead to changes in the mean body temperature, the difference being stored in the body. For short periods, the thermal capacity of the body is capable of coping with this temporary imbalance. The measurement of heat storage is difficult but can be calculated from changes in mean skin and core temperatures.

b Conduction and Convection

Heat transfer from the interior of the body occurs only partially by conduction through blood tissues. Cutaneous arteriolar and venous blood flows vary, and can be so reduced that heat transfer from core to skin falls and less heat is lost by conduction, convection and radiation. Cassie (1962) suggested that control of blood supply by the nervous system may be influenced by the type of fibre in contact with the skin sensors. However, this proposition has not been proved.

2.3 Environmental Factors - Cold

Feeling cold is not necessarily a measurable parameter, but is a sensation which results from heat loss. Any change in the environment which causes a heat loss greater than the body's heat production leads to a fall in skin temperature and is interpreted as 'cold'. However, this is relative to the thermal capacity of the absorber. A low ambient temperature contributes to the 'coldness' of the environment. Another factor of importance is the effect of high relative humidity related to a low ambient temperature, such as is found in mountain regions of the Northern Hemisphere and in the North Sea. McKie (1978) for example, found that the environmental conditions on a North Sea offshore installation for a December to February period were as follows:

Mean daily maximum - $9.7^{\circ}C$

Mean daily minimum - $0.8^{\circ}C$

The mean monthly temperature over a 12 month period was $8^{\circ}C$ coupled with a mean relative humidity level of 86%, giving an inhospitable environment. Man must cope efficiently with climatic changes and also maintain body comfort while performing physical work, including intricate tasks requiring high dexterity and accuracy.

Man's survival in extremes of cold, and independence from his environment, are attributed to his complex physiological, behavioural thermo-regulatory mechanism and his intelligent use of clothing and insulation mediums.

CHAPTER III

CLOTHING INSULATION

3.0 Introduction

The insulation provided by clothing, together with heat and shelter is of vital importance in enabling man to survive outside the tropics. If man is placed naked in a cold environment, the total insulation is the sum of his tissue insulation (I_t) and the insulation of the air layer immediately in contact with the skin (I_A), this being a function of air movement with a maximum of 1.55 tog in still air and 0.155 tog where the velocity is 22.8 m/s. (McIntyre 1978). As previously discussed, the limit of compensation against heat loss by the increase in tissue insulation is soon reached (Burton & Edholm 1955). Therefore, modern man must use a body covering which encloses as much still air as possible since thermal insulation largely depends on the thickness of the 'dead air' space. The optimum widths of air spaces in relation to insulation values are discussed more fully in Chapter IV, but in summary, still air, within an air gap of 0.5cm gives an insulation of 4 togs/cm. To prevent heat loss, a clothing assembly must retain its integrity as an insulator during severe conditions such as high wind velocities, wetness, high humidity levels and intense cold, and still provide freedom of movement for the wearer.

The total insulation of a clothed man is given by the sum of

$I_A + I_t + I_{cl}$ where

IA = insulation value of air layer at skin

I_t = insulation value of tissue, and

I_{cl} = insulation value of clothing assembly.

The effect of curvature on proportional heat loss is important and affects the theoretical calculation given above as the extremities of the body are cylindrical with a proportionately large surface area. This factor is important when considering insulation of the small extremities such as the fingers.

3.1 Clothing Physiology

A real contribution to textile science in the 18th century was made by Count Rumford, when he investigated the nature and transfer of heat through materials, including clothing fabrics. He advocated the use of flannel next to the skin and showed that silk was a better insulator than wool, cotton or linen, and although he experimented with clothing fabrics, his conclusions often referred to garments.

The next important landmark in textile work was that of Coulier (1858) on clothing for French soldiers. His thermal insulation experiments using the cooling cylinder method is the technique still used in some continental laboratories. Elaborating on Rumford's work, he differentiated, for the first time, between water absorbed as vapour into the fibres (l'eau hygrometrique - the modern moisture regain) from the liquid water entering the air interstices (l'eau d'interposition) by capillary action. Coulier appeared to be well aware that a difference in vapour pressure was the main cause of the movement of water vapour into a fabric. Parke's book (1864) gave descriptions of textile fibres and showed complete understanding of after-exercise chill and the properties of hygroscopic fibres. Linroth (1881) confirmed Coulier's findings that the amount of water vapour taken up by a fabric is determined mainly by the ambient relative humidity.

Max Rubner (1907) gave details of various physiological parameters of importance when assessing a clothing assembly, also including fabric thickness, compressibility, thermal insulation, air and water permeability. He repeated Coulier's work on thermal insulation using a Stefan calorimeter, recording the results in absolute units, and found that thermal insulation generally increased in proportion to thickness, and concluded that thickness is a fundamental insulating property of clothing. He separated primary properties of the fibre from the secondary properties of the weave and stressed that if dissimilar fibres were woven in exactly the same way, the physiological differences experienced when wearing the clothing would be small. He advanced the view that air and moisture properties are interacting factors and cannot be separated - a fact often ignored in modern research and only re-emphasised in the last 20 years.

3.2 Thermal Insulation

Much of the work on thermal insulation prior to 1930 is referred to by Marsh (1931) and from 1930 up to 1950 by Morris (1953) who conveniently arranges the investigators according to the methods employed in their experiments. For example, he cites Lees and Charlton (1896) and Rood (1921) and their association with the 'Disc Method' for measurement of thermal conductivity. Marsh concluded that the thermal insulation of fabrics varies with the weight per unit area and thickness and that the air enclosed in a fabric has an important bearing on its thermal insulation properties. The following methods and variations on these have been employed to assess this property.

3.2.1 Cooling Method

The Cooling Method is probably the simplest means of obtaining an estimation of the insulating properties of different fabrics. In this method a hot body is wrapped in a fabric whose outer surface is exposed to air and the rate of cooling of the hot body is monitored. This method was employed by Black and Matthew (1934) using Hill's katathermometer because of its simplicity in operation and its working temperature corresponding closely to that of the human body. Blackman (1930), Kruger (1936) and Mechaels (1938) all employed variations on this method.

3.2.2 Disc Method

The Disc Method measures thermal conductivity by using Lee's disc. Speakman and Chamberlain (1930) used this method to study thermal transmission and concluded that wool is a better insulator than cotton or viscose and subsequently found that thermal conductivity increased with density. Thick fabrics were generally made from wool, which had thus earned a name for being warm. In this method the fabric is held between two metal plates at different temperatures and the rate of heat flow is measured. They derived an equation which can be used to predict warmth simply in terms of thickness and density.

3.2.3 Constant Temperature Method

In this method a hot body is wrapped in fabric and the energy input required to maintain it at a constant temperature is monitored. The Constant Temperature Method tended to be regarded as the more accurate method of the time since it simulated actual wear in which the body temperature is constant and the outer surface is exposed to air. Haven (1918), Angus (1935), Niven and Babitt (1938), Cook (1942) and Rees & Ogden (1947) all used this technique. Marsh concluded that the constant temperature method was a superior method to any previously used and defined the 'Thermal Insulating Value' (TIV). The TIV is the percentage reduction in heat loss from the surface after covering it with a fabric. This is the forerunner of Pierce and Rees' (1946) concept of thermal resistance:

$$R = \frac{O_1 - O_2}{H}$$

where H is the heat loss from unit area of the cylinder surface and 0_1 and 0_2 are the temperatures on either side of the fabric surrounding the cylinder.

Much of the work between 1930 and 1950, which can generally be classified under the heading of measurement of the thermal properties of fabrics, has been reviewed by Morris (1953), who divided the work into three sections:

a) Thermal Insulation of fabric (effectiveness of the fabric in maintaining the normal temperature of the human body under equilibrium conditions)

b) 'Cold Feel' of fabrics, ie that property which is assessed by the initial reaction of a person on touching the fabric. The nature of the surface is of major importance since it is the area of contact between the fabric and the skin which determines the rate of heat loss from the skin on making this contact. Very little work has been done on this topic and subjective assessments of cold feel are very unreliable.

c) 'Chillproofness' of fabrics, ie the ability of a fabric to reduce the effect on the human body of sudden changes in atmospheric temperature and humidity. This is connected with the phenomenon of heat of sorption discussed in Chapter IV.

Workers on the thermal insulation of fabrics have continued to use the methods outlined above; namely disc methods, cooling methods and the constant temperature method. However, these all involve the fabrics being exposed to a certain amount of compression when being mounted for test and reproducible results were often difficult to obtain.

From his review of thermal insulation, Morris drew the following conclusions:

a) The thermal insulation of textile fabrics is due primarily to still air contained within the fabric and yarns; the type of fibre being of little consequence. A fabric of a given thermal insulation value can be produced from any fibre type provided the fabric is made sufficiently thick and is identically constructed.

b) The thermal conductivity of fabrics increases with density and there is very little difference between the conductivity of different fibres when measured under similar conditions.

c) Fabric thickness is the most important factor governing the thermal insulation of textiles.

d) When two fabrics are of equal thickness, the lower density fabric has the greater thermal insulation, but there is a critical density (about 0.06gm/cm^3) below which internal convection effects become more important and the thermal insulation falls.

e) The thermal conductivity of textiles increases with moisture content.

f) The thermal insulation of a fabric increases considerably with an increase in the air gap between the hot body and the fabric. There is a maximum air gap of about 9mm, above which insulation falls off, the decrease being attributed to increased convection effects.

g) Increased air velocity reduces the thermal insulation of a fabric compared with its insulation in still air; this effect being reduced for closely constructed fabrics with low air permeability.

h) The thermal insulation of fabrics is considerably increased if the insulating fabric is covered with a fine closely woven outer fabric. The improvement is very marked when there is appreciable external air movement.

i) The relationship between thermal insulating value and weight per unit area of a fabric is not very marked, but there is a slight increase in thermal insulating value with increasing weight per unit area. However, when associated with increased density, a reduction is obtained.

j) The area of contact between fabric and skin (or hot body) is the major factor in determining the 'cold feel' of a fabric.

k) Since the area of contact is the controlling factor, general statements about 'cold feel' of fabrics of different fibres cannot be made.

l) Chillproofness varies with the type of fibre in the fabric. Fibres with steep moisture regain/relative humidity curves, eg wool and viscose are more efficient than fibres whose regain varies only slightly with relative humidity, eg nylon.

m) Chillproofness is not always desirable in clothing, eg when worn in contact with the skin under conditions of exertion.

3.3 Thermal Resistance Measurements

The first scientific approach to the quantitative definition of clothing and its heat regulatory function came from Gagge, Burton and Bazett (1941) in the USA. They proposed a system of units for thermal activity and thermal insulation which would describe conditions of comfort in relation to the heat exchange of man with his environment. Their unit of thermal activity was called the Met, which is the energy generated by an average sitting/resting subject under conditions of thermal comfort ($21^{\circ}C$). Subsequent work introduced this as a new unit of clothing insulation known as a CLO, this being defined as '1 clo will maintain a sitting/resting man, whose metabolism is 50 $kcal/m^2/hr$ indefinitely comfortable in an environment of $21^{\circ}C$, relative humidity less than 50% and air movement 20ft/min.' This definition is illustrative rather than practically applicable and clo is also defined as a mean thermal insulation of $0.18^{\circ}C/m^2/hr/kcal$ ($0^{\circ}.155^{\circ}C/m^2/W$). The clo value of a common clothing assembly, namely jacket, trousers, long underwear and long sleeved shirt is approximately 1.4 clo which includes the external air layer of 0.8 clo: ie, over half the usual clothing insulation is contributed by the adhering still layer.

Pierce and Rees (1946) defined another unit of thermal resistance, the TOG, which is the resistance which will maintain a temperature difference of $0.1^{\circ}C$ with a thermal flux of $1Watt/m^2$. This is the resistance of a light summer suit, and 10 togs represents about the thickest clothing it is practical to wear.

Both tog and clo units are thermal resistance mesurements defined as the thickness of the assembly divided by the thermal conductivity: $m^2/^{\circ}C/W$; ie

$1^{\circ}C/m^2/W$ = 10 togs and

$0.1^{\circ}C/m^2/W$ = 1 tog or $0.418^{\circ}C/sec/m^2/kcal$.

The tog is used in Great Britain and the clo in the United States. The relationship between these units can be expressed as follows:

TABLE 3.0

Estimation of clothing insulation

	I_{comp}
Vest	0.06
Short sleeve or lightweight shirt, blouse	0.19
Warm shirt, blouse	0.29
Short sleeved pullover, waistcoat	0.2
Smock, tunic	0.2
Thick sweater	0.37
Thin sweater	0.25
Cardigan	0.35
Jacket	0.4
Thick trousers	0.32
Thin trousers	0.26
Thick long skirt	0.3
Thin long skirt	0.2
Thick short skirt	0.2
Thin short skirt	0.15
Thick long dress	0.63
Thin long dress	0.25
Thick short dress	0.5
Thin short dress	0.2
Slip	0.19
Waist slip	0.13
Stockings/tights	0.01
Shoes	0.04
Socks	0.03
Briefs	0.05

Estimate of clothing insulation in CLO units

Men – $I_{CLO} = 0.113 + 0.727 \Sigma I_{comp}$

Women – $I_{CLO} = 0.05 + 077 \Sigma I_{comp}$ (McIntyre, 1980)

TABLE 3.1

Insulation values of some clothing outfits

Insulation (CLO units)	Clothing
Nude	0
Light sleeveless dress, cotton underwear	0.2
Light trousers, short sleeve shirt	0.5
Warm, long sleeve dress, full length slip	0.7
Light trousers, vest, long sleeve skirt	0.7
Light trousers, vest, long sleeve shirt, jacket	0.9
Heavy three piece suit, long underwear	1.5

(McIntyre, 1980)

clo value x 1.55 = tog value

ie 6 clo ≙ 9.3 togs

Since the tog value is related only to pieces of fabric, it cannot functionally be converted into a clo value, which is the measurement of the average thermal insulation of the whole garment system.

Recent work using heated dummies or 'mannikins' reported the insulation of different clothing assemblies, Mecheels (1961), Seppamen (1972) and Spragne and Munson (1974). Table 3.0 and Table 3.1 give estimates of clothing insulation values. McIntyre (1980).

In studying the thermal efficiency of fabrics from the aspect of structure, Gagge et al (1941) found it convenient to express resistance as equivalent thickness of still air. As the weight of clothing is all important, the ratio of equivalent air thickness to weight/unit area was taken as a significant measure of efficiency. This quantity is called the THERMALLY EFFECTIVE SPECIFIC VOLUME (TESV) and its ratio to actual specific volume, which may be called the specific thermal resistivity, is a measure of the efficiency of the material. They also stated that the resistance of several layers of fabric of normally close construction is equal to the sum of the resistance of the separate layers. Very open weave fabrics show a relatively low resistance when exposed to moving air, owing to their failure to effectively immobilise air within the structure, but when covered with another fabric, the combination has a much greater resistance than the sum of the separate resistances. Rees (1946) stated that the cellular fabrics tested were very efficient for heat insulation because, although radiation occurred through the interstices, convection was largely restricted by the hairiness of the yarns and the result was a fabric of low overall conductivity. The most efficient type of structure for heat insulation was found to be not a woven fabric, but a fleece which has a lap of well-opened fibres spread evenly between two layers of muslin quilted together.

Renbourn (1960) was critical of the methodology of previous work and claimed that conventional guarded hotplate techniques of measuring thermal insulation on a flat horizontal plane may simulate the arrangement of blankets or sheets but could not take into consideration the realities of clothing on the human body. Apart from the shoulders, clothing is worn vertically and the air spaces beneath the clothing layers are related to their drape and fit to the contours of the body. The insulation value of clothing layers related to their compression is highly relevant but assessment of this without deformation is extremely difficult. The apparatus built by Clulow and Rees (1968) and illustrated in Chapter V represented an advancement in the technique of analysis of thermal resistance. O'Callaghan and Probert (1976) stated that thermal resistance to 'dry' heat transfer is proportional to fabric thickness. In 1977 they studied multiple layer assemblies under load and established that the thermal behaviour of multiple layer assemblies was identical to that of a single layer of the same material and overall thickness. They concluded that contact resistances between successive layers are usually of secondary or minor importance in air at atmospheric pressure and insulation is primarily dependent upon the value of air held stagnant within the matrix, provided that no radiation 'windows' are present.

Kaswell, Barish and Lermond (1961) studied a wide group of properties associated with comfort and concluded that fabrics made from synthetic fibres are more comfortable if made from bulked yarns than if made from continuous filament yarns. Apart from moisture properties, which will be discussed in Chapter IV, they investigated:

a) The physical characteristics of fibres.

b) Their surface characteristics (wet, dry and under various compressions).

c) Their thermal conductivity.

d) Their softness and compressional resilience.

e) Their air permeability.

They assumed that the ability of fabrics to maintain their original dimensions will govern the maintenance of thermal insulation. They found, as had others, that the comfort of a garment is much more dependent on the state of fibre aggregation in yarns and of yarns in fabrics, than on the intrinsic nature of the fibre. Alan and Pouryan (1981) also found that the resistance to heat transfer of a multilayer structure of identical fabrics without air gaps between the layers gave a linear relation with the total thickness. They found that knitted fabrics with a low stitch density (namely lower weight per unit area) insulate better than heavier fabrics, since interlock is a better insulator than a rib construction. They also showed that fabric knitted from two single yarns in parallel had a higher thermal resistance than the same fabric knitted from plied yarn.

Work by Pugh (1966), Kerslake (1973) and Jaksic (1975) showed that although nominal insulating values could be high, the actual insulation under wet/cold conditions could be reduced by 90% because of the combined effect of wind, wetting and displacement of trapped air by movement (bellows action).

Spencer Smith (1976, 1979) working on clothing comfort, pointed out irregularities in the understanding of various environmental and physiological parameters of heat loss because the work was being done in steady state conditions without consideration of the variance in cold conditions. He divided heat loss from a clothed body into a) thermal transfer through the clothing assembly and from its outer surface to the environment and b) the evaporative heat loss, which is the latent heat of the perspiration which passes through the assembly to the surrounding atmosphere as water vapour. He stated that most workers, eg Woodcock (1962), have incorrectly assumed that heat loss due to thermal transfer and evaporative heat loss are independent of each other, giving rise to serious miscalculations in much of the previous work. More recent studies, eg Nishi (1970) and Weiner (1971) took account of the close relationship.

Direct heat transfer, as defined by Spencer Smith (1977) defines transfer through clothing in terms of the resistance to thermal transfer of the individual layers of clothing and the resistance between the outer surface and the environment expressed in togs.

Spencer Smith's work (1977) enables heat losses through dry clothing assemblies, in the absence of perspiration, to be calculated for different conditions. His subsequent work will be discussed under moisture transmission through fabrics.

3.4 Textile Insulators

In the prediction of the thermal insulation of garments, the thermal conductivity of fibres and fabrics is one of the main factors for consideration. The table below shows how various materials differ in thermal conductivity:

Typical values of thermal conductivity (mW/m/°C at 20°)	
Aluminium	200,000
Glass	1,000
PVC tiles	700
Water	600
Brick	200
Still air	25

In this study an initial investigation of known insulators was undertaken in order to select one and establish its performance characteristics.

The table below gives the thermal conductivity of various fibres and where the volume of trapped air within a structure is equal, low thermal conductivity becomes an important factor:

Fibre	Thermal Conductivity mW/m/°C
Polypropylene	120
Polyvinylchloride	160

Fibre	Thermal Conductivity mW/m/°C
Polyester	140
Wool	180
Acrylic	200
Cellulose acetate	230
Nylon	250
Viscose	270
Polyethylene	340

(Morton & Hearle 1975)

The heat conductivity of hydrophilic fibres varies significantly with the water absorbed, being higher in the region of bound water, compared with that of the dry state. This will be discussed later.

Any fibrous material will offer some resistance to the transmission of heat and the low ratio of volume of fibre to air in the system, for example 20% - 10% fibre to 80% - 90% of air will create a good insulator. Air reduces the heat lost by conduction but offers little resistance to heat transfer by radiation, whereas fibres absorb radiation and inhibit radiative heat loss. Rees (1946) observed that fibres have a large specific surface so that a large frictional force produces a high 'drag' and hence high resistance to air movement, thus limiting heat loss by convection. In practice when the thermal resistance of a thin air layer is measured (ie. up to 0.5cm) a value of 4 togs/cm is obtained. When the air gap is widened, convection reduces the effect of air as an insulator, eg with an air gap of 1cm, thermal resistance is 3.5 togs/cm.

When the thermal resistance of fabrics is measured, the highest values obtained are of the order of 2.5 togs/cm for thin fabrics; while for thicker fabrics, this value is reduced to 2 togs/cm. Clearly the reduction from 4 togs/cm arises due to conduction of heat along the fibres since the reduction in tog value cannot be attributed to air convection for fabrics of 0.5cm thickness. Assuming that no

TABLE 3.2

Insulation values for various materials

	Togs/cm thickness of material
50:50 Down and feather mixture	2.6
Continuous filament polyester quilted fabric	2.08
Resin-bonded staple polyester quilted fabric	2.4
Sliver-knit acrylic high pile fabric	2.36
Sliver-knit polyester high pile fabric	2.24
Closed-cell expanded polyethylene	2.48
Reindeer skin	2.48

Note: The tog value of a textile is equal to ten times the temperature difference between its two faces when the flow of heat is equal to one watt per square metre.

(Adapted from Cooper SCRDE 1979)

TABLE 3.3

Insulation values for wet materials

	Thermal insulation (togs)			
	Staple polyester	Cont.fil. polyester	50:50 down/feather	Polyester pile fabric
Dry (ie. no moisture)	4.7	6.8	6.6	5.5
15% moisture	2.4	3.6	2.8	
50% moisture	1.8	2.4	1.5	2.0
100% moisture	1.7	2.3	1.3	

(Cooper SCRDE 1979)

convection occurs and that the idealised fabric is not thicker than 0.5cm, then the theoretical thermal resistance of the insulator can be calculated from the values of the thermal resistances of the fibres and a presumed fibre to air proportion.

The WARMTH TO WEIGHT ratio is another aspect of the calculation. This can be defined as the ratio of its thermal resistance in togs to its mass in g/cm^2. A high value for this factor is obviously desirable for the provision of the 'lightweight' warmth needed in clothing and bedlinen.

3.4.1 Natural-Down/Feather

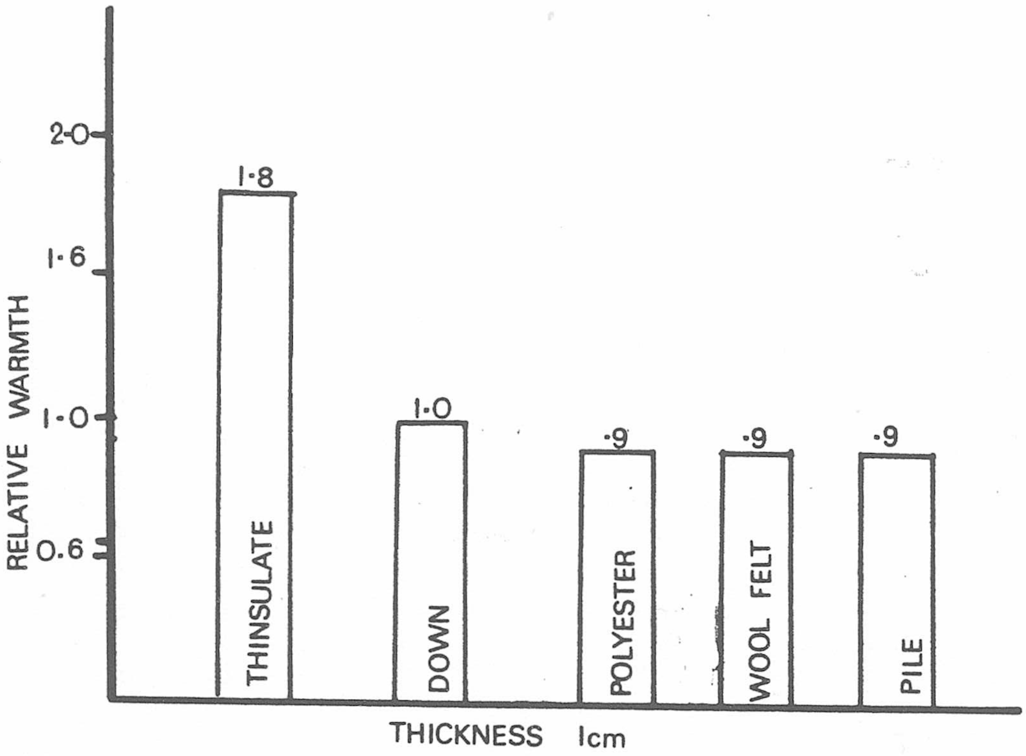
From the Tables 3.2, 3.3, it is clear that down-feather in a dry state is a good insulator. (Cooper SCRDE 1979). However, its insulation value decreases considerably when moisture is present and it becomes inferior to other insulators, supporting many workers' claims that synthetic fibres are superior to natural fillings where as little as 15% moisture content is present; an amount which may easily be present due to insensible perspiration. Natural fillings are relatively expensive and are difficult to handle, tending to behave as liquids and falling to the bottom of a container. The construction of the housing for filling must be carefully sectioned, with each area being of the optimum size to prevent 'cold spots'. It is also of vital importance that the sections do not compress the filling and restrict loft. All these factors contribute towards the need to find synthetic alternatives.

3.4.2 Synthetic Fillings

The properties of various synthetic fillings make them attractive alternatives to down, especially in production costs, after-care and response when wet.

Continuous filament polyester P3, resin bonded polyester and acrylic staple fibre are the most commonly used synthetic insulators, either as fibre ballings or as webs, quilted between two boundary fabrics to

Figure 3-O



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give a multi-layer assembly. Polyester staple with its crimp gives reasonable loft and absorbs little moisture (0.4% under normal conditions), thus making it effective when wet with the ability to dry easily. It also loses little loft when saturated with water, due to the hydrophobic properties of polyester and its loft retention under compression makes it a suitable insulator for use in wet conditions, for example as a filling for sleeping bags, where these provide the main protection against the elements.

Hollow fibres have been developed to simulate the cotton fibre with its natural lumen. The internal air space is believed to occupy 10% of the total volume of the fibre and since the volume of fibres within the insulation medium will only be 10%, the volume of air in the system will only be increased from 90% to 91%. This can hardly be considered significant in increased insulation value. There will be a saving in weight equivalent to 10% of the fibre weight, but this too is negligible. The fibre's hollow tubular structure gives more bulk for a given weight and the hydrophilic nature of the viscose gives high moisture absorption properties. The combination of properties enhances the value of this fibre as an insulator. However, their high bulk produced difficulty in handling during garment construction and a bulbous appearance in wear.

A fine fibre batt insulator was developed and is used where thinness, durability, resistance to crushing and shifting are important. A higher insulation value per unit thickness is claimed by the manufacturers and Fig.3.0 shows the results from their experiments. Work is still in progress to substantiate their findings.

3.4.3 Metallized Fabrics and Films

The efficiency of metallized fabrics and films as life saving heat preservers have been challenged (Light 1980). The insulation is supposed to be enhanced by the heat reflective properties of the metallized film. However, heat loss by radiation from the skin surface in a cold environment, especially in the windy conditions usually associated with emergencies and hypothermia, constitutes only a small percentage of heat loss; the most significant avenue being by convection (Burton & Edholm 1955). The effectiveness of metallic films is further reduced by several other factors.

a) Condensation of moisture vapour occurs on the surface of the film due to the impermeable nature of the material and the infra-red reflective properties are then lost. (Marcus et al 1977). Wetting of the surrounding clothing then occurs, giving extra discomfort. In sub-zero temperatures the condensation can freeze within the assembly.

b) If no air layer is maintained, the film will contact the next layer of material at pressure points and conduct heat away.

c) Radiation is strongly absorbed by any water vapour present.

3.4.4 Pile Fabrics

Animal furs used in clothing are good insulators but are heavy and liable to rot and infestation. When wet, their weight becomes excessive and their thermal value becomes greatly depleted. These drawbacks are not found in artificial furs or pile fabrics whose use has greatly increased in the area of survival clothing; their good thermal performance in wet conditions being a particularly valuable property. (Keighley 1980).

All pile fabrics contain a base fabric, which may be knitted, woven or non-woven, together with pile yarn or fibre, which is entangled with, extracted from, or adhered to the base. The classification of pile fabrics is according to their method of formation and the most common are SLIVER KNIT PILE FABRICS.

Sliver Knit Pile Fabrics

Abbas & Burnip (1981) describe sliver knitted fabric as 'a plain weft knitted fabric with the addition of some loose fibres being knitted together with yarn, into the knitted loop.

The geometry of plain weft knitted fabric has been studied by various workers (Munden, 1959 & 1962; Hepworth and Leaf, 1970; Abbas & Burnip 1973). However, the most recent work (Abbas & Burnip, 1981) draws together all the analytical models and the theoretical and experimental research on the mechanisms of production, plus dimensional and thermal properties.

3.4.4.1 Structure

The process involves pushing jets of fibres in the form of a card sliver (Abbas and Burnip, 1981) at the needles of a single jersey weft knitting machine while the fabric is being formed. Provided the jet is controlled and positioned, the fibres are trapped and form a 'fur type' fabric which has few limitations on its thickness. Acrylic and polyester fibre is the most commonly used card sliver, while the base is made of textured polyester and/or acrylic yarn. The pile created can vary in fibre, linear density and staple length and crimp to give variation in properties, even when sheared to produce a smooth pile of regular height. The pile fibres are anchored by the application of a resin finish to the backing of the knitted base, and the method of application, quality and quantity of the resin used can again alter the properties of the fabric considerably. A limited amount of work has been done in this area recently, mainly by Abbas & Burnip (1975 and 1981).

3.4.4.2 Properties

The processes of production have improved greatly. However, many prejudices on their use as insulators still exist, particularly among military users (Cooper 1980). The popularity of these fabrics as 'body warmers' and 'thermal underwear' for divers and mountaineers, and as exposure bags for mountain rescue (Brook, Keighley 1980) prompts further examination of their use and is classified below under the headings of 'Disadvantages' and 'Advantages'.

3.4.4.3 Disadvantages

Pilling

Pile fabrics acquired a bad aesthetic reputation due to pilling occurring after only limited usage. Pilling is the formation of balls of fibre, known as pills, on the surface of the fabric, giving an otherwise smooth textured fabric an unsightly appearane. When abraded all known staple fibres will form pills to some degree, and fibres with a round cross-section pill more readily than those of non-circular or multilobal cross section. The higher the yarn twist, the lower the fibre migration and potential pilling, and the tighter the construction, the less chance of fibre movement. Sliver knits, with their sliver card and knitted structure, have a high pilling potential. A technique to counteract pilling has now been developed which involves application of a cross linking resin emulsion, followed by heat treatment which bonds the fibres together at points of contact and prevents their movement thus giving a 'non-pilling' finish. Initially, this treatment gave a white, stiff finish, but it has now been developed to be non-visible and soft. An alternative and effective method of counteracting pilling is to cover the back of the base fabric with an outer layer.

Wind Resistance and Air Permeability

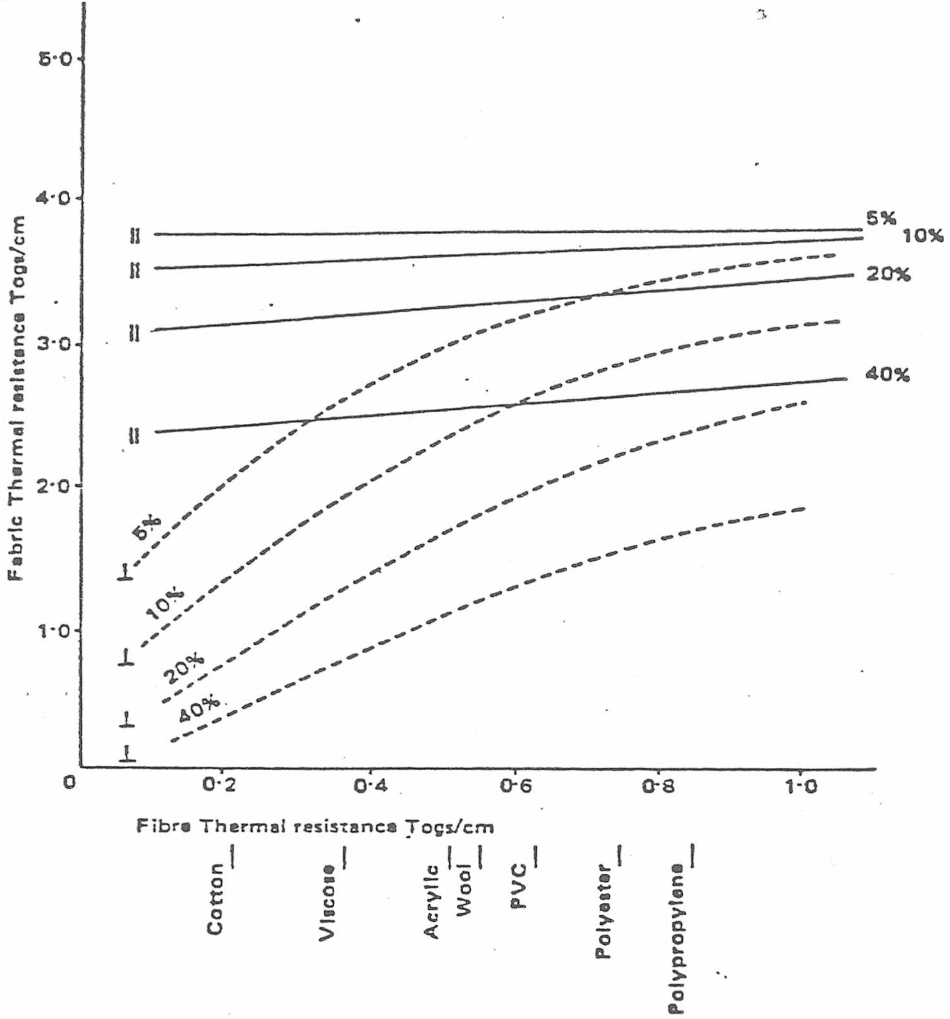
The permeable nature of an excessively open knitted structure becomes a disadvantage in moving air, but this can be reduced by the application of resins and increased pile density and height. The most effective means of reducing air permeability is to use a separate and/or integral outer cover as a barrier.

3.4.4.4 Advantages

Compaction and Resiliency

Pile fabrics with high density are very resistant to compression, thus facilitating good performance as survival clothing due to the elimination of cold spots at pressure points. Changes in pile density

FIG.3.1 Graphs of fabric thermal resistance plotted against fibre thermal resistance for a range of fibres oriented parallel to the fabric surface (full line) and for fibres oriented perpendicular to the fabric surface (dotted lines) at different percentage fibre volumes.



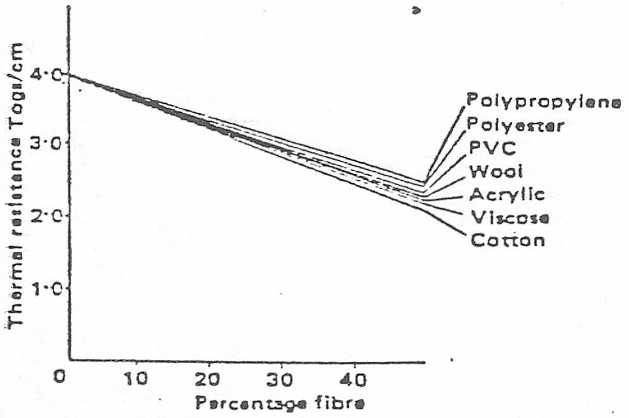


FIG.3.2(a) Graphs of fabric thermal resistance plotted against fibre volume (i.e. total volume of fibres x 100 ÷ total fabric volume) for different fibres oriented parallel to the fabric surface.

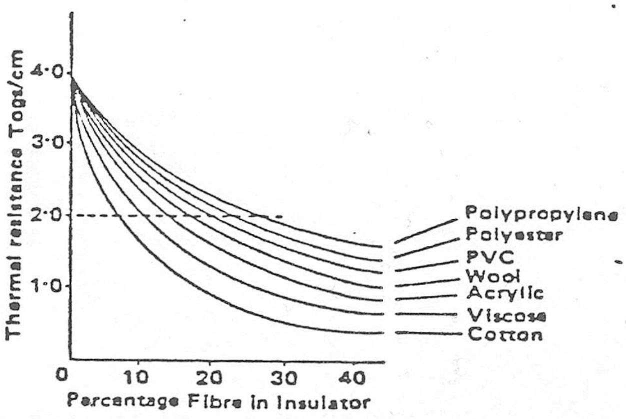


FIG.3.2(b) Graphs of thermal fabric resistance plotted against percentage fibre volume for different fibres oriented perpendicular to fabric surface.

and individual filament rigidity can be engineered into the fabric to give different compression resistance over the structure, as a fabric which is too incompressible has a poor warmth to weight ratio. Abbas & Burnip (1981) studied the bending of pile fibres and concluded that the smaller the distance between fibres (fibre density), the less bending or degree of keel that occurs, permitting a higher fabric thickness to be achieved.

Thermal Efficiency

Pile fabrics are at a great advantage in wet conditions. After saturation with water, they can be wrung out and still retain most of their dry insulation value as the fibres are hydrophobic. Even when thick pile fabrics are saturated, water moved from the pile by capillary action, keeping the pile dry and effective as a still air 'trap'. Body temperature measurements have shown that for best results the pile must be in contact with the body and a very close fit is necessary for high thermal performance (Brook and Keighley, 1980). The stretch characteristics of this knitted fabric allow body movement without restriction.

3.5 Thermal Resistance

If an idealised model of an insulator is examined the fibres can be considered to lie either parallel to the surface of the insulating layer, i.e. at right angles to the flow of heat as is the case in continental quilts; or to be aligned perpendicular to the plane of the insulating material, parallel to the flow of heat as in pile fabrics. For fibres orientated parallel to the surface, it can be calculated that for each proportionate fibre composition, the thermal resistance of the structure is almost independent of fibre type present (Fig.3.1) (Falconer and Keighley, 1981). When the values of thermal resistance are plotted against fibre composition, there is little difference between the thermal properties of the seven fibre types for a given fibre/air volume. (Fig.3.2a). Clearly, the higher the percentage fibre volume, the lower the effective thermal resistance, thus supporting earlier claims by Rees (1946).

The results when fibres are orientated perpendicular to the surface of the insulator, as in pile fabrics, are somewhat different. At each percentage fibre composition the calculated thermal resistance is very dependent on fibre type and their related thermal properties. The relationship is not linear (Fig.3.1) as was the case for fibres orientated parallel to the surface. If thermal resistance is considered in terms of percentage fibre composition, (Fig.3.2b), the curve for each fibre type again is non-linear. From Fig.3.1 it can be seen that for perpendicularly orientated fibres the following proportions of fibres to air are required to give values of 1.5 togs/cm and 2.0 togs/cm:

	1.5 togs/cm	2.0 togs/cm
Polypropylene	45%	25%
Polyester	37%	21%
PVC	32%	18%
Wool	27%	16%
Acrylic	23%	14%
Viscose	17%	10%
Cotton	10%	6%

Based on ICI figures

Thus, the thermal properties of pile fabric are dependent on the fibre type used in construction and the conductivity of the fibre contributes directly to the overall conductivity of the material. Field trials on survival bags (Keighley 1980) showed that a lower calculated TOG value for the pile fabric was not reflected in an inferior user performance compared with fibre-filled and down-filled equivalents. In fact, completely contrary findings were recorded. This established that the calculated TOG value cannot be used as the sole measure of thermal efficiency when comparing fabrics of dissimilar structure. It is for this reason that sliver-knit pile fabrics alone are considered in this study.

CHAPTER IV

MOISTURE RETENTION AND TRANSMISSION IN TEXTILES

4.0 Introduction

The moisture retention and transmission properties of clothing are of considerable importance in determining clothing comfort. The moisture transferral properties of fabrics involve both the passage of water vapour and the passage of liquid water from the skin to the outside air. The various aspects of the problem are:

a) the water vapour permeability of fabrics

b) the water absorption and wicking of fibres and fabrics

c) fabric drying rates and after-exercise chill

d) the significance of heat of sorption in fabrics.

4.1 Water Vapour Permeability

Black and Matthews (1934), in a review article, concluded that the actual structure of the fabric has little effect on water vapour permeability and that this channel for removal of body moisture is of small importance in comparison with that supplied by the usual openings of a garment and by absorption and drying. The question as to whether or not ventilation is more important than permeability has also received consideration by more recent workers.

Renbourn (1960) postulated that the movement of moisture laden air from the skin is aided by 'bellows effect' at the openings in the garment. Mecheels (1965) considered that ventilation has two effects. The first of these is that well ventilated garments encourage evaporation of body perspiration by forced convection caused by the pumping action created by the physical movement of the body. Secondly, the disturbance of the otherwise static air layer will allow heat loss by convection and the insulation value is consequently reduced. Methods of measuring the ventilation properties of clothing have not been developed.

A detailed study of water vapour permeability of fabric was made by Hall (1930) where he aimed to correlate coefficients of water vapour diffusion with a) type of fibre, b) fabric thickness and c) fabric density. His method involved supporting a drying agent a known distance above the fabric, which in turn was supported a known distance above the water surface, and the amount of water evaporating from the containers in a given time was determined. The relationships established were as follows:

a) the rate of evaporation and the distance of the water from the fabric with the drying agent at a fixed distance

b) the rate of evaporation and the distance of the drying agent from the fabric with the water at a constant level.

From this he hoped to extrapolate to the hypothetical circumstance of a fabric in contact with water on one side and the drying agent on the other. It is important that a major fraction of the vapour concentration gradient should be within the fabric itself, and this would be achieved with one side of the fabric approaching saturation and the other side approaching dryness; these circumstances being comparable with those existing under actual conditions of wear next to the skin. The distance of the water from the fabric was of paramount importance since it was found that up to a gap of 17mm, the process of evaporation was one of true diffusion, and over that distance convection took place in the air gap between the water and the fabric. Hall defined diffusion coefficient as the quantity of water vapour diffusing in unit time through a section of unit area under unit concentration gradient. The variable 'thickness' is thus eliminated, and for clothes of the same material it is possible to correlate the above quantity with density and distribution of density although it is still possible to determine the total resistance of a fabric from the relation:

$$\text{resistance} = \frac{\text{thickness}}{\text{diffusion coefficient}}$$

The most important feature of Hall's work is undoubtedly his demonstration that, over a very wide range of fibrous materials and fabric structures, the moisture diffusion coefficient is a simple experimental function of bulk density and that, in consequence, it is unnecessary to employ the relatively elaborate technique for measuring moisture diffusion coefficient when a straightforward determination of bulk density will, in the average case, give a result of equal significance.

Another major work was that of Whelen et al (1955) where two component resistances were distinguished, which together constitute the total resistances of the fabric to the transmission of water vapour by diffusion. These are a) the presence in the path of a vapour flow of a surface which is heterogeneous in its vapour transmission properties, and b) the resistance to the passage of vapour from one surface to another, ie within the fabric itself. These factors associated with surface geometry and fabric thickness as well as air spaces within the fabrics are significant when considering the total resistance within a fabric. The work concluded that a reduction in the number of layers of clothing is very much more effective in assisting the diffusion of water vapour away from the skin than would be indicated by the sum of the resistances of the fabrics themselves but more precise knowledge of distances between layers is necessary. Spencer Smith (1977) agreed that a great deal more work was necessary before any real understanding of moisture vapour transmission between layers of an assembly in non steady-state condition were understood.

Woodcock (1962) recognised that the CLO unit refers only to the dry insulation of clothing and does not incorporate a factor for heat loss through perspiration. Each unit quantity of sweat evaporated from the skin removes a quantity of heat equal to the latent heat of evaporation of water, and for an average man this would be equivalent to heat loss of 333 kcal/m^2/hr, which is sufficient to balance out a similar heat production. He claimed that although the results of previous moisture diffusion experiments were valid, they generally measured resistance to diffusion through the textile from one mass of still air to another and could not readily be applied to the sweating man - clothing - environment complex, where not only the diffusion of water vapour, but also its transfer by convection takes place.

Woodcock developed a new clothing parameter, the moisture permeability index, which describes the ability of a fabric to transfer moisture vapour and its associated latent heat of evaporation from the skin to the ambient air. This he included as a second clothing parameter (dry thermal insulation being the first) in a general equation for heat transfer between the skin and the environment. After the introduction of this index, a range over which man can maintain thermal equilibrium was established, for which the insulation concept provided the lower limit. This was a shift from the concept that clothing must keep man as warm as possible, to one in which the purpose is to keep him in thermal equilibrium with his environment. Woodcock showed that for clothing to be adaptable to a wide range of environments, the permeability index must be high. Further, the body is able to adjust to minor changes in atmospheric conditions by an alteration in evaporative heat loss, but alternative methods such as the addition or removal of clothing layers must be available to compensate for larger changes in the ambient temperature and humidity. He appreciated that his concept of a permeability index depends upon the variability of latent heat transfer over time, since neither man's heat production nor outdoor environmental conditions remain constant. If excess perspiration is produced, it may appear as a liquid on the skin or it may be condensed in the clothing, and even if perspiration is secreted in amounts which can be transferred as vapour, the relative humidity within the clothing assembly will not remain constant. Should the clothing be hydrophilic, its moisture content will vary with the relative humidity, and equilibrium conditions as previously defined will not occur. Under all these conditions, the distribution of moisture in the system will not remain constant and an equilibrium state with respect to time will not exist. This fact was also corroborated by David (1965). Weiner (1970) took the work of Woodcock (1962), Fourt and Hollies (1947), Fourt et al (1955) and Whelan et al (1955) further and proposed several equations to obtain an approximation of the resistance and moisture vapour transmission. Concurrently Spencer Smith (1965) was undertaking similar work and looked critically at previous work. In a 1977 paper he provided tables on forced and natural convection losses through dry assemblies to assist in future calculations. Nishi and Gagge (1970) had previously defined a 'permeation efficiency factor' which was derived theoretically in terms of convective heat transfer coefficient and the thermal insulation of the clothing. This also had been an attempt to simplify an otherwise difficult problem.

4.2 Water Absorption and Wicking of Fabrics

Textiles can absorb moisture in two different ways; a) hygroscopic moisture, absorbed naturally if the fabric is first dried and then placed in a humid atmosphere, and b) water held in the inter-fibre interstices. (Black and Matthews, 1934). Mecheels (1965) enumerated the ways in which liquid water can be transferred through the clothing

a) water is absorbed by hygroscopic fibres, passed through the swollen fibre and given off outside the clothing. This is the basic process in the case of natural and regenerated fibres which have relatively high moisture contents at normal relative humidities.

b) water take-up through the capillary spaces between the fibres and yarns. This transport mechanism is important mainly in the case of textiles made from synthetic yarns of low or very low moisture content when absorbency is referred to.

Mecheels et al (1965) examined the mechanism of swelling in cotton and stated that this offered a reasonably efficient means of water transfer and consequently was linked with the satisfactory comfort properties of the natural fibres. Their results indicated that this mechanism had no important influence on moisture transfer through cotton fibres in the steady state. The varying wettability of fibres, however, has a considerable influence both on the moisture transfer and also on the water-influenced thermal heat flow. They showed that the wicking power in the capillary system is less responsible for after-exercise chill than sorption within the fibres. Keswell, Barish and Lermond (1961) in their study of the comfort properties of bulked synthetic yarns versus continuous filament synthetic yarns included a study of water absorption and wicking. They examined four mechanisms:

a) absorption of water in the fibres (regain)
b) absortion between fibres
c) absorption between yarns
d) deposition on to fabric surfaces.

The lower the maximum water absorption capacity of the fabric, the sooner saturation will occur, with the accompanying spread of liquid water. Experimental work showed that the bulked nylon structure did not produce any increased capacity to hold moisture, but in the saturated state it holds about twice the water of the filament nylon and about the same as cotton and viscose. The rise of water holding was greater in bulked nylon than filament nylon or cotton or wool.

Hollies et al (1977) showed the wicking behaviour as mainly a reflection of difference in yarn structure rather than differences in the chemical nature of the fibres. Water transport in yarns occurs through the capillaries formed by the individual fibres and hence the rate of travel of liquid water is governed by the nature of the fibre arrangement within the yarns which control capillary size and continuity. The overall ease of wetting of the yarn is strongly influenced by the rough texture of the yarn surface and it is this, rather than fibre wettability, which controls the rate of water transport in many blended yarns and fabrics. The magnitude of the water holding capacity was shown to depend almost entirely on fabric construction, and for fabrics of similar construction, mainly on fabric thickness.

The delay in water travel along a fabric is a direct result of the fact that it takes relatively longer for the water to penetrate the fabric surface than to move in the interior.

4.3 Fabric Drying Rates

Fourt et al (1951) studied the drying rates of fabric exposed to air of low velocity and summarised their findings as follows:

a) the major portion of time required for drying is occupied by removal of liquid water which takes place at a constant rate for any given fabric.

b) drying rates calculated as a percentage of fabric weight vary with fabric weight, but when expressed as weight of water per unit area of surface are nearly uniform for fabrics up to 10mm thick.

c) the 2.4mm of still air near the fabric surface which smoothes out the effects of surface irregularities, is the factor which governs the rate of drying.

d) The only difference in drying rate was found to arise from a very high and open nap, in which the projecting hairs appear to have an effect in increasing the thickness of the insulating layer, which is not compensated for by their being wet by capillarity.

Kaswell, Barish and Lermond (1961) could find no direct relationship between speed of drying and comfort, but established the existence of a cooling effect resulting from the evaporative drying of moist or wet fabrics which may influence skin temperature. Confirming previous work, the data showed that the popular belief that all synthetic hydrophobic fabrics are quick drying is fallacious. The time required for a fabric to become dry is a function of the amount of water which it can hold, and this in turn is dependent on the nature of the yarn and the fabric structure and texture. The regain capacity of the fibre is of little consequence and so-called quick drying fabrics are so mainly because of their construction. The problem related to fabric drying rates is that of after-exercise chill, which occurs when moisture which has accumulated as condensation within the clothing assembly during exercise continues to be evaporated after exercise has ceased, producing further unwanted cooling.

Woodcock (1962) found that an increase in sweating is immediately accompanied by an increase in heat loss due to evaporation. Some of the sweat initially evaporated at the start of exercise will be absorbed by the clothing and its heat of absorption will appear in the clothing as sensible heat, thus temporarily reducing heat loss, but eventually a new equilibrium moisture constant will be established. After exercise and sweating cease, the moisture accumulated in the clothing will be absorbed or evaporated and tend to cool the clothing and the man wearing it. During this time lag, the heat loss will exceed heat production and the amount of excess heat loss represents a quantitative measure of the after-exercise chill. The moisture in the clothing need not be only that collected by absorption, as it is possible that sweat which is evaporated at the skin will recondense when it reaches colder layers of the clothing assembly. In cold, wet conditions or in severe conditions of frost, this recondensation can result in severe after-exercise chill or, at extreme cold, exposure, the moisture turning to ice within the assembly (Marcus et al, 1977: Light, 1980). Woodcock (1962) found that absorptive textiles such as wool/nylon can give an after-exercise chill which will last for 2 hours, because of the moisture drying out of the wool slowly, whereas a fabric with low moisture regain will have only negligible after-exercise chill. Moncrieff (1963) disagreed with Woodcock, quoting that wool can hold a lot of moisture without feeling damp, whereas clothing made from a non-absorptive synthetic fibre can still hold water in the fibre interstices and it is this liquid condensate which causes chill. The disagreement arises from the confusion over what causes chill, since a certain amount of chill occurs regardless of how the moisture is contained, and the different feel occurs because of the different drying rates. Keighley (1980) showed that polyester fibre pile sleeping bags maintained a lower percentage decrease in tog value as relative humidity increased, and the bag remained usable when wet as the moisture travels by capillary action to the knitted surface. The movement of water along the fibres does not disturb the trapped air in the interstices, thus allowing this type of fabric to retain its high insulation value.

4.4 Heat of Sorption in Fabrics

Rees (1946) determined experimentally that the absorption of water by hygroscopic textiles is accompanied by an evolution of heat which depends on:

a) the nature of the textile materials
b) the moisture regain prior to commencement of absorption
c) the quantity of water absorbed
d) whether the water is absorbed from the liquid or vapour phase.

If the relative humidity is increased, water will be absorbed by the clothing from the vapour phase and heat will be evolved. He found the greater the moisture absorption of the material, the greater is the heat liberated for a given change in relative humidity, and if absorption is rapid, a greater magnitude of protection will occur than if absorption is slow. Cassie (1962) confirmed these findings and concluded that the hygroscopic nature of wool clothing can delay the effects of temperature change for up to 3 hours.

David's (1965) experiments showed that when sorption takes place in a fabric, only 30% to 50% of the total heat of sorption is effective in reducing the heat loss through the fabric instead of the 100% predicted by Cassie. The results suggest that the buffering efficiency is reduced when the desorbing of absorbing fabric is moved outward from the hot body. It was found that sorption in the woollen suit could provide extra heat equivalent to approximately 12% of the normal metabolic rate initially but falling to approximately 3% after 20 minutes.

Spencer Smith (1978) described work similar to David (1965) aimed at investigating the buffering action which occurs in hygroscopic clothing at the onset of sensible perspiration. He found that the initial change in hygroscopic material is a rapid, temporary temperature increase, accompanied by a small change in regain at the onset of sensible perspiration. This is followed by a gradual decrease in the temperature of the clothing, coupled with a gradual increase in its regain until equilibrium is reached. No similar buffer action occurred with hydrophobic materials such as polyester, acrylic and nylon. Spencer Smith determined, as did Nishi et al (1976) and Naka et al (1977) that the physical processes involved in the passage of heat and moisture through clothing was rather more complicated than Woodcock (1962) and other workers in the field had previously assumed. Using Woodcock's formula, an underestimation of maximum heat loss can occur. This is in the region of 10% for hydrophobic materials, but around 50% for hygroscopic materials. Any

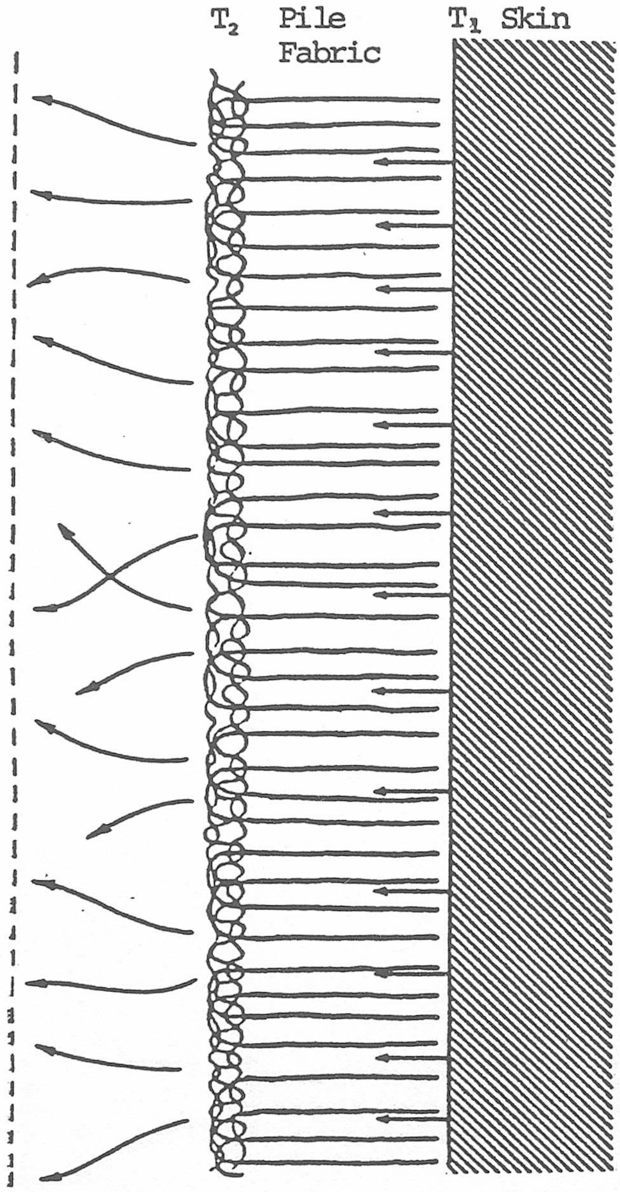


FIGURE 4.0 Schematic diagram of pile fabric mounted close to the skin in its most effective position as an insulator.

buffer action is reduced as moisture regain approaches steady state conditions and the corresponding decrease in the resistance of clothing to both heat and water vapour transfer occurs. Spencer Smith believed it was the lack of appreciation of hygroscopic effects that had been the cause of the lack of progress in the knowledge of the functions of clothing.

4.5 Moisture Vapour Transmission - Pile Fabrics

Sliver-knit fabrics exhibit some unique qualities in relation to moisture vapour transmission, which enhance their use as textile insulators.

Figure 4.0 is a schematic diagram of a fibre pile assembly in which the skin, at temperature T_1 loses vapour into the fibrous mass, which is usually bounded on the outside by a fabric layer, at a lower temperature T_2. Water vapour diffuses through the insulating layer, and diffuses through the outer fabric, forming a boundary layer with a higher water vapour concentration than the environment. The limit of this boundary layer is shown by the coarsely dashed line. The psychrometric chart is shown in Figure 2.1. This is a chart on which are plotted lines of constant air temperature (vertical lines) and constant wet bulb temperature (lines at approximately 45° to the vertical). Using a wet and dry bulb hygrometer to obtain air temperature and wet bulb temperature, the relative humidity can be found. Curves of constant RH are shown on the graph for values of 20, 40, 60, 80 and 100% RH. From the graph, it can be seen that an air temperature of 25°C and a wet bulb temperature of 20°C are obtained when the RH is 60% since all lines coincide. Similarly, lines of constant water vapour concentration (absolute humidity) are shown as horizontal lines.

A sample of air at 30°C with a water vapour concentration of 10×10^{-3} kg of water per kg of dry air is taken. When this is cooled, the water vapour concentration remains unchanged. On the chart, the

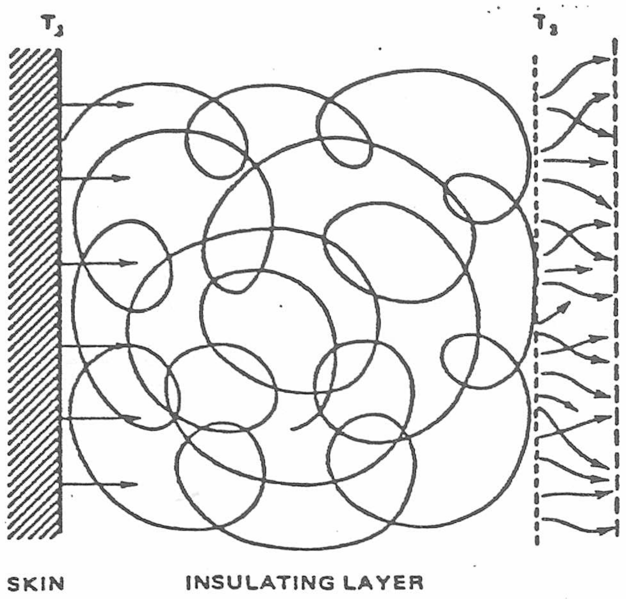


Diagram of water vapour diffusing from skin surface through an insulater where $T_2 >$ Dew Point temperature.

FIGURE 4.1

Diagram of water vapour diffusing from skin surface through an insulater where T_2 = Dew Point temperature.

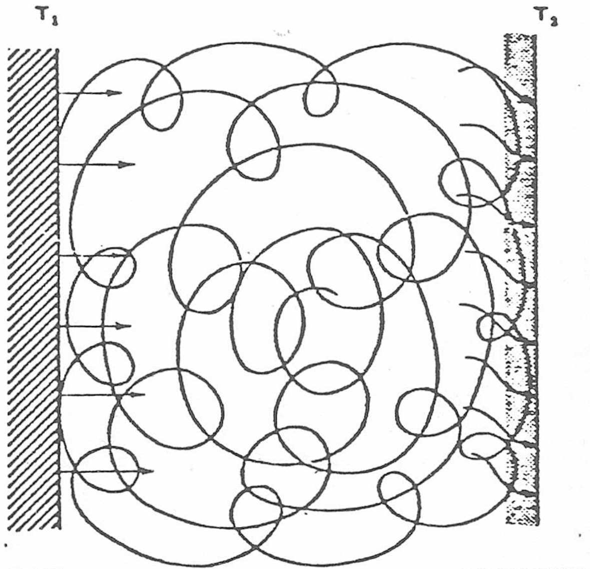


FIGURE 4.2

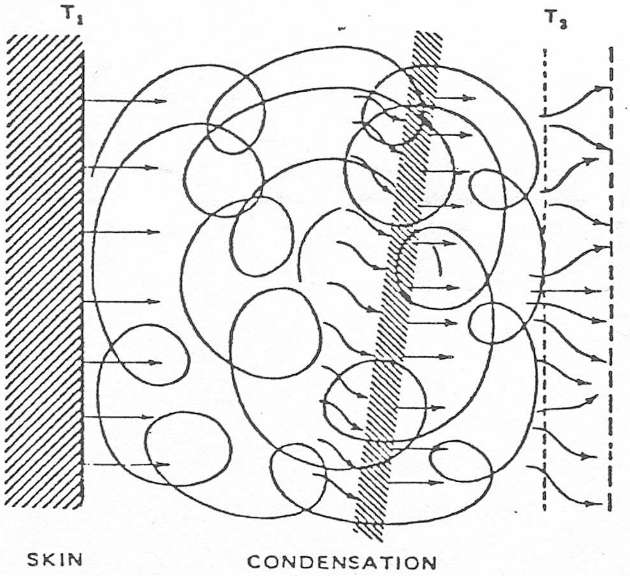


FIGURE 4.3

Diagram of water vapour diffusing from skin surface through an insulation where $T_2 <$ Dew Point temperature.

horizontal line can be followed towards the left. It can then be seen that at 28°C, the RH is 40%; at 21.5°C, the RH is 60%; at 16.5°C, the RH is 80% and at 13°C, the RH is 100%. The temperature of 13°C is that at which the moist air becomes saturated, and this is known as the Dew Point. Cooling below 13°C will ensure condensation of water. Figure 4.1 therefore, shows a system in which water vapour is diffusing through the encased fibrous assembly, and since T_1 is greater than T_2, the vapour is cooling as it moves away from the skin surface. In this case, however, the RH inside the assembly does not increase to 100%. In Figure 4.2, the situation is illustrated when 100% RH is achieved at the surface of the outer fabric layer, ie T_2 is the Dew Point. Hence condensation occurs on the inner side of the outer fabric layer, and this situation is often found in practice when an outer waterproof garment of low air and low water vapour permeability eg. a polyurethane coated nylon jacket is worn over normal clothing.

The Dew Point can be reached within the insulating material when the temperature T_2 is low (Figure 4.3). In this situation, a layer of water is formed inside the insulating layer with the result that the layer effectively acts as a short circuit to both water vapour flow and heat conduction by the air. The rate of water vapour diffusion is dependent on the vapour pressure difference across the system. The water vapour pressure is effectively and considerably reduced on condensation, with the result that the rate of transfer of water vapour will be increased and hence heat is lost at a higher rate. In addition, the total path length through the insulator is reduced. This phenomenon is common in very cold environments and leads to a number of important conclusions. Firstly, it is important to prevent condensation inside an insulator since this process will reduce its efficiency. Secondly, a fabric with "Ventile" type properties (permeable to water vapour) is essential when heavy work is to be undertaken. Thirdly, in cold conditions, it is possible to wear too many clothes since this will lead to condensation, and loss of insulation with increased weight of the garments due to condensed water. In addition, the actual weight of the garments worn cannot be ignored.

In practice, loose insulation of this type is bounded on both inner and outer sides by a layer of fabric, as illustrated in Figure 2.0. Since the body is never completely at rest, this layer will be in motion so that a proportion of the water vapour and heat will be pumped away between the insulating layer and the skin by bellows action. Thus heat will be lost at a higher rate, both from the effects of water vapour loss and the more rapid loss of air warmed by contact with the skin. This mechanism reduces the effective thermal resistance of the insulator.

Experiments on the thermal resistance of a variety of insulators used in sleeping bags have shown anomalies between performance in use and that obtained in the laboratory (Keighley, 1980). It was shown that although the thermal resistance of pile fabric bags was lower than many, they proved good performers in use if they were close fitting. This leads to the conclusion that when a pile fabric is used as shown in Figure 4.0 the surface of the pile will remain in good contact with the body even during body motion so that the bellows action will be considerably reduced. Air movement will also be inhibited by the surface characteristics of the pile fabric. Since such fabrics have a high air and hence water vapour permeability, the passage of water vapour will be restricted only to a minor extent, while the bellows action will be either virtually eliminated or considerably reduced. This suggestion indicates that a high proportion of the heat lost from clothing occurs as a consequence of air movement towards and past the edges of the clothing rather than through the fabric layer.

Comparisons of down bases and fibre pile based insulators (Keighley,

1980) indicate that heat loss by the bellows action is eliminated from the fibre pile based clothing. For duvet type constructions, at least as much heat is lost by the bellows mechanism as occurs by transfer of heat through the insulating assembly, therefore the need for good clothing design, and use of appropriate outers and construction techniques is of the utmost importance.

The permeable nature of the backing structure of pile fabric, which assists the wicking process, also allows the material to breathe. The fact that water vapour will pass through reduces the problem of overheating of the wearer at high levels of activity. Too loose a structure is a disadvantage in moving air and although the air permeability may be lowered by increasing the density and height of the pile, the most effective solution is to use a windproof outer cover. This cover immobilises the trapped air in the insulator, especially in windy conditions, and may also protect the insulator against rain, thus complementing the effectiveness of the assembly. However, as shown earlier, it is essential that this wind/waterproof outer is able to breathe to prevent overheating and condensation occurring during high activity programmes. A fabric with 'ventile' type properties (permeable to moisture vapour and impermeable to liquid water) appears to be essential. Various impermeable and 'ventile' type outers were compared during this project, and are discussed later.

CHAPTER V

CLOTHING COMFORT

5.0 Clothing Comfort

'Comfort' is a subjective concept (Dupont 1976), and each individual will have a slightly different interpretation of the word. Comfort may be related to fibre and fabric properties, their smoothness and texture, stretchability, hydrophilic or hydrophobic properties, weight, design and fit and also to the individual's attitude to the appearance and colour of the final garment.

To understand the various stimuli which result in comfort or discomfort, Pontrelli (1977) grouped the key parameters into four categories as follows:

1) The Physical/Environmental	Relative humidity
	Mean radiant temperature
	Temperature
	Air speed
2) The Physical/Personal	Metabolic rate (activity level)
	Fit and stretch of garment
	Fibre content and properties
	Fabric construction and properties
	(Fourt and Hollies 1970)
3) Psycho-physiological	Fulfilment of function and end use
	Occasion of wear
	Style of fashion
	Tactile aesthetics
	(Flugel 1950, Kemp 1971)
4) Experiences and Attitudes	Past experiences
	Expectations, Fantasies
	Prejudices, Life style.

Pontrelli defined his research on the theme of the 'comfort gestalt' looking at clothing comfort analysis, as a complex system. However, other workers, especially Mecheels (1981), while appreciating the many variables involved in analysing the system used physical objective analytical techniques and teamed these with the more subjective comfort voting of individuals in field testing and wearer trials. Mecheels pioneered objective testing and developed a clothed manikin 'Charlie' as a more realistic piece of apparatus to test body heat loss, without involving large numbers of people in wearer trials. This instrument takes into account such factors as the effects of different thicknesses of clothing on different parts of the body, different types of openings and the complicated geometry of the total clothed body.

For over fifty years, the American Society of Heating, Refrigerating and Air Conditioning Engineers Inc (ASHRAE) have supported research into thermal comfort and recently a move from the empirical approach to one of theoretical modelling has been adopted.

The study of the relationship between sensation and stimulus is known as psychophysics and is one of the earliest branches of psychology developed by Weber (1850). In cold weather research, the thermal sense is the response which plays a predominant role and which is a factor far less easily predicted and more variable than other sensory responses. The major principles involve the physiological responses, the pain threshold, sensations of warmth and cold, thermal pleasure and response to change in the ambient temperatures (Gagge et al 1967). Research has shown that thermal comfort may be predicted more accurately from a knowledge of air temperature and environmental conditions than from skin and body temperatures alone (Bedford 1936). Comfort research during sedentary conditions in an artificial indoor climate is the most easily conducted. The variables involved in the study of clothing comfort in non-steady state conditions during exercise are far wider, but such work must be carried out to achieve more realistic results.

It has been shown that exercising subjects are less aware of a fall in temperature than sedentary subjects (McIntyre and Gonzalez 1976). Quantitative relationships between metabolic rate, preferred skin temperature and preferred sweat rate form the basis of Fanger's Comfort Equation (McIntyre 1980). This has superseded work done by Bedford (1936) and Haughton and Yaglan (1924). The original work involved lines of equal comfort being plotted on a psychrometric chart and was classified as an 'Effective Temperature Index' (ET) and defined as 'an arbitrary index which combines into a single number the effect of the dry bulb temperature, humidity and air movement on the sensation of warmth or cold felt by the human body. The numerical value is that of still, saturated air which would induce an identical sensation'. (ASHRAE). Vernon and Warner (1932) applied a correction to this which allowed for thermal radiation to produce the Corrected Effective Temperature Scale (CET), and although this has been used extensively, its shortcomings have been acknowledged and ASHRAE no longer recommends its use.

Bedford (1936) investigated the relationship between the physical environment and personal feelings of warmth. Environmental variables and skin and clothing temperatures were measured and correlated and analyses of warmth votes against several comfort indices were performed. He produced an analytical empirical formulation for equivalent warmth which stands as a classic in the field.

The seven point scale used by Bedford (1936) and the one used by ASHRAE (Chapter 6.3.4) are widely used in laboratory work in climatic chambers and in field studies on comfort; the comfort votes being assigned numbers and treated quantitatively. However, they are not physical measures and must be interpreted with caution preferably by non parametric methods.

Fanger based his Comfort Equation on the premise that it is possible to define the comfortable state of the body in physical terms which relate to the body, rather than the environment. He set down three conditions for comfort:

1) the body must be in thermal balance
2) the mean skin temperature must be at an appropriate level for comfort
3) the preferred rate of sweating for comfort must be attained, this being a function of the metabolic rate.

The recognition of the above factors allowed Fanger to construct his comfort equation. However, further research is still needed to establish a formula for all variations of climatic conditions and activity levels.

All the physical parameters of the textile assembly and the related physiological and environmental aspects must be treated collectively as the determining factors in the final analysis of any clothing system. In general many of the previous workers investigations have been conducted under steady-state conditions at standard temperatures and limited work has been carried out into the wider factors which determine comfort. Spencer Smith (1977), stated that much more work was needed before any assessment methods devised can become conclusive. However, he did outline the theories and parameters involved. Mecheels (1971) and Spragne et al (1974) created a reproducible system, simulating conditions of wear using a "copper manikin man". However, most workers have continued to use human subjects objective and subjective reaction in comfort experiments. Many workers, (eg Rohles (1974) and Kerslake (1972)) investigated comfort, but only considered briefy the physical properties of the clothing assemblies worn while Nishi et al (1976) and many others only looked at clothing and man as theoretical models in examining clothing comfort. Many physiologists, (eg. Vokac (1972) and Light (1980)) while studying physiological effects in cold climates have had to consider the clothing worn during their trials but this examination was peripheral to the main thrust of their work.

Many workers have acknowledged the wide parameters which contribute towards clothing comfort and recent work has examined the physical properties of fibre, yarn and fabric, the clothing structure, including design and fit, and human physiology teamed with environmental conditions and psychological attitudes. Some studies (Latham 1969, Tanner 1979, Light 1980, Reischt and Stansky 1980, Vickroy et al 1982) have used laboratory tests of physical properties and wearer trials. Attempts have been made to correlate experimentally determined fabric properties with comfort votes of participants in the wearer trials. Latham (1969) found that only fabric bulk density, thickness and fibre content correlated with comfort votes and therefore were the only objective measures required to predict comfort when examining shirting fabrics. Wallenberger (1982) summarised ongoing research into comfort of mass consumption garments rather than specialist apparel and showed that more work is necessary to advance fabric and garment design in relation to clothing comfort.

Mecheels (1981) summarised modern experimental thinking related to the development of clothing systems with optimal functionality, as originally defined by R Goldman, (1977) viz.

1 Physical Analysis of Textiles. After a list of criteria for the specific clothing system is formulated, physical laboratory testing is necessary to analyse if these conditions are being met.

2 Bio-Physical Analysis. These may be conducted on a copper-manikin in a climatic Chamber; and combined with the above analysis give many answers about the assembly.

3 Controlled Wearing Tests. Human subjects test the clothing under determined climatic and activity conditions in a controlled chamber

using normal physiological techniques. The data is usually recorded on-line by a computer and processed immediately.

From these three methods it is possible to accumulate enough data to design a satisfactory clothing system. However, many refinements may be necessary.

4 Limited Field Tests involve 10 to 30 persons wearing the clothing under realistic conditions and recording their experiences on questionnaires.

5 Field Tests conducted on a great number of subjects in realistic conditions.

Quantitative comfort calculations derived from the physical and bio-physical studies with the physiological data of human body functions in wearing conditions, may be used instead of wearer trials (3) as it is far less expensive, especially when checking only one new part to an established clothing system. When examining new clothing not previously investigated Mecheels accepts that all 5 stages of analysis should be employed in the investigation.

The aim of the present work is to investigate the use of three different outer fabrics combined with an insulator for use as outer work-wear for wear in severe cold climatic conditions. The preliminary work will involve investigation of the physical properties of selected sliver-knit fabrics so that the optimum fabric can be chosen and used as a constant in the wearer trials. The desired criteria for the ideal sliver-knit insulator are given in page 89 and one will be chosen from an original collection of 12 samples. Five commonly used outers were investigated and three outers were chosen to be used in wearer trials, in order to examine the effect of permeable and impermeable outer layers during "high activity programmes" on the wearers complete clothing assembly, his physiological mechanisms and his subjective assessment of comfort. Physiological measurements will be recorded on a computer programme, weighing of all clothing will be carried out and subjective comfort votes will be recorded while each participant wears each of the 3 jackets during rest and exercise in a cold chamber at -5°C. During this programme of research the reaction of subjects to the use of outers impermeable and permeable to water vapour will be investigated and by recording physiological data together with the subjects assessment of their comfort on a hedonic rating scale. Correlation between objective data for laboratory trials and subjective assessment will be investigated and discussed.

CHAPTER VI

EXPERIMENTAL METHODS

6.0 Material Investigated - Insulator

Two sliver-knitted pile fabrics were used in all tests except in the thermal insulation measurements where twelve different samples were tested coded a to l. Descriptions of the main samples tested are as follows:

i) 100% Polyester - polyethylene terephthalate derived from petroleum melt spun to form fibre, knitted in a sliver-knit structure.

ii) Modacrylic - a synthetic fibre consisting of 50-85% by mass of acrylonitrile units, copolymerised with vinyl chloride, knitted in a sliver-knit structure.

6.1 Experimental Methods

All laboratory tests were conducted in a Standard Atmosphere for the testing of textiles, i.e. a relative humidity of 65% ± 2% and a temperature of 20°C ± 2°C. All fabrics tested were conditioned in the Standard Atmosphere for 24 hours prior to test. (BSI Handbook II: 1974 1051). (Tests are arranged in alphabetical order).

Air Permeability

The Shirley Air Permeability Meter was used and the mean air flow in millilitres per second was divided by 5 to give the equivalent measurement per square cm. (BSI Handbook II 1974 4/169).

Bulk Density

Samples 10cm x 12cm = $120 cm^2$ were weighed.

Bursting Strength

Sample strengths were tested on the Heals Bursting Strength Tester for original strength and strength after pilling.

Pill Testing

Four samples were tested for 20,000 revolutions in an approved Pill

Box.

Thickness Analysis

Thickness measurements were taken at regular intervals across the sample using a Shirley Thickness Gauge. (BSI Handbook II: 1974). The average measurement was used.

Thermal Resistance of Textiles

Definitions

Thermal Resistance (R) of a fabric

This is defined as the ratio of the temperature difference between the two faces of the fabric to the rate of flow of heat per unit area normal to the faces. (BSI Handbook II: 1974).

Thermal Conductivity (K)

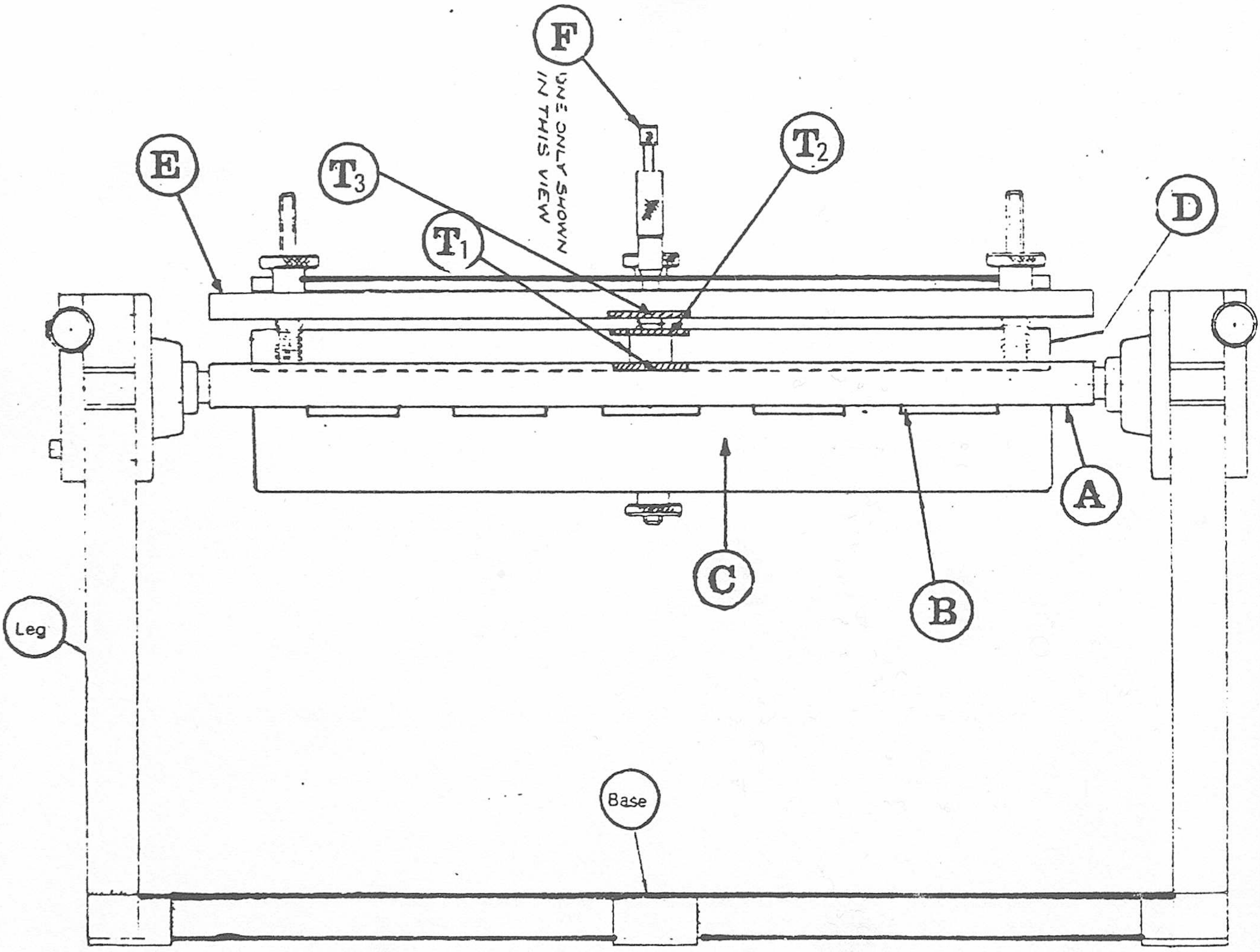
Thermal conductivity is defined as the quantity of heat that passes in unit time through unit area of a slab of infinite extent and of unit thickness when unit difference of temperature exists between its faces. Thermal conductivity is the reciprocal of thermal resistance per unit thickness. (BSI Handbook II: 1974). The principal is anlaogous to Ohm's Law whichstated that the flow of heat is similar to the flow of electricity and that if "difference in temperature" is substituted for "difference of electrical potential" and "flow of heat" is substituted for "current" then all the results for the conduction of electricity hold equally for the conduction of heat.

In the thermal case with conductors mounted in series with respect to the heat flow, the ratio of the temperature drop across the conductors is equal to the ratio of their thermal resistances. Thus if the temperature drop across a material of known thermal resistance (known as the standard resistance) and that across a fibrous structure placed in series with it are measured the thermal resistance of the fibrous structure can be evaluated. This principle was utilised by Clulow and Rees (1968) and adopted as British Standard 4745 (1971) for determining the thermal resistance of textile fabrics or fibre

FIGURE 6.0 DISC TOGMETER

KEY

A - Hot plate
B - Heating elements
C - Glass-fibre insulation
D - Marinite disc
E - Cold plate
F - Micremeters
T_1)
T_2)- Thermocouples
T_3)

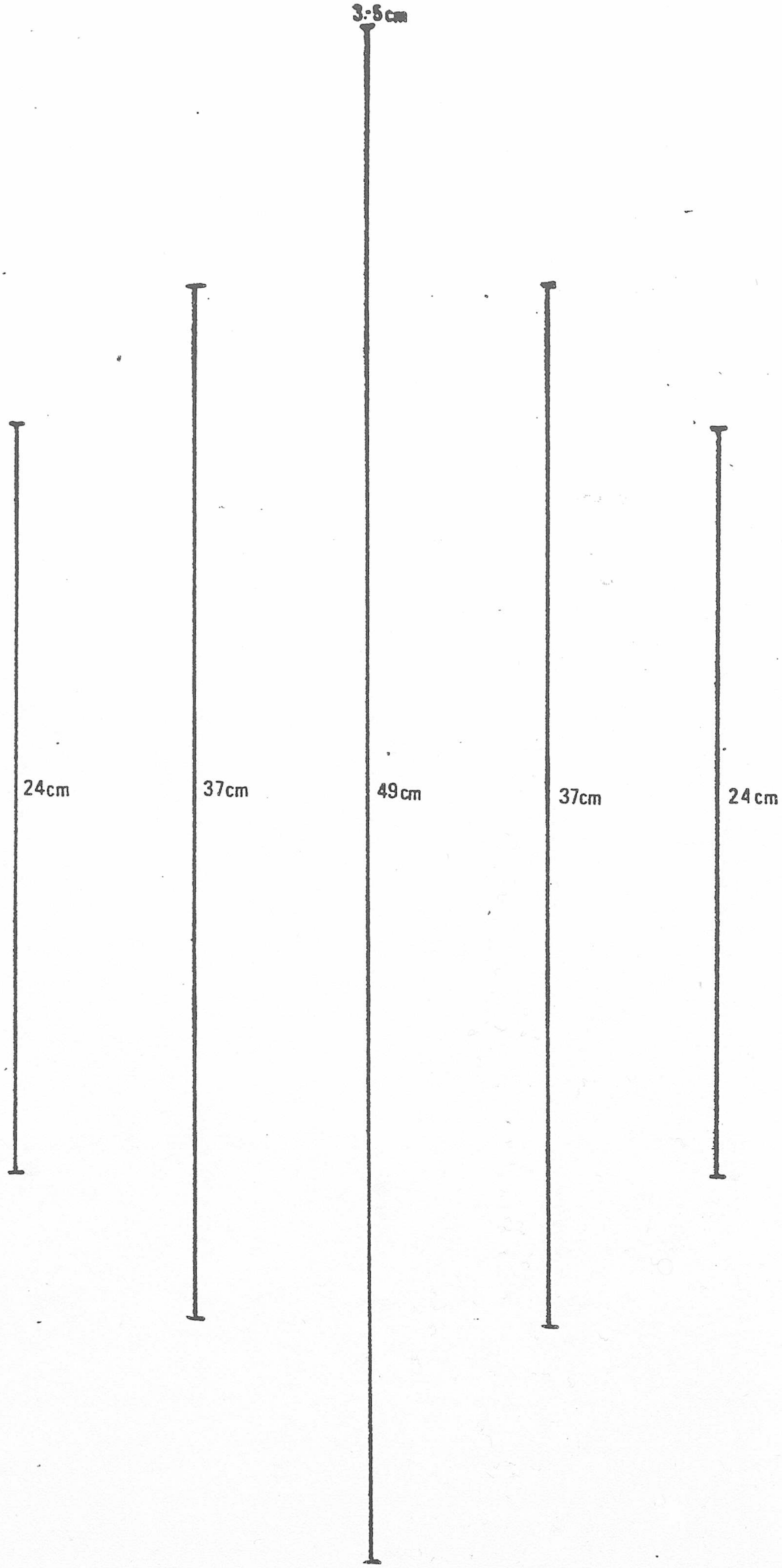


aggregates in steady state conditions.

Disc Togmeter

This apparatus was used to measure thermal resistance. The Disc Togmeter uses a modified form of the principles and design of Clulow and Rees (1968).

The main features of the apparatus are shown in Fig.6.0. It consists of a hot plate (A) of 50cm diameter and 0.64cm thickness constructed from a flat Duraluminium alloy disc which has been annealed to relieve internal stresses. Heat is supplied to this plate, which forms the base, by means of five parallel heating elements arranged as shown in Fig.6.1 (B). The bar elements are of three lengths, but are all 3.5cm wide and 0.7cm thick with the two terminals for the power supply at one end. The elements are equally spaced so that the width of the plate is covered evenly. The elements are connected in parallel to a commercially manufactured temperature controller giving proportional control. The temperature control of this supply is operated by a Ni/Cr.Ni/Al thermocouple recessed and cemented into the central area of the base plate. To avoid heat losses from the space at the back of the elements, glass fibre insulation (C) was used to fill it. A standard disc (D) of known thermal resistance, made of Marinite 36 (Clulow & Rees 1968) is mounted on the upper face of the hot plate (A). The Marinite disc is 47.5cm in diameter and 2.5cm thick. Calibration of the standard thermal resistance complies with BSI Handbook II: 1974 Clause 9.1. The cold plate (E) of the apparatus is a disc of Tufnol 52.5cm in diameter and 0.48cm thick which is fixed to a Duraluminium disc 52.5cm in diameter and 0.95cm thick acting as a carriage to the cold plate. The test sample is sandwiched between the cold plate (E) and the standard disc (D). The thickness of the sample can be found by means of the micrometer scales (F) attached to the cold plate. Measurements of thermal resistance under compression can also be made using this apparatus. The whole apparatus is mounted on



Heating Element Arrangement

FIGURE 6.1

a frame which allows its rotation through 360°.

Temperature Measurement

The temperatures on both faces of the Marinite disc (D) and the lower face of the cold plate (E) are measured by 3 Copper Constantan thermocouples (T_1, T_2, T_3). These thermocouples are cemented into recesses in the upper and lower faces of the Marinite disc and into the centre of the lower face of the cold plate. The thermocouple wire is recessed into a shallow groove on the disc. A shallow groove is also cut in the centre of the disc to incorporate the hot junction of the thermocouple which is soldered to a 100μ thick copper foil disc of 2.5cm diameter attached to the Marinite disc by epoxy-resin adhesive. Temperature measurements were recorded by connecting the thermocouples directly to a flat-bed recorder with a range of operation of the order of 0-5mV for a typical thermocouple, ie the temperature range -30°C to +60°C should be detectable. Temperatures T_1, T_2, T_3 were noted over at least a 2 hour period at the positions shown in Fig 6.0. Heat passes from the hot plate through the known thermal resistance (D) and subsequently through the insulator whose properties are being measured.

If T_1 = lower surface temperature of reference material

T_2 = upper surface temperature of reference material (and lower surface temperature of insulator being investigated)

T_3 = upper surface temperature of test sample

R_r = thermal resistance of reference sample

R_s = thermal resistance of test sample,

then the relationship

$$\frac{R_s}{R_r} = \frac{T_2 - T_3}{T_1 - T_2}$$

Since all the quantities except R_s are known, the value of R_s can be calculated. As previously stated, measurement of thermal efficiencies

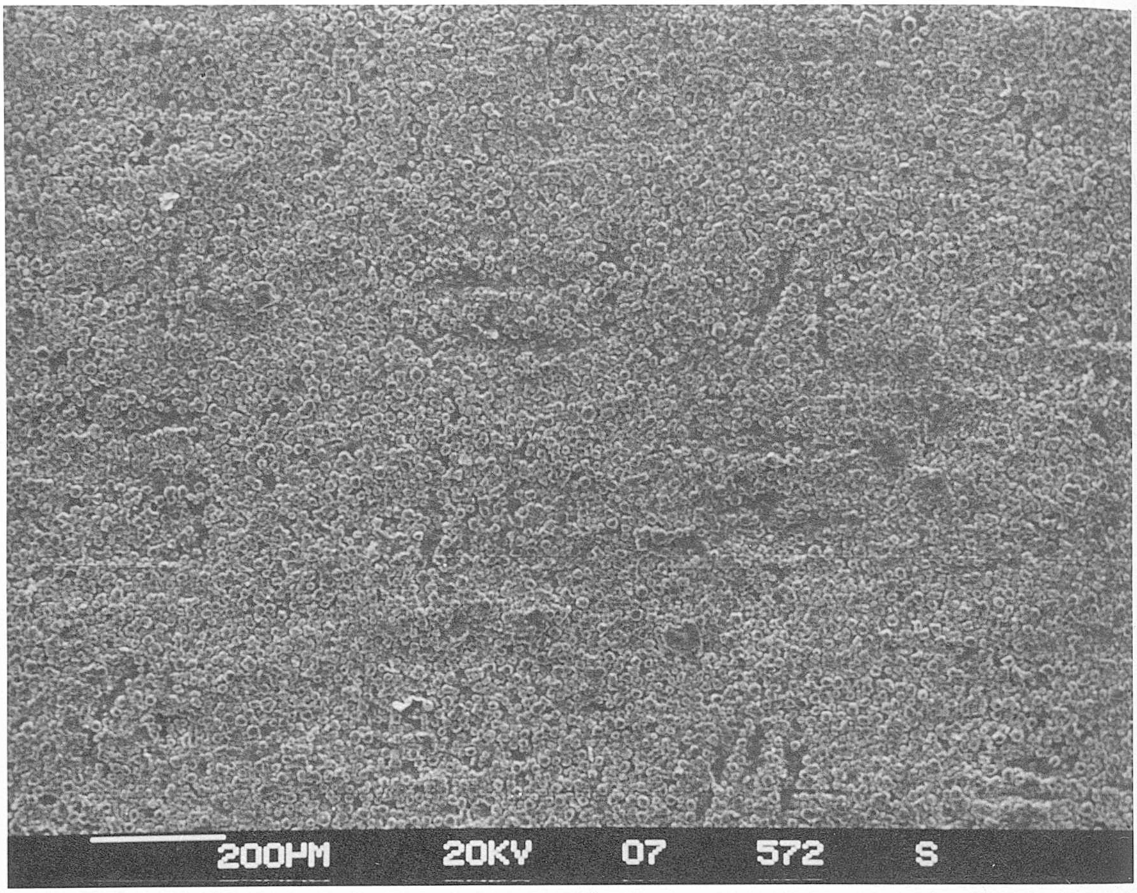


FIGURE 6.2 Reverse side of Neoprene coated nylon at 100 magnification.

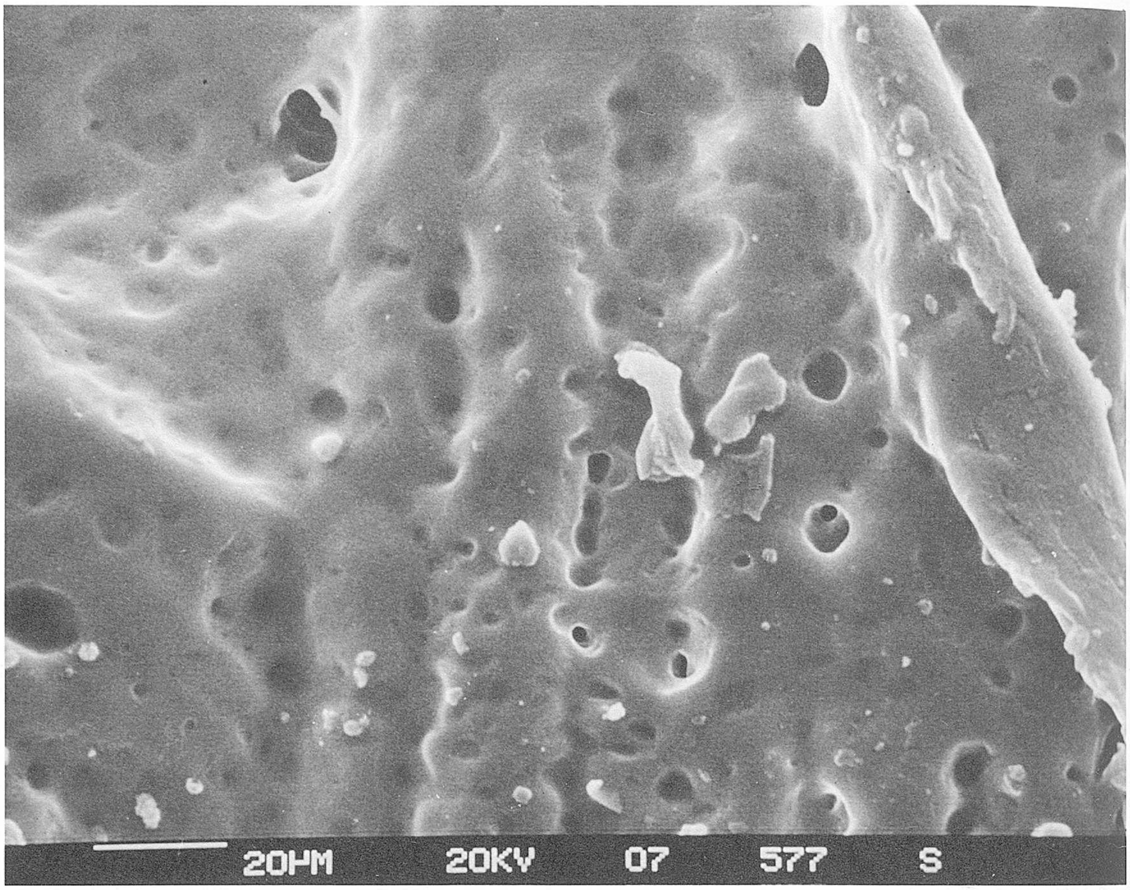


FIGURE 6.3 "Ventile" type reverse side at 1000 magnification.

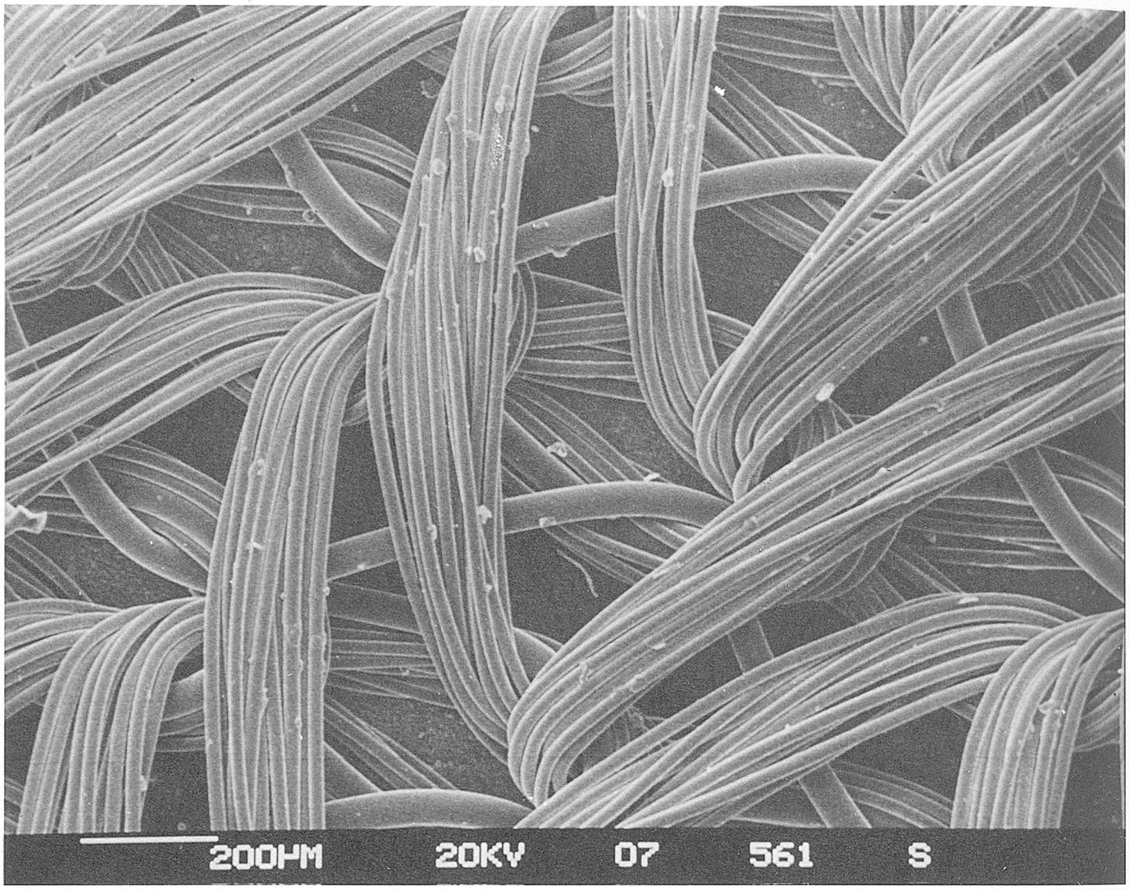


FIGURE 6.4 Reverse side of GORETEX at nominal magnification 100, showing PTFE under the knitted backing.

of assemblies as insulators are given in the terms of 'togs'. However, in order to make comparisons of one type with another, such values may have little meaning and a better comparison is gained by dividing the tog value by the sample thickness, thus enabling clearer comparisons of different constructions and compositions in terms of togs/cm.

Water Repellency

The Bundesmann apparatus was used and samples with pile facing upwards and pile facing downwards were subjected to a 20 minute test, equivalent to a heavy rainfall of 45 cm/hr. (BSI Handbook II: 1974 4/181).

6.2 Materials Investigated - Outers

Five common outer fabrics which are used for severe weather clothing were investigated. Weight per unit area g/ m^2.

i) Rip-stop nylon. (87.7g/m^2)

ii) Neoprene coated nylon (4 oz). FIG.6.2 (415.9g/m^2)

iii) Polyurethane coated acetate. (136g/m^2)

iv) 'Ventile' type - 40% nylon, 20% cotton, 40% polyester which was siliconized. FIG.6.3 (105g/m^2)

v) 'Goretex' Phase 1 fabric (nylon/PTFE/nylon) 3 layer laminate. FIG.6.4 (147.3g/m^2)

6.2.1 Experimental Methods

All laboratory tests were conducted in Standard Atmosphere conditions, unless otherwise stated and the assembly was conditioned for 24 hours prior to test. The following methods were used on all five samples. (These tests are arranged alphabetically).

Abrasion

Abrasion characteristics of each fabric was measured using the Martindale abrasion tester (BSI Handbook No.II 1974: 4/49). In this, the circular sample of 12.5cm diameter was loaded with a 600gm weight, which was then abraded against a standard nylon abradant.

Air Permeability

Measurements of air permeability were made using the Shirley Air Permeability apparatus (BSI Handbook No.II 1974: 4/169). The rate of transport of air through $1cm^2$ of fabric per second for a pressure difference across the fabric of either 10mm or 30mm of water was measured.

Drape

The drape coefficient of the outers was found by using the Cusick Drape Tester and standard technique at room temperature. The sample was also held at -10^oC overnight and then tested at room temperature.

Determination of resistance to damage by flexing

The outers were flexed using the Schildknecht method as described in BSI Handbook No.II 1974: p4/231 on an adapted apparatus consisting of six pairs of metal cylinders instead of the usual two. Flexing was carried out in both standard atmosphere and at $+10^oC$, 0^oC, -10^oC and -20^oC in a controlled chamber. In this test, samples 9cm x 9cm were clamped on to a 2.5cm diameter cylinder mounted on the same axis, one cylinder being moveable along this axis to give a maximum separation of 19mm and a minimum separation of 12mm, with the rate of flexing being 500 cycles/minute. In order to monitor any change in the original properties eg. cracking or delamination, a hydrostatic head test was used.

Resistance of fabrics to penetration by water (Hydrostatic head test)

The behaviour of the five outers was tested prior to and after flexing to determine their effectiveness as protection against water penetration after exposure to cold flexing. The standard method (BSI Handbook II 1974: p4/186) was used, but as coated fabrics resisted the amount of pressure produced by the pump, a higher range of pressures were applied with the same head being used. Two valves were inserted, the first being hand operated, while the second was operated by a chain driven motor. The main supply line is able to give pressures up to 80 to 100 psi and when the main tap is opened, compressed air enters the line: when the first pressure valve is in a closed position, the compressed air will be released through the release valve. The hand operated valve is then opened to a desired value. Therefore a maximum amount of compressed air, set by the first pressure valve, now enters between the two valves while excess air is still being released by the released valve. With this system high pressures up to 50-60 psi can be reached and heavily coated fabrics can be tested for their break-down pressures.

Moisture Vapour Transmission

Petri dishes, 5cm in diameter were filled to within 5mm of the surface and were tightly covered with each fabric and weighed. After a period of 16 hours in a standard atmosphere they were reweighed giving the moisture vapour transmission through the fabric per hour from 100%TH to 65%RH and thus an indication of the transmission of perspiration vapour to the exterior.

Stiffness

The Shirley Stiffness Tester (BS Handbook No.II 1974: page 194) was used to find the bending length, flexural rigidity and the bending modulus at 20°C, 10°C, 5°C, 0°C and -10°C.

Bending length c. This is the length of fabric that will bend under its own weight to a definite extent. It is a measure of the stiffness that determines draping quality. The calculation is as follows:

$$C = lf_1\ (\Theta)$$

$$f_1(\Theta) = \frac{\cos \frac{1}{2}\ \Theta}{8 \tan \Theta}^{\frac{1}{3}}$$

Flexural rigidity, G. This is a measure of stiffness associated with handle. Abbot (1951) suggested that flexural rigidity as determined by this test shows a close relationship with the personal judgement of stiffness. The calculation is as follows:

$$G = wC^3 \times 10^3 \text{ mg/cm}$$

where w = cloth weight in gram per square centimetre

TABLE 6.0

Subject	Age (yr)	Height (cm)	Weight (kg)	Surface Area (m^2)
HD	27	1.85	65.9	1.87
AF	38	1.85	72.8	1.95
DC	36	1.73	68.6	1.81
IL	28	1.82	84	2.05

TABLE 6.0 Physical characteristics of subjects involved in cold chamber trials.

Bending Modulus q This value is independent of the dimensions of the strip tested and may be regarded as intrinsic stiffness. For its calculation the thickness of the fabric^{q} must be measured at a pressure of 6894.7 Nm^{-2}. The bending modulus is

$$q = \frac{12G \times 10^{-6}}{g^3} \text{ kg/cm}^2$$

Water Permeability

Measurements of water permeability were made using the Bundesmann apparatus (BSI Handbook No.II 1974: 4/11) in which, over a 10 minute period, 640ml of water fell 1.5m in droplet form on to a circular piece of fabric 10cm in diameter. This corresponds to a total water droplet energy of 6 times the most severe storm experienced in mountains in the United Kingdom. The percentage of water penetration was measured on both plain and seamed fabrics.

6.3 Cold Chamber Evaluation

6.3.1 Subjects and Experimental Plan

Four adult male volunteers participated in this study. Table 6.0 shows the subjects' physical characteristics. The potential hazards were explained to the subjects and the strict safety criteria described below were rigidly adhered to during all experiments. The subjects were able to communicate with the investigator at will.

The cold chamber experiments involved trials of hooded jackets of identical design which used Modacrylic Sliver knit pile as the insulator and three different outers. The outers were 4 oz Neoprene coated nylon, coded NEO; 'Goretex', coded GOR; and a ventile type, coded VEN, the rationale of selection of inners and outers and construction of the jackets is discussed later.

The first set of trials was performed in a cold chamber maintained between -3°C and -5°C with minimum air movement. The subjects were provided with a dry assembly of 100% cotton knitted T-shirt and underpants, a sweater of brushed cotton/polyester, trousers of 100% modacrylic sliver knit pile with a ventile waterproof outer, woollen

FIGURE 6.5 A subject dressed in the assembly prior to chamber trials.

socks, snow boots and mittens of polyester sliver knit pile with waterproof outers. The hooded jackets described above were worn over this assembly. All garments were pre-conditioned at an air temperature of 20°C and 65% RH for a period of 24 hours. The assembly insulation value was approximately 4 togs.

The subject was instrumented as described below and donned the complete assembly. FIGURE 6.5. Prior to entering the chamber, temperature readings were taken at 5 minute intervals over a period of 20 minutes. Expired air was collected for a 5 minute period during this time, and wet and dry bulb temperature of the environment was monitored. The subject then entered the chamber.

During the first set of trials, the subject sat at rest, relaxing and reading. Expired air was collected for 5 minutes during each 20 minute period of the 2 hours each trial lasted. Skin and rectal temperatures were logged at 5 minute intervals.

During the second set of trials, the subjects were dressed as above and exercise was achieved by the subject using a 'Monark' exercise cycle, at half his previously determined maximum work load. A sequence of 15 minutes steady exercise followed by a 5 minute rest period, over a total trial time for each jacket of 2 hours, was used as a simulation of a high activity programme. A collection of expired air was made over a two minute period during each 15 minutes of exercise. FIGURE 6.6. Skin and rectal temperatures were logged at 5 minute intervals.

Prior to, and after, completion of each exercise trial, the subjects were weighed both nude and fully clothed. Each garment was weighed individually before and after being worn.

6.3.2 Safety Criteria

The exposure trials were to be terminated after a 2 hour period, or if

a) the subject requested earlier termination, or

b) the rectal temperature fell by 1.5°C, or

FIGURE 6.6 A subject in the cold chamber on the exercise cycle during an oxygen collection.

c) if the temperature of any extremity fell to less than 10°C for a period of more than 30 minutes, or

d) at the discretion of the observer.

It was never necessary to terminate any test early in practice.

6.3.3 Instrumentation

Rectal temperature was measured with thermistor probe (Edale Instruments Ltd) inserted to a depth of 12cm beyond the anus. Mean skin temperature (T_{sk}) was calculatd from a weighted mean of the temperatures measured in accordance with the QREC technique (Mitchell and Wyndham, 1965). The specially designed surface thermistors (Edale Instruments Ltd, Type EU) were attached to the subjects by means of adhesive tape at the following sites:

a) Arm

b) Chest

c) Thigh

d) Calf.

All thermistor leads were fed into an interface which monitored time, temperature of chamber and autoscan of rectal and skin temperatures and which was attached to an Apple II computer with disk drive. Temperature monitoring was controlled by a computer programme and was logged every five minutes, giving 28 readings per experiment. Heart rate was monitored by an ECG monitor.

Metabolic heat production was determined using the Douglas bag technique of indirect calorimetry. The volume of expired air collected as described above was measured using a dry gas meter (Parkinson Cowan CD4) and was analysed for oxygen content by a paramagnetic oxygen analyser (Taylor Servomex OA 570) and for carbon dioxide by a CO_2 Medical Gas Analyser (Beckmann LB-2). Metabolic heat production (M) was calculated in accordance with Weir's (1949) method. Respiratory and evaporative heat losses, mean body temperature and mean skin temperature were all estimated from the calculations shown in Appendix A.

Body Surface Area of the subject was calculated (Table 6.0) using Du Bois' formula (Appendix A). From the weights recorded before and after exercise, the change in body weight was calculated. Using a computer programme, the substrate utilisation was computed for each of the six time periods, the mean being the measure used. The mean vapour loss due to ventilation was also calculated from the six recordings taken. The total uptake of the clothing was calculated from the recordings of weights before and after exposure of the following:

a) Jacket (variable)
b) Jumper (constant)
c) Vest (constant)
d) Underpants (constant)
e) Fleecy long pants (constant)
f) Outer trousers (constant)
g) Socks (constant)
h) Boots (constant)

An equation to calculate the moisture vapour/liquid transfer was formulated:

$$\Delta BW = \frac{(\text{Up Cl} + \text{Substrate} + \text{Vent})}{\text{SA} \times 1.5} \text{g/m}^2\text{/hr}$$

where ΔBW is change in body weight

Up Cl is uptake in clothing (change in weight)

Substrate is substrate utilisation

Vent is mean vapour loss due to ventilation

SA is surface area.

6.3.4 Thermal Comfort Questionnaire

The subjects were requested to score their thermal comfort during the chamber trials. A vote on a numerical scale of 1 to 7, known as the Bedford Scale (Bedford 1936) was used.

Bedford Scale - values

1 Much too cool.

2 Too cool.

3 Comfortably cool.

4 Neither cool nor warm.

5 Comfortably warm.

6 Too warm.

7 Much too warm.

On completion of the experiments, the subject undressed and was escorted to a warm shower where he remained until his rectal temperature had returned to pre-exposure levels. Hot drinks were made available thereafter and were gratefully accepted.

6.3.5 Statistical Analysis

The physiological data recorded during the wearer trials was analysed statistically using a repeated measures design with randomised block factorial, followed by analysis of variance. The H.S.D. (Turkey 1953) was used to compare a posteriori difference among the material means.

CHAPTER VII

RESULTS AND DISCUSSION - FABRICS

7.0 Insulators - Sliver Knit Pile Fabrics

The purpose of investigating sliver-knit pile fabrics was to find the most suitable for use as the insulator. After the initial investigation into thermal insulation, further studies were used to eliminate all but one, which was used in subsequent wearer trials. The criteria desired of the insulator were as follows:

a) Low thermal conductivity while retaining adequate flexibility for body movement

b) Adequate strength to withstand degradation in wear

c) Low air permeability

d) High fabric drying rate

e) Cost effective in use, therefore likely to be used in mass-market manufacture.

7.1 Thermal Insulation

Bulk density and thickness were measured prior to the measurements of thermal resistance and TABLE 7.0 shows the results for a variety of sliver knit fabrics. Where fibres (a to k) were orientated perpendicularly to the surface it can be seen that density and thickness of pile operate in conjunction to increase thermal resistance, substantiating Rees' (1946) hypothesis that large specific surface assists insulation value. Where a brushed pile (l) was involved, even with high density of fibres, a lower thermal resistance was found. Using the same fibres of low thermal conductivity, thermal efficiency is related to an increase in pile height and/or density. Although the 32mm fabrics (a and b) were superior in thermal resistance, their flexibility is limited for clothing purposes, and their tog rating too high for work-wear. Three fabrics (e, g and k) were selected for further study as all showed adequate thermal

TABLE 7.0

KEY	DENSITY (gm/m^2)	THICKNESS (mm)	FIBRE TYPE	TOG RATING
a	1050	32	Polyester	8.0
b	690	32	Polyester	6.3
c	440	13	Polyester	2.7
d	550	11	Modacrylic	2.7
e	422	13	Modacrylic	2.4*
f	425	12	PVC	2.3
g	370	10	Polyester	2.1*
h	365	13	Acrylic	2.1
i	320	13	Modacrylic	1.9
j	470	8	Modacrylic	1.9
k	293	8	Polyester	1.9*
l	505	8	Polyester brushed on horizontal plane	1.6

TOG ratings on a variety of different pile lengths and densities of different sliver-knit fabrics.

* indicates fabrics selected for further study.

TABLE 7.1

PILL TEST (60 revolutions per minute for 5 hours)

KEY	FABRIC TYPE	PILLS	GRADE	
k	Polyester	21 - 40	2	(high pill)
g	Polyester	3 - 7	4	(low pill)
e	Modacrylic	0	5	(non pill)

TABLE 7.2

BURSTING STRENGTH TEST (psi)

KEY	FABRIC TYPE	SAMPLE NO	BEFORE PILLING	MEAN	AFTER PILLING	MEAN
	Polyester					
	(high pill)	1	200		215	
		2	205		220	
		3	225		225	
		4	185		200	
		5	190		210	
		6	190		195	
				199psi		211psi
g	Polyester					
	(low pill)	1	205		190	
		2	195		225	
		3	225		210	
		4	175		200	
		5	180		205	
		6	200		220	
				197psi		208psi
e	Modacrylic					
	(non pill)	1	195		230	
		2	180		235	
		3	210		175	
		4	225		215	
		5	210		210	
		6	190		180	
				202psi		208psi

TABLE 7.3

AIR PERMEABILITY

KEY	FABRIC TYPE	SAMPLE NO.	AMOUNT	MEAN
k	Polyester	1	229	
		2	218	
		3	214	
		4	268	
		5	235	
		6	222	
		7	245	
		8	223	
		9	241	
		10	229	232.4 = 46cm^3/cm^2/sec
e	Modacrylic	1	111	
		2	121	
		3	130	
		4	141	
		5	101	
		6	118	
		7	106	
		8	121	
		9	125	
		10	140	121 = 24cm^3/cm^2/sec
g	Polyester	1	110	
		2	108	
		3	101	
		4	114	
		5	107	
		6	108	
		7	111	
		8	105	
		9	112	
		10	103	107.9 = 21cm^3/cm^2/sec

insulation value, lightness in weight and adequate flexibility for use in clothing, were relatively inexpensive and readily available.

7.2 Degradation After Wear

7.2.1 Pilling

TABLE 7.1 shows the results of the three selected sliver-knit pile fabrics after testing for pilling. Fabric (e) was superior, showing no degradation.

7.2.2 Bursting Strength

TABLE 7.2 shows that in all cases the pilled samples had a higher bursting strength than the originals. The redistribution due to pilling increases the overall strength although the surface appearance is altered, no overall weakening of the fabric was found.

The pilling and bursting strength tests were carried out to assess degradation in wear as another parameter for the choice of the best insulator.

7.3 Air Permeability

TABLE 7.3 shows that sliver-knit fabrics have a high air permeability and hence a high water vapour permeability. Air permeability is lowered when the density increases (fabrics e and g), thus allowing less air from the environment to penetrate towards the body while still permitting the passage of moisture vapour through the structure.

The higher density and characteristics of the pile allow close body fit, thus reducing 'bellows action' and inhibiting heat loss by forced convection.

7.4 Water Repellency

TABLE 7.4 shows that where the pile faced downwards and the knitted structure was exposed to 'rainshower', a great quantity of water, close to the control measurement, passed through. The open knitted structure allows water at pressure to penetrate easily, indicating that this area must be protected by a water and wind-proof covering, if it is to be used as an insulator in foul weather clothing. The low

TABLE 7.4

WATER REPELLENCY (BUNDESMANN)

FABRIC	QUANTITY COLLECTED
13mm modacrylic pile	
1) Pile up	15ml
2) Pile down	405ml
3) Control cup (no cover)	416ml

TABLE 7.5

KEY	FIBRE TYPE	DENSITY (gm/m^2)	THICKNESS (mm)	TOG RATING	PILL GRADE	AIR PERMEABILITY ($cm^3/cm^2/sec$)
e	Modacrylic	422	13	2.4	5	24*
g	Polyester	370	10	2.1	4	38
k	Polyester	293	8	1.9	2	46

* Fabric selected for insulation in jackets for wearer trials.

TABLE 7.6 AIR PERMEABILITY

FABRIC	AIR PERMEABILITY $cm^3/cm^2/sec$
Rip stop nylon	1.4
Neoprene coated nylon	0
Polyurethane coated acetate	0
Ventile type	0.15
Goretex	0.04

water penetration result obtained when the pile faced upwards could have been due to water being dispelled by the close dense pile and the hydrophobic and non-compressible nature of the modacrylic fibres. This result indicates that more work needs to be done before a complete understanding of the varied physical properties of sliver knit pile fabrics in relation to water repellence is completely understood.

7.5 Final Selection Of Insulator

TABLE 7.5 shows all results collated. Fabric e, a modacrylic sliver-knit fabric complied with the majority of previously determined criteria, (page 89) and was selected for use as the insulator in the rest of the study, predominantly because of its tog-rating, low air permeability and availablity at low cost.

7.6 Outers

The main criterion of efficiency of a clothing assembly used in a cold environment is that where heat loss has been limited, the body should remain dry and in a comfortable state during all activity.

An assembly designed to function in cold, wet conditions must fulfil the following criteria:

a) Be waterproof and windproof.

b) Allow moisture vapour transfer through the assembly without affecting the efficiency of the insulator.

c) Remain thermally and psychologically acceptable to the wearer in a variety of temperatures and conditions.

d) Must be cost effective and therefore likely to be utilised in the mass clothing market.

Since the insulator was held constant throughout the wearer trials, any variation in performance of the assemblies was due to the varying performance of the outers only.

7.7 Air Permeability

TABLE 7.6 shows that all five samples have either very low air permeability or are completely impermeable. Thus they can be

TABLE 7.7 'BUNDESMANN' TEST AFTER ABRASION (MARTINDALE)

FABRIC	OBSERVATIONS	WATER COLLECTION
Rip-stop nylon	Darker	2 droplets
Neoprene coated nylon	Outer nylon darker	Nil
Polyurethane coated nylon	Backing Wet	Nil
Ventile type	Darker	Nil
Goretex	No change	Nil

TABLE 7.8 'BUNDESMANN' TEST ON SEAMS

FABRIC	SEAM TYPE	COLLECTION
Neoprene coated nylon	Lockstitched size 11 needle	30ml
Neoprene coated nylon	Taped and doped	Nil
Goretex	Goretex method	Nil
Ventile type	Stitched only needle size 9	2.5ml
Ventile type	Stitched only needle size 11	20.0ml
Ventile type	Stitched only needle size 14	33.0ml
Ventile type	Stitched with needle size 11 and 8 stitches per cm	37.5ml
Ventile type	Stitched with needle size 11 and 5 stitches per cm	20.0ml
Ventile type	Stitched with needle size 11 and 2.5 stitches per cm	12.0ml

classified as windproof. As heat loss is increased by air movement, it follows that the outer must be impermeable to wind so that the insulator can be effective in maintaining its primary function of trapping still air within the assembly. It is commonly accepted that if fabric is impermeable to air it will be impermeable to liquid water. The priority in clothing for severe cold, wet conditions must be to protect all elements of the assembly from rain, thus allowing correct functioning of the insulating medium.

7.8 Abrasion And Water Permeability

All five samples stood up well to the 'Martindale' abrasion tester and were subsequently subjected to the Bundesmann test in standard conditions. All fabrics could be classified as waterproof even after abrasion. (TABLE 7.7).

7.8.1 Water Permeability Of Seams

TABLE 7.8 shows that where complete 'waterproofing' of seams occurred, no water was allowed through. Where lockstitch only was employed, if fewer stitches per inch and a fine needle was used, less water penetration occurred than when more stitches per inch and a thick needle was used. The method of assembly of the outer is relevant to the waterproof performance of the assembly, since the lockstitching of seams is not adequate on its own. Thus a method of waterproofing seams is essential. This process does add to the final cost and weight of the garment, and on the ventile sample, less water ingress was evident when a fine needle was used in conjunction with a long stitch, very few per inch, giving fewer and finer needle penetration holes. If the garment is of a non-coated nature, such as a ventile type with the seams being strategically placed so that water penetration is unlikely, and the end-use is for 'shower-proof' conditions, then complete sealing of the seams may be unnecessary. In cicumstances where foul weather clothing is being produced the 'waterproofing' of seams is essential for a good end-performance.

TABLE 7.9

HYDROSTATIC HEAD (RESISTANCE TO WATER PRESSURE)

BEFORE AND AFTER FLEXING (SCHILDKNECHT METHOD)

WATER ENTRY PRESSURE (psi)

BEFORE FLEXING		AFTER FLEXING FOR 500,000 cycles				
FABRICS	STANDARD CONDITIONS 20°C	20°C	10°C	0°C	-10°C	-20°C
Rip stop nylon	0.4psi	0.014psi	0	0	0	0
Neoprene coated nylon	60 psi	60psi	60psi	34psi	17psi	9psi
Polyurethane coated acetate	37.5psi	21psi	6psi	2.6psi	0	0
Ventile type	0.41psi	0.26psi	0.13psi	0	0	0
Goretex	50psi	5.5psi	3psi	0	0	0

150 cm of water pressure or

150 gm/cm^2 = 2.14 psi (MOD requirement)

1 psi = 6894.76 Nm^2

1 pascal (Pa) = 1 Nm^{-2}

TABLE 7.10 MOISTURE VAPOUR TRANSMISSION

FABRIC	g/m^2/24hr
Rip stop nylon	392
Neoprene coated nylon	46
Polyurethane coated nylon	182
Ventile type (wet)	357
Ventile type (dry)	708
Goretex	861
Cotton ventile	425

7.8.2 Determination Of Resistance To Damage By Flexing

All five fabrics were very resistant to abrasion using the 'Martindale' apparatus at standard conditions. However, at colder temperatures and with more intense abrasion, using the Schildknecht flexing machine, breakdown occurred. TABLE 7.9 shows that while three of the fabrics can withstand a great deal of water pressure at 20° prior to flexing, neoprene coated fabrics resist mechanical breakdown better than the other fabrics examined. Breakdown on all other fabrics was quite dramatic after flexing at standard conditions (20°C), but at lower temperatures, breakdown occurred at a faster rate. For a high percentage of the year in the United Kingdom, the temperature of rain droplets is low and near to freezing point, and so for 'waterproof' fabrics to be used as rain protection, their performance should be examined at low temperature. Of the two coated fabrics examined, neoprene coated nylon resisted mechanical breakdown better than any other fabric examined. However, polyurethane coated acetate degraded quite rapidly, especially at lower temperatures, and this is one of the reasons why garments constructed from such fabrics generally have a short lifespan.

Neoprene coated nylon was chosen for the wearer trials due to its excellent waterproof performance after flexing, and the fact that it is widely used in waterproof clothing manufacture. 'Goretex' was found to break down on flexing, the hydrostatic head reading falling from 50 psi to 5.5 psi at room temperture; the rate of breakdown being greater at lower temperatures. (<u>NOTE</u> The fabric under test was a Phase 1 product and later 'Goretex' fabrics tested, but not included in this study, did not show this tendency to breakdown, thus it is obvious that further development by the manufacturer has taken place).

Both rip-stop nylon and ventile type fabric performed badly on hydrostatic head after flexing, but the ventile type performed better than the rip-stop nylon.

7.9 Moisture Vapour Transmission (MVT)

TABLE 7.10 shows that neoprene coated fabrics have a very poor rate of moisture vapour transmission, while 'Goretex' allows a great deal of moisture vapour to pass through. The impermeable nature of neoprene coated nylon and polyurethane coated acetate classified them as a barrier to rainwater, but also rendered them impermeable to moisture vapour transmission from the body, and allowed condensation to build up within the assembly.

Outer fabrics with good moisture vapour transmission performance allow perspiration to be wicked and vapour to pass through the sliver-knit pile insulator to the environment, keeping the skin and assembly dry. The ability of a fabric to hold large amounts of moisture without feeling damp is of great importance to comfort (Mehta 1984). 'Goretex' and dry ventile type performed very well and would allow perspiration to pass through the assembly enabling the insulator to perform to its maximum heat retention capability regardless of environmental and physiological changes. The performances of both dry ventile type and Goretex were 40% and 51% respectively superior in moisture vapour transmission than cotton ventile traditionally accepted as having excellent MVT. When the ventile type was exposed to a long period of damp and became wet its moisture vapour transmission was further reduced by 50% of its dry state performance. Neoprene coated nylon exhibited virtually no moisture vapour transfer, therefore being classified as impermeable to moisture vapour.

7.10 Drape

TABLE 7.11 shows the results obtained in standard conditions after exposure in laboratory conditions and at $-10^{o}C$ overnight. Within the scope of this thesis these results did not make any significant contribution. As can be seen in TABLE 7.11 the neoprene coated nylon, which is subjectively classified as the stiffest, showed the most drape therefore this test cannot be used to examine stiffness. The

FIGURE 7·0 BENDING LENGTH (cms)

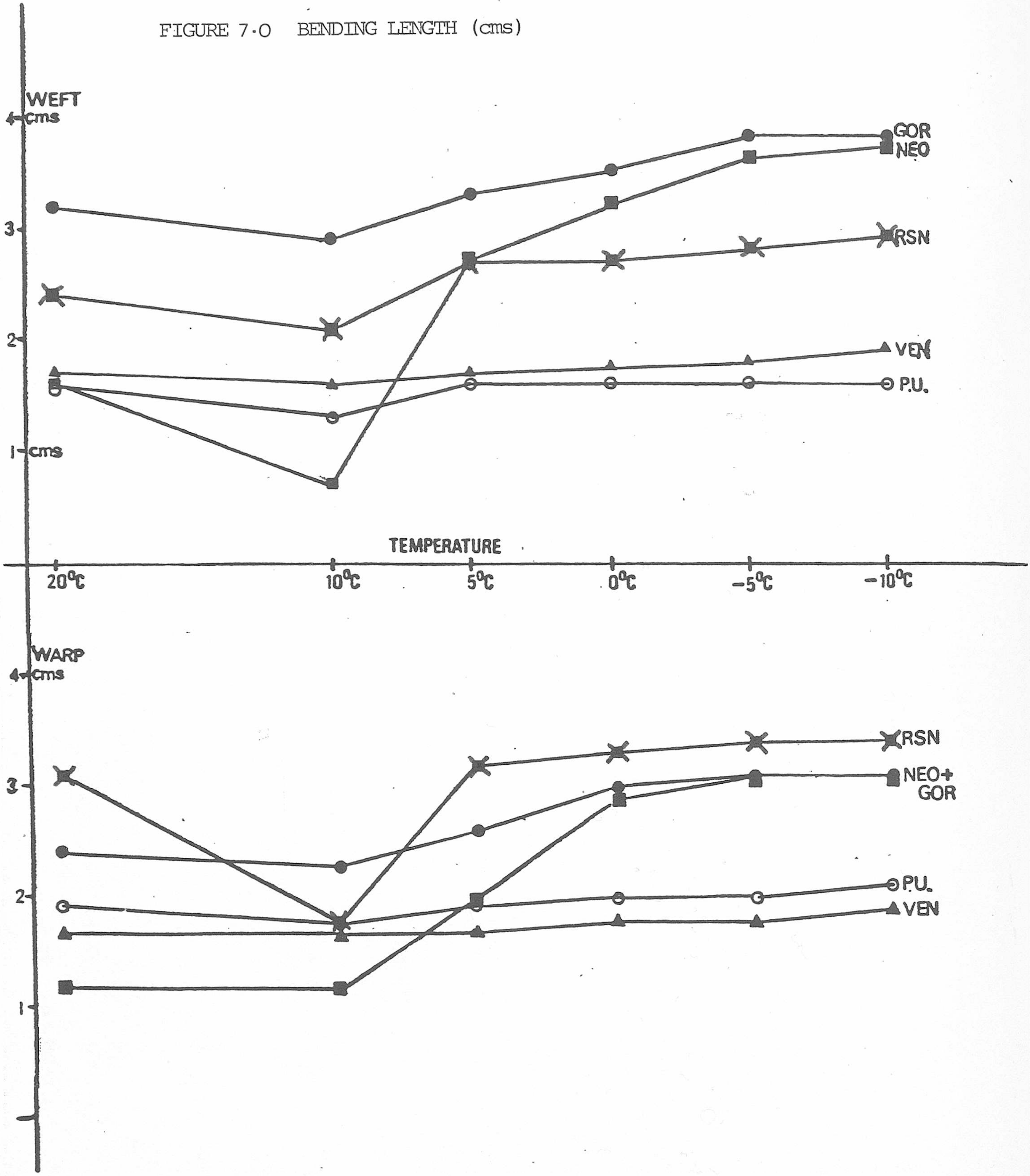


TABLE 7.11 DRAPE COEFFICIENT

	TEST 1	TEST 2	MEAN
AT 20°C			
Rip stop nylon	0.82	0.75	0.79
Neoprene coated nylon	0.69	0.48	0.59
Polyurethane coated nylon	0.64	0.61	0.62
Ventile type	0.78	0.76	0.77
Goretex	0.87	0.82	0.84
AT ZERO			
Rip stop nylon	0.78	0.76	0.74
Neoprene coated nylon	0.53	0.45	0.49
Polyurethane coated acetate	0.60	0.54	0.57
Ventile type	0.78	0.71	0.74
Goretex	0.85	0.78	0.82

TABLE 7.12 DIMENSION OF FABRICS TESTED

FABRIC	THICKNESS(cm)	WEIGHT(g/m^2)
Goretex	0.04	147.3
Neoprene	0.04	415.9
Rip-stop nylon	0.02	87.7
"Ventile" type	0.03	105.0
Polyurethane coated acetate	0.03	136.0

TABLE 7.13 BENDING LENGTH

WEFT STRIPS	20°C	10°C	5°C	0°C	-5°	-10°
Goretex	3.2	2.9	3.3	3.5	3.7	3.8
Neoprene coated nylon	1.6	0.7	2.7	3.2	3.6	3.7
Rip stop nylon	2.4	2.1	2.7	2.6	2.8	2.9
Ventile type	1.7	1.6	1.75	1.8	1.8	1.9
Polyurethane coated acetate	1.6	1.3	1.6	1.6	1.6	1.6
WARP STRIPS						
Goretex	2.3	2.2	2.5	2.9	3.0	3.0
Neoprene coated nylon	1.1	1.0	1.9	2.9	3.0	3.0
Rip stop nylon	3.0	1.7	3.1	3.2	3.3	3.3
Ventile type	1.6	1.5	1.6	1.7	1.7	1.8
Polyurethane coated acetate	1.8	1.7	1.8	1.85	1.9	2.0

TABLE 7.14 FLEXURAL RIGIDITY G (mg/cm)

WEFT STRIPS	$20^{\circ}C$	$10^{\circ}C$	$5^{\circ}C$	$0^{\circ}C$	$-5^{\circ}C$	$-10^{\circ}C$
GORETEX	405.3	367.5	546.9	648.5	776.8	807.6
NEOPRENE	172.6	13.2	799.7	1350.1	1946.9	2067.6
RIP STOP NYLON	126.6	80.5	177.9	168.6	197.7	213.5
VENTILE TYPE	47.7	43.6	52.0	59.0	61.4	69.2
P.U. ACETATE	54.0	30.9	56.4	56.4	56.4	56.4

WARP STRIPS						
GORETEX	176.7	155.1	239.1	367.5	386.3	386.3
NEOPRENE	51.1	48.4	263.8	889.6	1090.7	1090.7
RIP STOP NYLON	230.0	43.5	253.3	278.3	318.6	318.6
VENTILE TYPE	43.6	39.7	43.6	52.0	52.0	56.6
P.U. ACETATE	73.3	61.8	73.3	86.3	93.1	100.5

TABLE 7.15 BENDING MODULUS q(kg/cm^2)

WEFT STRIPS	20°C	10°C	5°C	0°C	-5°C	-10°C
GORETEX	76.0	68.9	102.5	121.6	145.6	151.4
NEOPRENE	32.4	2.5	149.9	253.1	365.1	387.7
RIP STOP NYLON	189.9	120.8	266.8	252.9	296.6	320.2
VENTILE TYPE	21.2	19.4	23.1	26.2	27.3	34.9
P.U. ACETATE	24.0	13.8	25.1	22.9	25.1	25.1

WARP STRIPS						
GORETEX	33.1	29.1	44.9	68.9	72.4	72.4
NEOPRENE	9.6	9.1	49.5	166.8	204.5	204.5
RIP STOP NYLON	345.0	65.2	379.9	417.5	477.9	477.9
VENTILE TYPE	19.4	17.6	19.4	23.1	23.1	25.1
P.U. ACETATE	32.6	27.4	32.6	38.3	41.4	44.7

tests conducted after the fabrics had been held overnight at $-10^{\circ}C$ showed more drape and so this test was disregarded. More work needs to be done to examine drape at different temperatures and conditions.

7.11 Stiffness

TABLE 7.12 shows the dimensions of the fabrics tested; TABLE 7.13 and FIGURE 7.0 the calculated Bending Length; TABLE 7.14 the Flexural Rigidity and TABLE 7.15 the Bending Modulus. In all cases, as the temperature fell below $5^{\circ}C$, the fabrics showed that they stiffened. However at $10^{\circ}C$ an unusual result was obtained. This is inexplicable at the present and outwith the scope of this thesis. More work needs to be done to examine stiffness at a variety of temperatures and conditions.

7.12 Final Selection of Outer

The performance criteria of good waterproofness, moisture vapour transmission and non-stiffening in cold conditions are desired for a good severe weather outer garment. As well as these criteria, an important factor is cost, and this, as well as customer acceptance, are important considerations prior to construction.

Neoprene coated nylon, although it performed badly in many of the trials, was selected to be used as a control as it proved completely impermeable to moisture vapour. This would allow the other two chosen, Goretex and a Ventile type, both permeable to moisture vapour, to be judged against it. Another reason for the choice of neoprene coated nylon was its present wide use in severe weather clothing due to it being the only water proof fabric readily available until recently. The other two fabrics selected have performed well in the laboratory trials. However, the Ventile type was far cheaper, and providing it performed well, may prove more cost effective for use in garments than Goretex.

CHAPTER VIII

8.0 Results and Discussion - Cold Chamber Wearer Trials

After the selection of the three outers, jackets of identical style, fit and insulation were constructed for use in wearer trials. The jackets were assembled identically using a close fit shaping and integral hood to eliminate as much "bellows action" as possible and so prevent unnecessary heat loss. Zip shields with velcro fastening covering the zip openings were used and wrists were tightened with velcro bands. The hood had a drawstring fastening and the zip came up to the chin and lower edge of the hood, FIGURE 6.5. All these design features were included so that convective heat losses were minimal and yet the garment was both functional and fashionable. The rest of the assembly was typical of that worn in winter by mountaineers in Scotland. The cotton vest and underpants were particularly selected for use due to their common usage by men in this region. Their hydrophilic performance teamed with the hydrophobic modacrylic sliver-knit stucture was to be observed. The simulated cold conditions in the cold chamber were easily monitored and controlled to a -5°C setting throughout both the tests at rest and at exercise.

The conditions for the experiments at rest simulated those when a hill-walker takes shelter and remains immobile. The exercise experiment examined the performance of the jackets while the subjects were involved in a high activity situation with short periods of rest.

8.1 Cold Chamber Wearer Trials at Rest

8.1.1 Rectal Temperature at Rest

The effect of exposure to cold on the subjects rectal temperatures is shown on TABLE 8.0 and FIGURES 8.1 and 8.2. The rectal temperatures in the first hour decreased in all three jackets at approximately 0.3°C whereas during the second hour this decrease virtually doubled in all cases being 0.5 °C for NEO, 0.5 °C for VEN and 0.6 °C for GOR, GOR having initially lost less heat in the first hour period. At the

TABLE 8.0

Readings in °C taken on 4 subjects wearing all 3 jackets at REST in an environmental chamber at approximately -5°C.

TIME (mins)	MEAN RECTAL TEMP	MEAN SKIN TEMP	MEAN BODY TEMP
		NEO	
OUT 1 - 20	37.6	32.8	36.9
C			
H 40	37.5	31.4	35.4
A 60	37.3	30.8	35.1
IN M 80	37.2	30.4	34.9
B 100	37.0	30.2	34.7
E 120	36.8	29.8	34.4
R	ΔTre = -0.8°C	ΔTsk = -3.0°C	ΔMBT = -1.6°C
		VEN	
1 - 20	37.6	32.3	35.9
40	37.5	31.5	35.5
60	37.4	30.9	35.2
80	37.1	30.5	34.9
100	37.1	30.2	34.8
120	36.9	30.3	34.6
	ΔTre = -0.7°C	ΔTsk = -2.0°C	ΔMBT = -1.3°C
		GOR	
1 - 20	37.6	32.6	36.0
40	37.5	31.0	35.8
60	37.4	30.3	35.0
80	37.2	29.9	34.8
100	37.0	30.6	34.9
120	36.8	30.9	34.6
	ΔTre = -0.8°C	ΔTsk = -2.4°C	ΔMBT = -1.4°C

Time periods 1- 20 spent outside chamber, 20 onwards in chamber.

KEY

ΔTre = change in rectal temperature

ΔTsk = change in skin temperature

ΔMBT = change in mean body temperature

Others as described in TABLE 8.10

FIGURE 8.1 MEAN TEMPERATURES AT REST

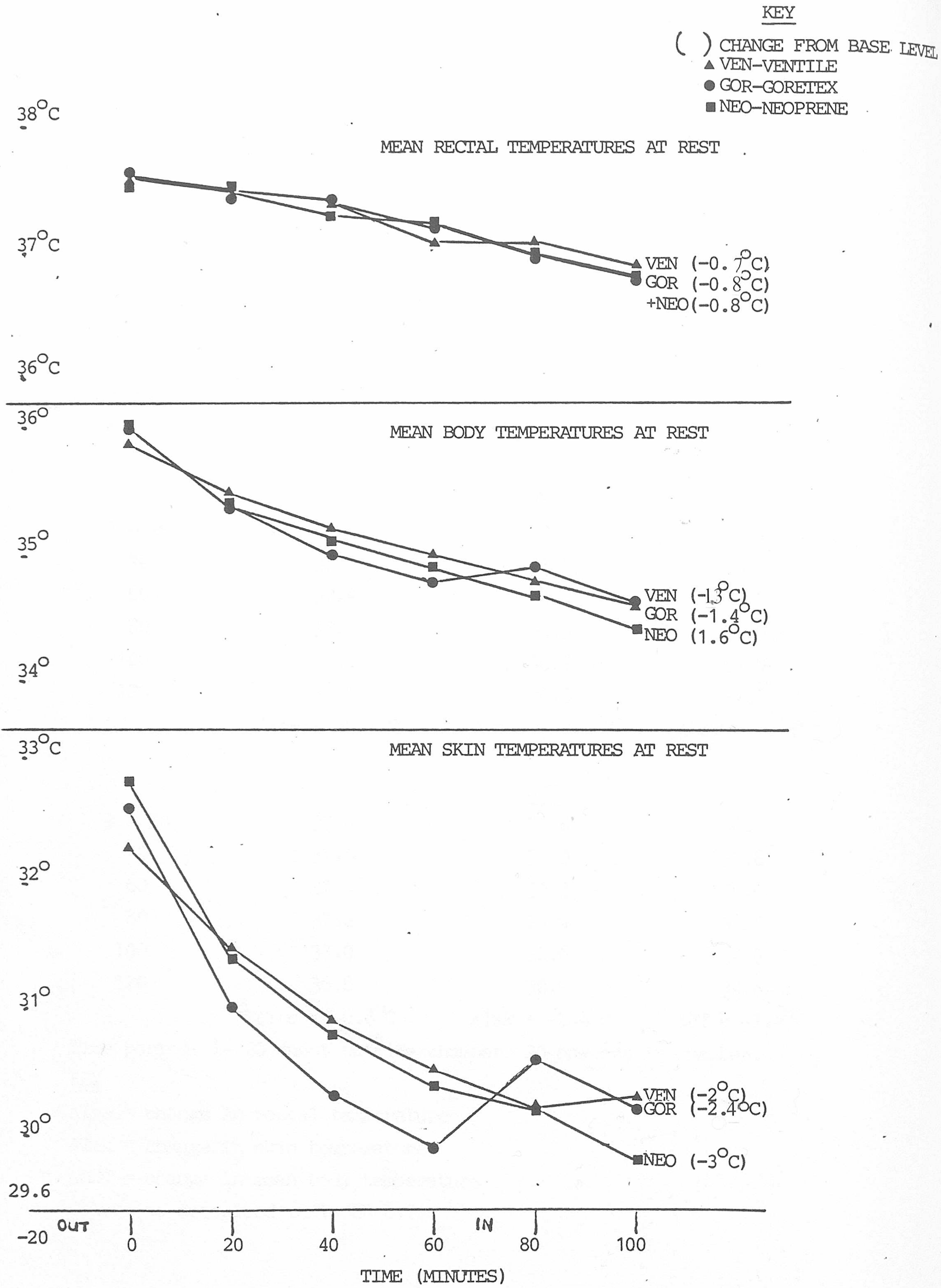


FIGURE 8.2 RECTAL TEMPERATURE AT REST

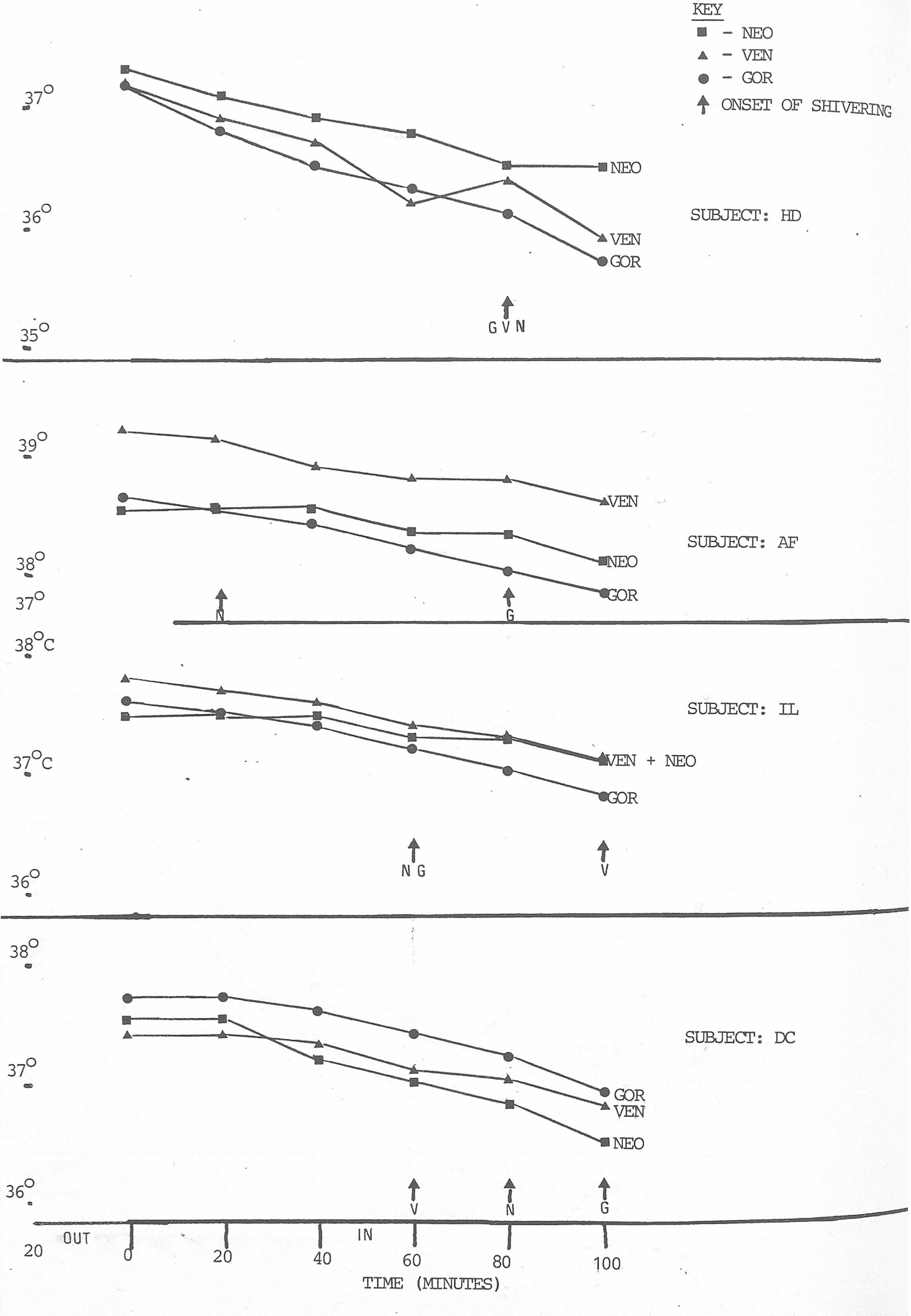
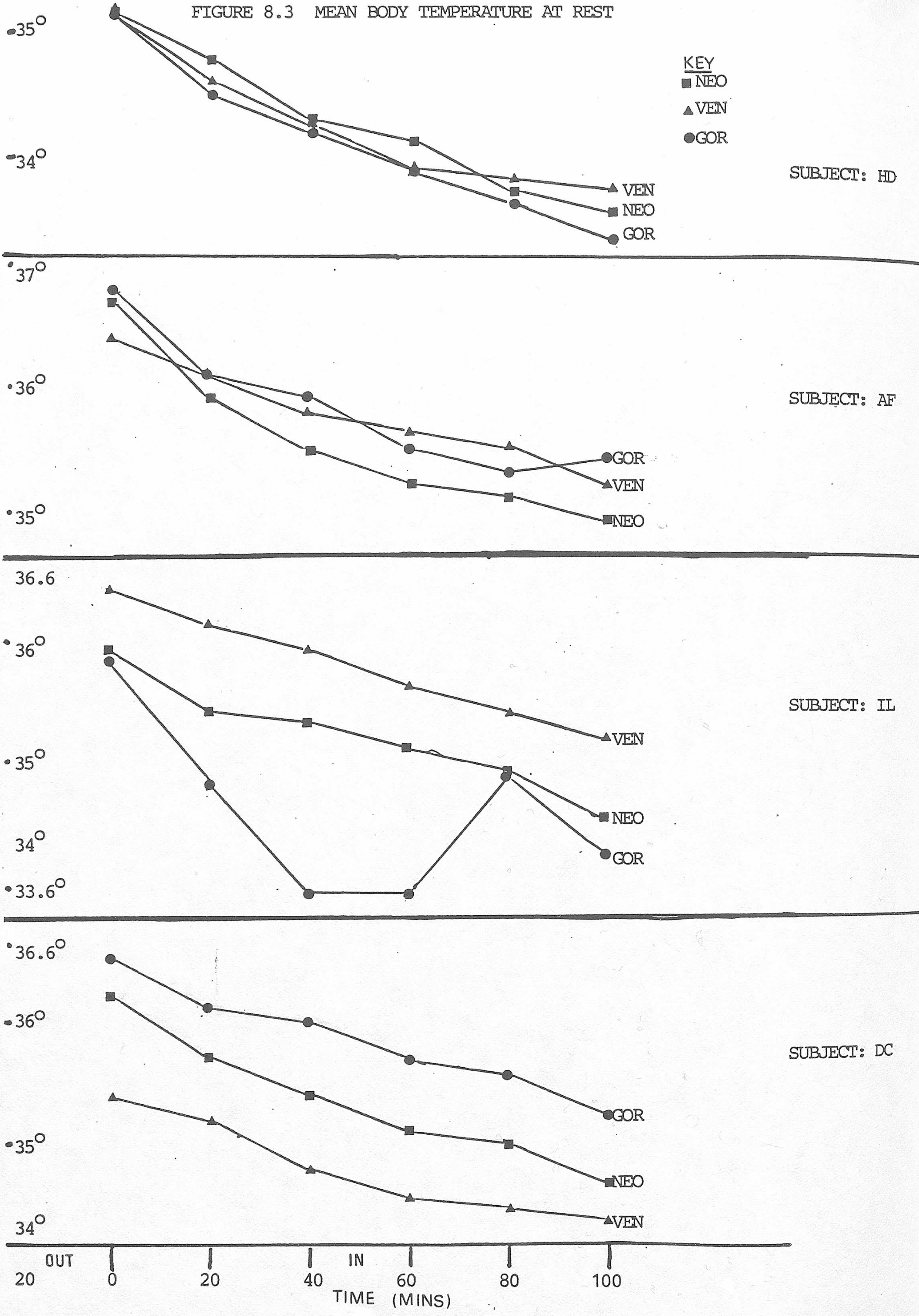


FIGURE 8.3 MEAN BODY TEMPERATURE AT REST



end of the experiment rectal temperatures had fallen by 0. 8°C; 0.7 °C 0.8°C in NEO, VEN and GOR respectively. The shivering points are also indicated in FIGURE 8.2 but no correlation between individuals was found. Although the rectal temperatures fell slightly there was no significant difference between these final rectal temperatures. The differences in mean rectal temperatures before and after exposure are shown in FIGURE 8.1 but the decrease was not significant.

8.1.2 Mean Body Temperature at Rest

The calculated mean body temperatures and changes in mean body temperatures for each subject are shown in TABLE 8.0 and FIGURES 8.1 and 8.3. After the first hour NEO and VEN temperatures decreased by approximately 50% of their total heat loss over the 100 minute period GOR lost 1°C of its total heat loss of -1.4 °C in the first hour. After exposure for the total experimental time, the mean body temperatures decreased by 1. 6°C in NEO, 1. 3 °C in VEN and 1.4 °C in GOR.

No significant difference is found between any of the three jackets all giving an equivalent stored heat loss over the 100 minute period. The greater proportional heat loss in GOR in the first hour was possibly caused by cold being transmitted inwards, the body mechanisms taking this time to react and counteract this, however further studies need to be done in this area.

8.1.3 Skin Temperature at Rest

The mean skin temperatures at rest are shown in TABLE 8.0 and FIGURE 8.1 and the individual mean skin temperatures in FIGURES 8.4a, 8.4b. The initiation of shivering are also noted in FIGURES 8.4a and 8.4b. In the first hour the mean skin temperatures had fallen -2.0°C 1.4°C and 2.3 °C in NEO, VEN and GOR respectively, this showing a reasonably steady decrease in all three. In the next period they fell by -1.0C, 0.6 °C and 0.1 °C and so this trend appears significant. However, on examining the individual graphs the small decrease in GOR can be

FIGURE 8.4a MEAN SKIN TEMPERATURE AT REST

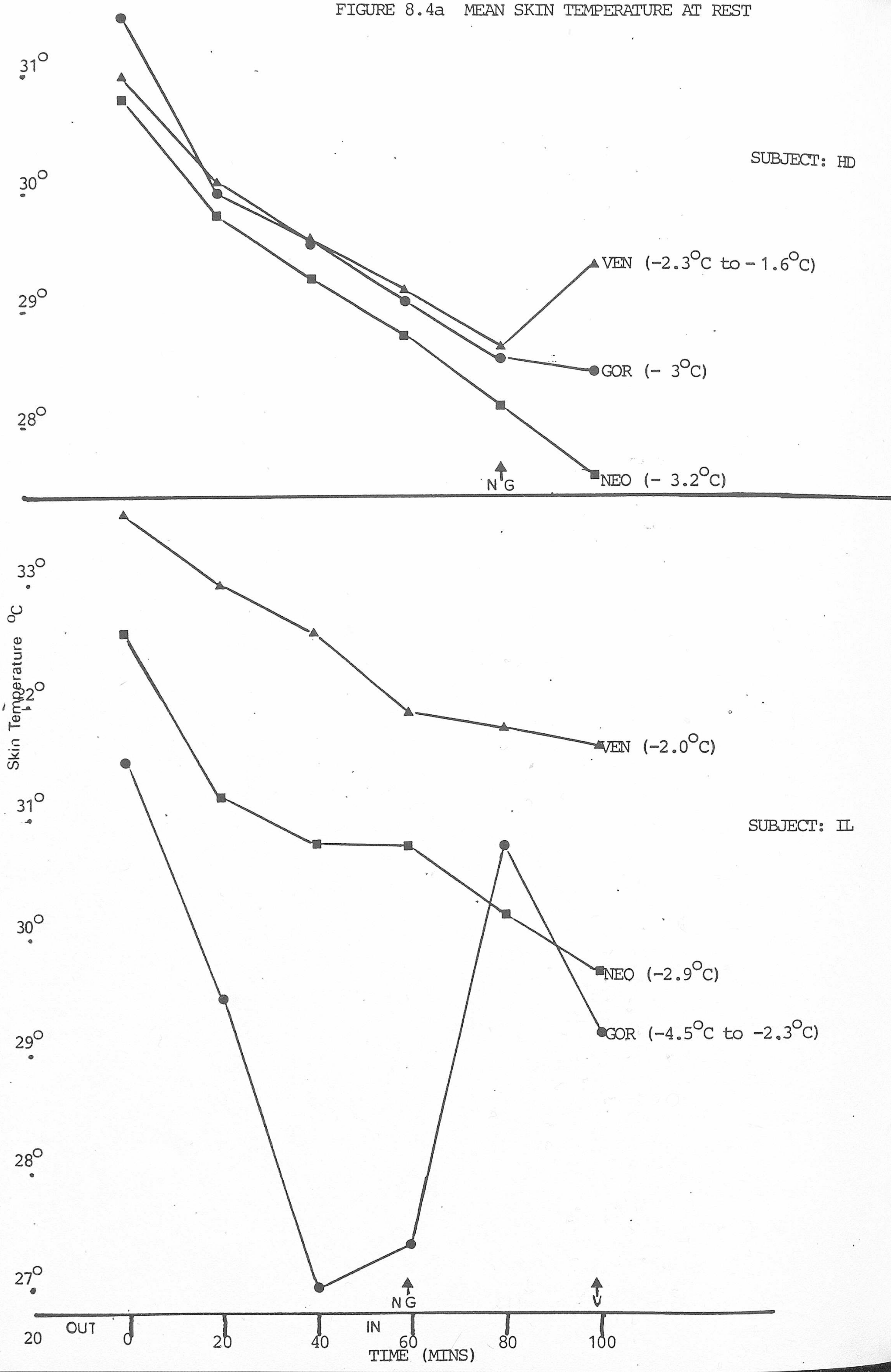
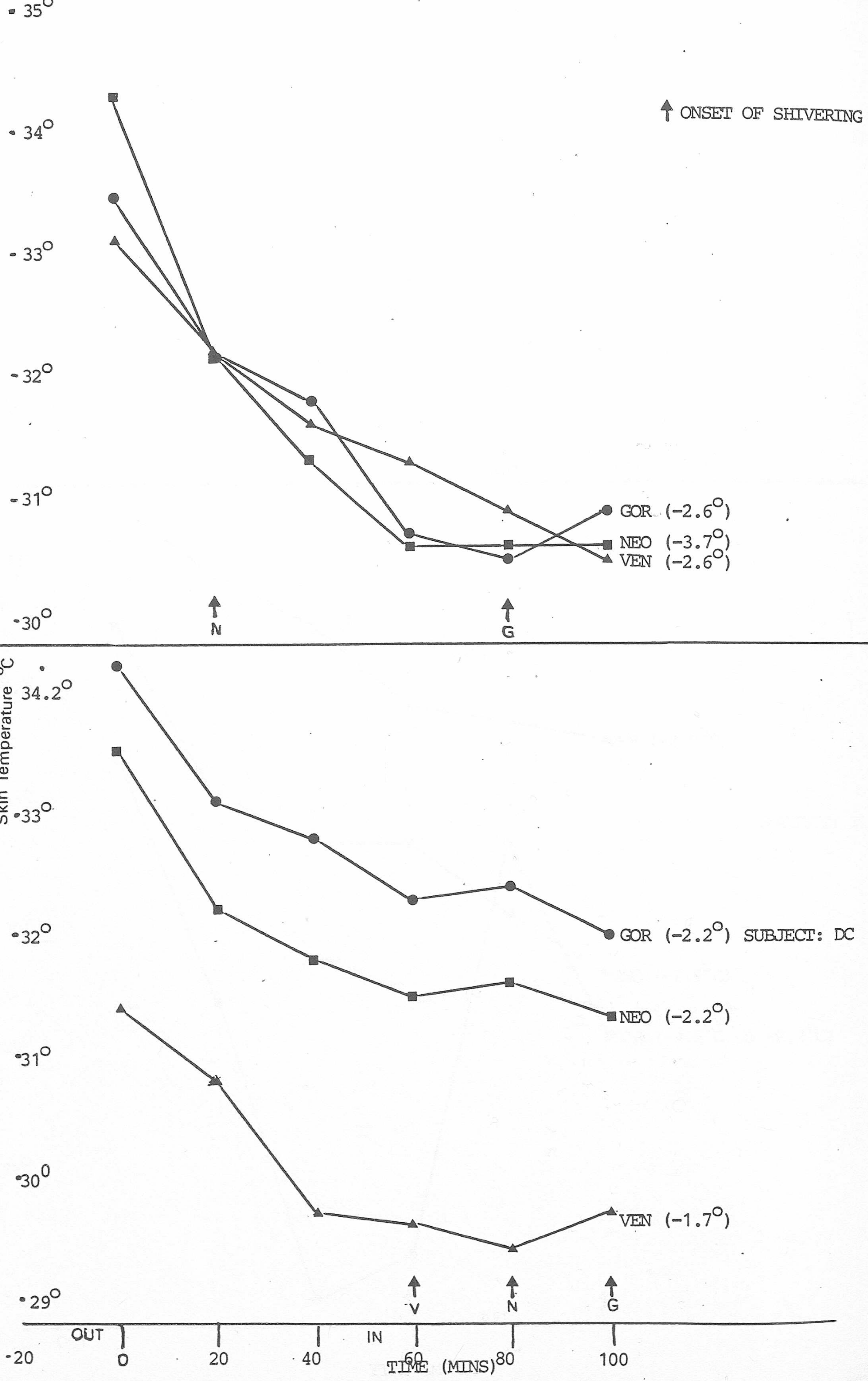


FIGURE 8.4b SKIN TEMPERATURE AT REST



explained by the sudden increase in skin temperature in subject IL after the start of shivering. The skin temperature recordings showed that all subjects became colder while wearing all three jackets, the decrease of - 2.$^{\circ}$C VEN - 2.4 $^{\circ}$C GOR and -3.$^{\circ}$C NEO and the fall in the individual subjects' temperatures show that these temperature changes are beyond the recognised span of the comfort zone, this being 3.3°C wide (Goldman 1982) classifying them all as uncomfortably cool.

8.2 Statistical Analysis of Wearer Trials - Rest and Exercise

The skin temperatures, core temperatures and calculated mean body temperatures from garment wearer trials were compared statistically. A repeated measures design with randomised block factorial was used and the summary analyses of variance tables are given overleaf.

As significant differences were found to exist between the materials under exercise conditions Turkeys' (1953) HSD test was used to compare the a posteriori differences among the material means.

The test statistic

$$HSD = q_{\alpha\ \nu} * \sqrt{\frac{MS\ error}{n}}$$

was computed with $\alpha = 0.01$ and certain differences between means for all three temperatures were found to be significant i.e. real differences do exist between the materials for the temperatures measured under exercise conditions, (there being no significant differences under rest conditions).

Summary Tables for HSD - STATISTIC

	Average Temp.	Differences of Means			HSD	Representation		
RECTAL						NV		G
NEOPRENE	38.2792	-	0.0583	0.1333*	0.620			
VENTILE	38.3375		-	0.0750*				
GORETEX	38.4125			-				
SKIN								
NEOPRENE	33.1167	-	0.3375*	0.6583*	0.2298	N	V	G
GORETEX	33.4542		-	0.3208*				
VENTILE	33.7750			-				
MBT.					0.1871	N		GV
NEOPRENE	36.5542	-	0.2041*	0.2558*				
GORETEX	36.7583		-	0.0517				
VENTILE	36.8100			-				

*SIGNIFICANT - ≡NS.

ANOVA TABLE

		Rest						Exercise					
		Rectal		Skin		MBT		Rectal		Skin		MBT	
Source	ν	MS	F	MS	F	MS	F	MS	F	MS	F	MS	F
Subj	3	4.571	89.08*	19.0298	14.25*	7.3681	39.63*	1.0694	28.86*	23.7071	75.97*	4.1573	57.82*
Material	2	0.0250	0.54	0.1372	0.10	0.0304	0.16	0.1073	2.90+	2.6010	8.83	0.4392	6.11*
Time	5	1.0882	23.76*	10.8404	8.12*	3.1144	16.75*	0.4891	13.20*	0.7111	2.28	0.5488	7.63*
M x T	10	0.0076	0.16	0.3210	0.24	0.0325	0.17	0.0079	0.21	0.1085	0.35	0.0231	0.32
Error	51	0.0467		1.3355		0.1859		0.0371		0.3121		0.0719	

*Significant at 5% Level; + Significant at 10% level.

$F_{3,51,0.05} = 2.796$

$F_{2,51,0.05} = 3.186$ $F_{2,51,0.10} = 2.4125$

$F_{5,51,0.05} = 2.406$

$F_{10,51,0.05} = 2.0305$

TYPE Randomised Block Factional Design : RBF – 36, with materials and time as fixed effects and subjects as a random effect. The model fitted is,

$$X_{ijm} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \pi_m + \Sigma_{ijm}$$

where, μ = grand mean of treatment populations

α_i = effect of treatment i, which is a constant for all subjects within treatment population i

β_j = effect of treatment j, which is a constant for all subjects within treatment population j

$\alpha\beta_{ij}$ = effect, which represents non-additivity of effects α_i and β_j

π_m = a constant association with block m

ε_{ijm} = experimental error, which is NID, $\mu = o$, $\sigma^2 = \sigma_\varepsilon^2$

Therefore it is concluded that:

(1) The type of material had a significant effect on the temperature at exercise only.

(2) The level of time significantly affected the temperature at exercise and rest; apart from the mean skin temperature at exercise.

TABLE 8.1 Change in Comfort Votes Over 2 Hours

	NEO	VEN	GOR
HD	6 - 3 (-3)	5 - 4 (-1)	6 - 3 (-3)
AF	3 - 2 (-1)	6 - 5 (-1)	4 - 3 (-1)
IL	4 - 2 (-2)	5 - 4 (-1)	4 - 3 (-1)
DC	6 - 3 (-3)	6 - 3 (-3)	7 - 5 (-2)
	-9	-6	-7

8.3 Discussion

In rectal temperature at exercise NEO and VEN were not statistically different while GOR was significantly different to the other two, remaining higher with steady increase. In skin temperatures there was a significant difference between all three, all gave an initial decrease however the permeable outers (VEN and GOR) behaved in a more desirable way retaining some heat and allowing a very slight increase over the temperature at rest even during exercise while the NEO temperatures reflect a decline and a final temperature below that of the base level. Throughout the ambient temperature remained at -5°C and the subjects were exercising and sweating and yet VEN and GOR retained and increased the skin temperatures whereas NEO's skin temperatures were lower latterly than at the start of exercise. This indicates that the retention of moisture due to the impermeable properties of NEO causes this decline in skin temperature despite exercise.

In mean body temperature NEO was found significantly different from VEN and GOR. Here VEN and GOR increasingly retained heat similarly levelling off during the last period whereas NEO was always lower and remained static however slight decline occurred in the last 2 recordings.

NEO shows the lowest values throughout and is significantly different from VEN and GOR, these being closely related throughout. This would indicate that this impermeable outer allows greater heat dissipation and the retention of moisture within the assembly causes the insulation and undergarments to become wet and thus less effective in maintaining warmth and comfort.

8.4 Comfort Analysis at Rest

The change in the subjects' comfort votes are recorded in TABLE 8.1. The decrease in skin temperature resulted in the subjects reporting feeling colder. In all cases the subjects experienced some level of discomfort at the end of each two hour period. One subject, HD in NEO at a skin temperature of 27.6^{O}C had to be rewarmed in a hot bath while the others only required hot drinks. The comfort votes offered whilst wearing NEO fell lower than those given whilst wearing GOR. The VEN garment was recorded as the most comfortable in all cases. The comments made by the subjects and subsequent observations proved to be a useful combination of analyses.

The NEO garment became very stiff, hard and gave an uncomfortable "feel". The stiffness and inflexibility resulted in an undesirable feature that manifested itself as being "crinkly and noisy". GOR also stiffened, but was not so hard and brittle as NEO. The VEN garment was least affected in terms of stiffness, hardness and other handle characteristics. It was observed that the body water vapour passing through GOR resulted in surface frosting on the outer fabric. This phenomenon may contribute to the degree of stiffness.

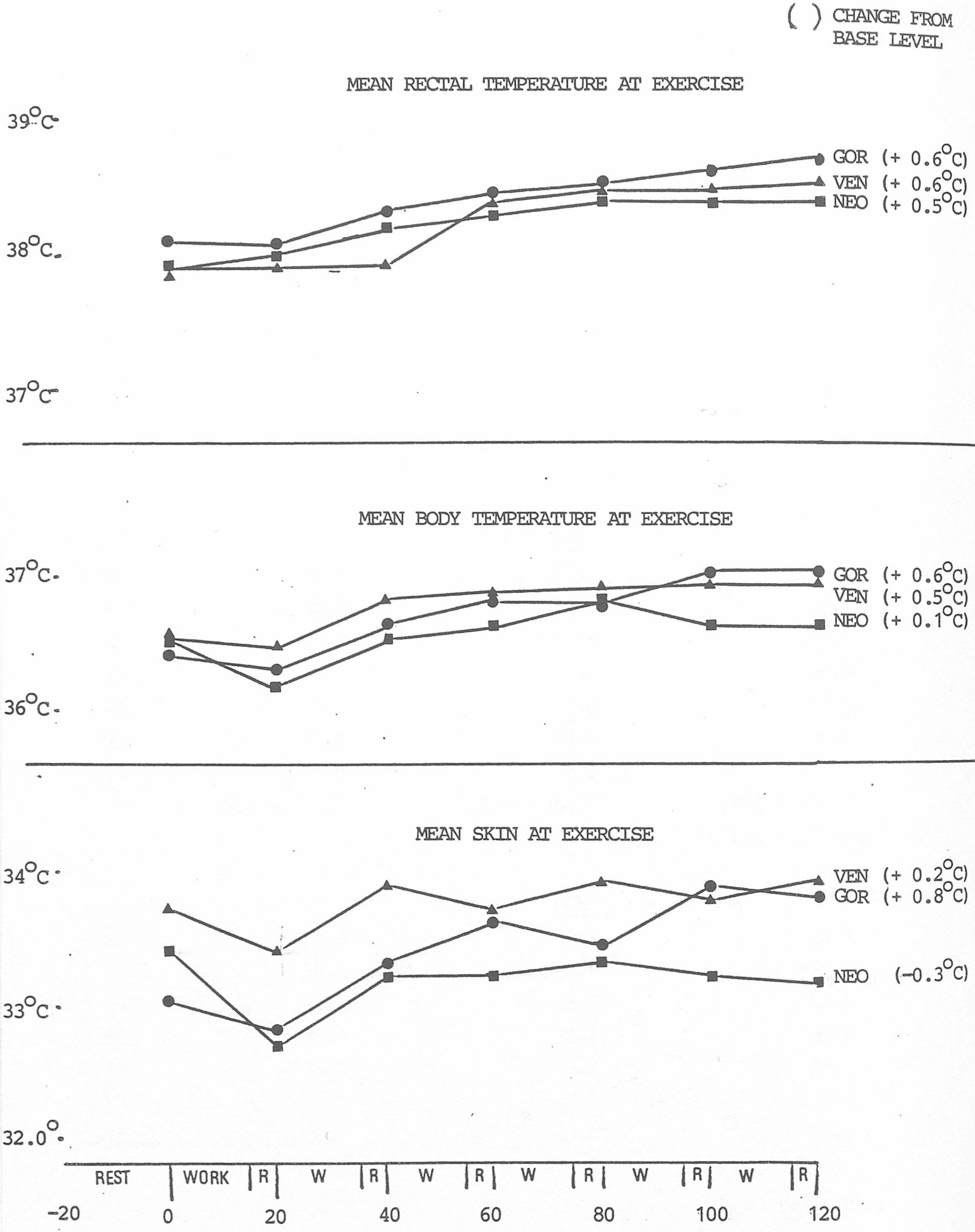
The subjects reported that the performance of NEO was less acceptable than the other garments, while VEN was reported as being the most acceptable. There is a correlation on this point between the subjects' feelings about stiffness in wear and the increase in stiffness at low temperature found during stiffness trials in the laboratory, where Bending length Flexural rigidity and the Bending modulus all showed increasing stiffness as temperatures decrease from 5^{O}C. NEO and GOR are relatively stiff in normal conditions. VEN, which is by nature a far softer fabric initially, showed a final bending modulus 14% greater than at 20^{O}C during laboratory trials and was found to be the most acceptable during wearer trials.

The most important aspect relating to acceptance was the fabric handle characteristics. The stiffening and increasing inflexibility demonstrated by the NEO garment classified it as the most unacceptable. The statistical analysis found no significant differences between thermal comfort votes whilst wearing the garments

TABLE 8.2 Readings in ^{O}C taken on 4 subjects wearing all 3 jackets at EXERCISE in an environmental chamber at approximately $-5^{O}C$.

TIME	MEAN RECTAL TEMP	MEAN SKIN TEMP	MEAN BODY TEMP
		NEO	
Rest	37.9	33.4	36.5
1 - 15	38.8	32.7	36.2
35	38.2	33.2	36.6
55	38.3	33.2	36.6
75	38.4	33.3	36.7
95	38.4	33.2	36.7
115	38.4	33.2	36.7
	ΔTre = $+0.5^{O}C$	ΔTsk = $-0.2^{O}C$	ΔMBT = $+0.2^{O}C$
			∴ΔS = 8.5kcal
		VEN	
Rest	37.9	33.7	36.5
1 - 15	38.00	33.4	36.4
35	38.00	33.9	36.8
55	38.40	33.7	36.9
75	38.5	33.9	36.9
95	38.5	33.8	36.9
115	38.5	33.9	37.0
	ΔTre = $+0.6^{O}C$	ΔTsk = $+0.2^{O}C$	ΔMBT = $+0.5^{O}C$
			∴ΔS = 27.8kcal
		GOR	
Rest	38.1	33.1	36.4
1 - 15	38.1	32.8	36.3
35	38.3	33.3	36.6
55	38.4	33.6	36.8
75	38.5	33.4	36.8
95	38.6	33.8	37.0
115	38.7	33.8	37.0
	ΔTre = $+0.6^{O}C$	ΔTsk = $+0.7^{O}C$	ΔMBT = $+0.6^{O}C$
			∴ΔS = 38.7kcal

FIGURE 8.5



MEAN RECTAL TEMPERATURE AT EXERCISE

MEAN BODY TEMPERATURE AT EXERCISE

MEAN SKIN AT EXERCISE

FIGURE 8.6

RECTAL TEMPERATURE AT EXERCISE

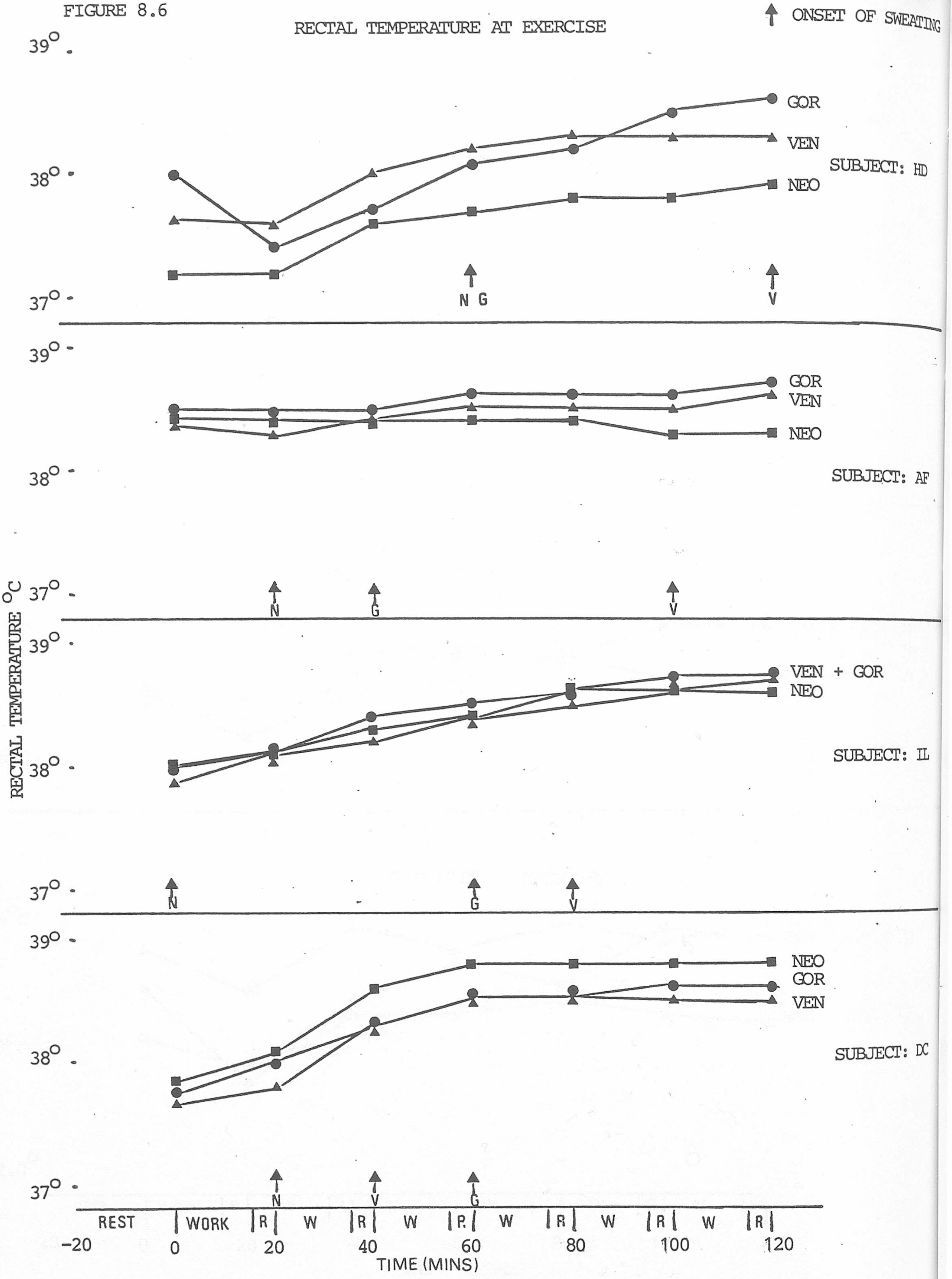
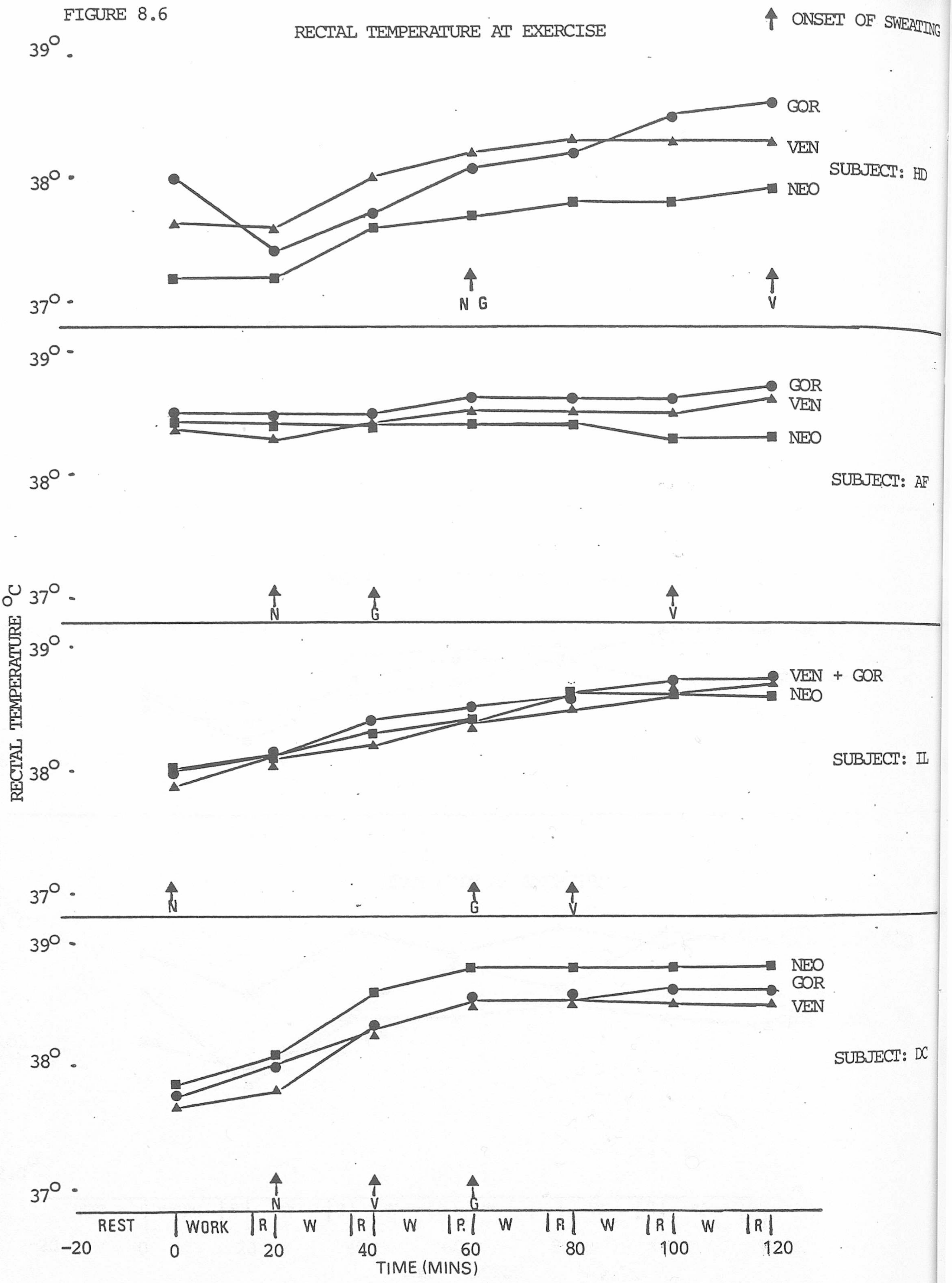


FIGURE 8.6


RECTAL TEMPERATURE AT EXERCISE
ONSET OF SWEATING
RECTAL TEMPERATURE °C
39°
38°
37°
GOR
VEN
NEO
SUBJECT: HD
N G
V
SUBJECT: AF
N
G
V
VEN + GOR
NEO
SUBJECT: IL
SUBJECT: DC
REST
WORK
R
W
-20
0
20
40
60
80
100
120
TIME (MINS)

during cold exposure at rest. This may be expected since the laboratory estimation of their insulation value showed all garment assemblies to have similar insulation properties.

The recorded temperatures and subjective feelings expressed showed that conditions of relative inactivity develop an increase in heat loss and possible development of hypothermia would only be prevented by the inclusion of additional thermal protection beyond that worn by the subjects in the wearer trials. An increase in activity and subsequent heat production may compensate for a lower level of insulation.

8.5 General Discussion

In both mean body temperature and mean skin temperature all jackets showed similar total heat loss at the end of the experimental period however NEO and VEN performed similarly, losing heat steadily, at an average rate of 54% of MBT total in the first hour and 46% in the second hour. Skin temperature results showed a similar performance losing an average of 69% in the first hour and 31% in the second hour. However in GOR 70% of the total heat loss in MBT occurred in the first hour and for mean skin temperature 94% was lost in the first hour. The experiments were not exhaustive enough to draw any firm conclusions but this trend indicates that more work is necessary.

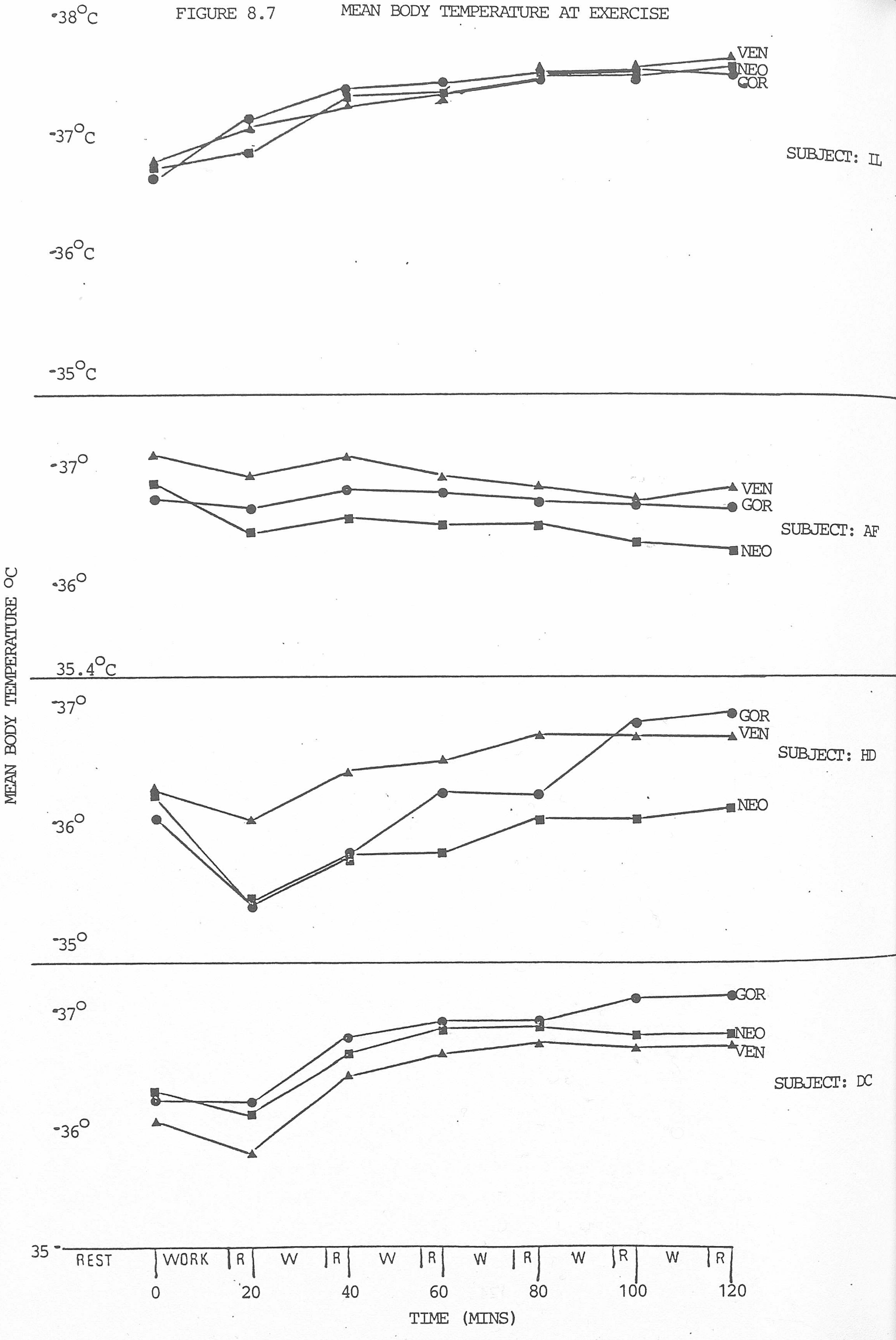
Both statistically and physiologically all the jackets, when worn at $-5^{o}C$ by inactive subjects, were classified as having similar properties, all uncomfortably cool. However the change in handle characteristics at low temperatures was the only discriminating factor in subjects choice.

8.6 Cold Chamber Wearer Trials at Exercise

8.6.1 Rectal Temperature at Exercise

The mean rectal temperatures and individual recorded rectal temperatures are shown in TABLE 8.2 and FIGURES 8.5, 8.6. The statistical analysis showed that GOR was significantly different to

FIGURE 8.7 MEAN BODY TEMPERATURE AT EXERCISE



the other two. In the first hour of exercise the rectal temperatures increased by 0.5 °C NEO, 0.4 °C VEN and 0.3 °C GOR however in the second hour the further increase was 0.1°C NEO, 0.1 °C VEN and 0.3 °C in GOR, GOR had allowed a further increase in temperature whereas NEO and VEN only increased slightly. The points where onset of sweating was detected are also shown in FIGURES 8.6 and 8.8. The subjects felt sweating to start in NEO before any of the other two, however no definite conclusions could be drawn from the onset of sweating at specific time periods or temperatures.

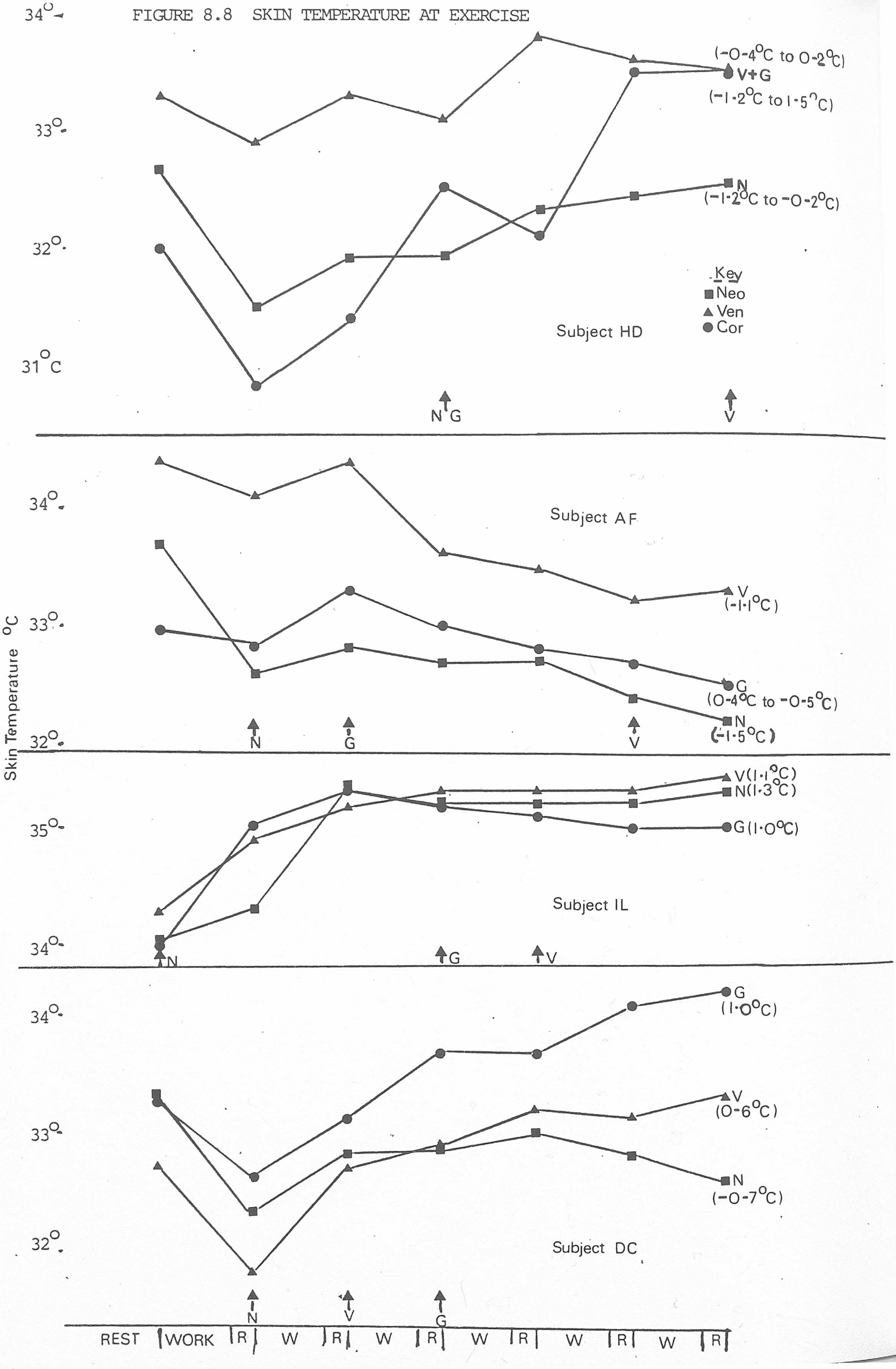
Rectal temperature is a direct function of the relative work load and with a 50% of VO_2 maximum work load the rectal temperature rise will be comparable. The increase in the rectal temperature is related to physical fitness, state of training and the evaporative heat loss as a result of sweating. A variation occurs between the subjects, IL is highly fit and a heavy sweater whereas HD although fit hardly sweated, and with such a small sample it is impossible to make a positive statement about the result found. However this small rise, +0.6°C, was within the acceptable level of core temperature at exercise, 38°C. (Reinberg et al 1980). The individual rectal temperature graphs shows DC expressing discomfort, sweating and yet reaching a high rectal temperature indicating no cooling from sweat and too high a maintained core temperature for comfort and thermal balance.

The mean rectal temperatures show VEN to have the highest increase from base level being 1°C greater at the finish of the experiment than NEO. GOR increased by 0.6°C above the base line and the rectal temperature increase was more regular over the two hour period than the other two. GOR gave a steadier performance throughoout.

8.6.2 Mean Body Temperature at Exercise

The calculated mean body temperatures and changes in mean body temperature at exercise are recorded in TABLE 8.2 and FIGURE 8.5 while individual mean body temperatures are shown in FIGURE 8.7. After the

FIGURE 8.8 SKIN TEMPERATURE AT EXERCISE



first period of exercise a decrease of 0.3 °C NEO, 0.1°C VEN and 0.10°C in GOR was observed compared with the rest temperatures outwith the chamber. An increase in the first hour of 0.10°C NEO, 0.4 °C VEN and 0.4 °C in GOR was recorded. By the end of the second hour NEO had increased by 0.1 °C, VEN by 0.1 °C and GOR by 0.2 °C. During this time period NEO showed an increase followed by a decrease while VEN showed a steady increase of 0.05°C per 20 minute period and GOR showed a decrease followed by gradual increases. The individual mean body temperatures revealed no significant trend.

The statistical analysis showed that NEO was significantly different to VEN and GOR. In TABLE 8.2 and FIGURE 8.5 VEN and GOR are similar giving little decrease during first period of exposure, whereas NEO fell 0.3 °C, a greater decrease. The initial decrease and the small temperature increase from base level show NEO to be inferior in establishment and maintenance of temperature.

8.6.3 Skin Temperature at Exercise

The mean skin temperatures at exercise are shown in TABLE 8.2 and FIGURE 8.5. The individual skin temperatures with the points where onset of sweating was noted are shown in FIGURE 8.8. In 3 cases out of 4 the subjects experienced decrease in skin temperature from the previous temperatures recorded outwith the chamber in the first 20 minutes of exercise. The mean skin temperatures revealed this fall to be -0.7°C NEO, -0.3°C VEN and -0.3 °C GOR, an increase showed during the next time period and after the first hour +0.5°C NEO, +0.3°C VEN and +0.8°C GOR had occurred. During the next hour of exercise NEO had decreased by -0.05°C whereas VEN and GOR had increased by 0.2°C. When relating the change in skin temperature from the resting temperature prior to exercise to the temperatures at the end of the experiments the following occurred, -0.2 °C NEO, +0.2°C VEN and +0.7 °C GOR. This reflects the statistical analysis which showed significance between all three outers in relation to skin temperature. In all cases except

TABLE 8.3 Body Weight Loss After 2 Hours Exercise

	NEO	VEN	GOR
HD	230	310	340
AAF	800	630	700
IL	1140	1390	1360
DC	760	480	630
TOTAL	2930g	2810g	3030g

TABLE 8.4 Body Weight Loss Other Than Absorbed Into Clothing

	NEO	VEN	GOR
HD	166	246	282
AAF	500	316	348
IL	529	836	786
DC	468	358	474
TOTAL	1663g	1756g	1890g

TABLE 8.5 Total Increase In Weight Of Clothing Assembly After Exercise

	NEO	VEN	GOR
HD	64	64	58
AAF	300	314	182
IL	611	758	574
DC	292	168	156
TOTAL	1267g	1304g	970g

TABLE 8.6 Increase In Weight Of Lower Garments (Below Waist)

	NEO	VEN	GOR
HD	14	20	24
AAF	64	69	66
IL	155	204	174
DC	78	42	58
TOTAL	311g	335g	332g

after the first 20 minute period in NEO the skin temperatures were within the 33°C-34°C band indicating thermal balance. The action of evaporation of sweat has the effect of lowering skin temperature and during physical work people prefer conditions which demand some sweating (Fanger 1970). The fact that NEO showed a lower skin temperature may have been the sweat condensing and lowering skin temperature. The initiation of sweating and the feeling of wetness of the skin do not occur simultaneously and so on FIGURE 8.8 the onset of sweating points are when the subjects were conscious of the wetness. In most cases this occurred in NEO well before GOR and VEN. This fall in skin temperature in NEO to below that of base level was not detected when rectal temperature was examined. This substantiates work done by Ebaugh and Thauser (1950) Gagge et al (1967) and Light (1980) where they stated that evidence concerning skin sensitivity to heat or cold was independent of core temperature. In physiological terms the span of 1°C between the jackets is minor however in terms of thermal comfort the subjects' opinion is a better indicator than his skin temperature.

8.7 Uptake of Moisture by Clothing

The individual component parts of the complete clothing assembly were weighed before and after the exercise trials and the results are shown in TABLES 8.3 to 8.9.

TABLE 8.3 shows that body weight loss after 2 hours exercise was similar in all three cases, so this can be categorised as contant.

TABLE 8.4 shows the total increase in weight of the total assembly after exercise. Examination of this table shows that VEN held 3% more than NEO, whereas GOR held 34% less water than the other two. If the vapour/liquid is not held within the clothing, then it must be assumed to have passed through. The GOR assembly thus appears to be 34% more effective than the other two.

TABLE 8.6 shows the total increase in weight of the clothing assembly

TABLE 8.7 Increase In Weight Of Vest Jacket & Jumper After Exercise (Above Waist)

	NEO	VEN	GOR
HD	50	44	34
AAF	236	245	116
IL	456	554	400
DC	214	126	98
TOTAL	956*g	969g	648g

TABLE 8.8 Increase In Weight of Vest & Jumper Only After Exercise

	NEO	VEN	GOR
HD	8	12	8
AAF	78	102	52
IL	224	326	268
DC	78	42	48
TOTAL	388*g	482g	376g

TABLE 8.9 Increase In Weight of Jacket Only After Exercise

	NEO	VEN	GOR
HD	42	32	26
AAF	158	143	64
IL	232	228	132
DC	136	84	50
TOTAL	568*g	487g	272g

* - plus sweat on floor

Others as explained in TABLE 8.10

In the above TABLES, all weights are expressed in grams.

for the lower part of the body. As the garments worn were identical in all experiments, then this constant weight increase could be assumed, allowing this area to remain a constant and to be excluded from further discussion.

TABLE 8.7 shows the increase in weight of the assembly on the upper part of the body. NEO and VEN have very close readings, although in the case of NEO, liquid sweat dropped on to the floor after exercise and thus the weights recorded should have been higher. This must be accepted as experimental error. No heavy sweating, and thus no liquid perspiration loss, was observed with either VEN or GOR. The readings recorded for NEO and VEN were high, showing a high holding capacity in those assemblies. GOR held 50% less moisture than the other two, thus indicating the superior moisture transfer property of GOR.

TABLE 8.8 shows a further breakdown of the upper body assembly recordings to give details of the increase in vest and jumper weights. The readings of the moisture vapour/liquid holding capacity of the undergarments is affected by the performance capabilities of the outer part of the assembly.

GOR is shown as having 28% less weight gain than VEN. Because of the inability to quantify the amount of liquid sweat dropped on to the floor, it is not possible to make such a comparison with NEO, but it seems reasonable to assume that there would be, at minimum, such a difference as that mentioned above. Although this was observed and noted, the investigation continued to examine the performance of the jacket alone.

TABLE 8.9 shows that GOR performed well, being 79% better than VEN and 108% better than NEO. This figure would have been higher if it had been possible to quantify the amount of sweat on the floor. It is thus difficult to make a positive statement about the performance of NEO, except that its assembly showed the highest build-up of moisture of the three on trial.

TABLE 8.10

	ΔBWg	Up Clg	Substrate g	Vent g	SA m^2
NEO					
HD	230	64	81	68	1.87
AAF	800	300	114	142	1.96
IL	1140	611	186	144	2.05
DC	760	292	142	144	1.81
VEN					
HD	310	64	93	83	1.87
AAF	630	314	128	148	1.96
IL	1390	758	185	179	2.05
DC	480	168	92	146	1.81
GOR					
HD	340	58	84	79	1.87
AAF	700	182	113	137	1.96
IL	1360	574	160	142	2.05
DC	630	156	128	119	1.81

KEY

NEO - Neoprene
VEN - Ventile
GOR - 'Goretex'
ΔBWg - Change in body weight in grams
Up Clg - Uptake of clothing in grams
Substrate g - Substrate
Vent g - Ventilation in grams
SA m^2 - Surface area of subject's body in square metres
HD)
AAF)
IL) - Initials used to identify subjects
DC)

TABLE 8.11 Moisture Vapour/Liquid Transfer Through Assembly In gm

	NEO	VEN	GOR
HD	6.06	24.95	42.42
AAF	82.57	13.61	91.62
IL	64.40	87.15	157.40
DC	67.03	27.41	83.38
TOTAL	220.06*	153.12	374.82 $g/m^2/hr$
MEAN	55.01*	38.26	97.70 $g/m^2/hr$

* plus liquid sweat dripping on floor after 2nd reading.

KEY

As in TABLE 8.10

TABLE 8.12 Change in Comfort Votes At Exercise

	NEO	VEN	GOR
HD	4 6 (+2)	6 – 6 (0)	5 6 (+1)
AF	4 5 (+1)	6 5 (-1)	5 6 (+1)
IL	4 7 (+3)	4 5 (+1)	6 5 (-1)
DC	4 6 (+2)	4 5 (+1)	4 6 (+2)
	(+8)	(+1)	(+3)

In the laboratory tests on the fabrics alone, the moisture vapour transmission rate of dry ventile type fabric was 98% better than when the same fabric was wet. This was due to the wetting of the fabric gradually inhibiting any moisture vapour transmission. There is a definite correlation between the laboratory trials and the performance in wear. GOR performed in a highly superior manner in both circumstances, being 141% better than wet VEN in bench trials, and 79% better in wearer trials. The wearer trials started with the VEN dry, but as sweating built up, it became wet, moisture vapour transfer became inhibited, as in the bench trial, and the moisture vapour transmission performance deteriorated. It is observed that the trends found in the laboratory are substantiated in parallel in the wearer trials, and therefore, when investigating the functional performance of a clothing performance, elaborate physiological wearer trials are not essential.

8.8 Moisture Vapour/Liquid Transmission

Using traditional physiological experimental methods already described, TABLE 8.10 was collated, and using the formula devised (page 84), the following conclusions were derived TABLE 8.11. The rate of moisture vapour/liquid transmission through 'Goretex' is excellent, being 145% better than the ventile type. The calculation for 'Neoprene' must be classified as experimental error, as the moisture vapour/liquid lost was observed to be dripping as liquid sweat on to the floor, therefore not passing through the outer fabric. Although it was impossible to quantify the amount so lost, it can be reasonably assumed that a large proportion of the 220g/m^2/hr can be accounted for as lost in this manner. A close correlation between the figures for 'Goretex' and ventile type when wet, in the bench trials in the laboratory and in the physiological trials was noted. TABLE 8.11 shows the 'Goretex' is 145% better than the ventile type, and TABLE 7.10 showed 'Goretex' as being 141% better than wet ventile. In the bench trial, 'Neoprene' showed virtually no moisture vapour/liquid transmission, and the reason that the liquid sweat dropped on the floor was because the impermeable nature of the material did not allow it to pass through the outer fabric. As a result, excessive wetting of the insulation would occur, giving a lower insulation value and causing an uncomfortable feel for the wearer. The close correlation of performance between the bench and physiological trials means that if fabric performance is to be examined, then the more elaborate physiological trials can be eliminated.

8.9 Comfort Analysis at Exercise

TABLE 8.12 shows the change in comfort votes recorded during exercise at -5°C.

In all cases, NEO was described as being 'noisy', although not as hard as during the tests conducted at rest. Both VEN and GOR were classified as being 'comfortably warm' (5). NEO showed the greatest increase in warmth, becoming 'too warm' (6), or 'much too warm' (7). VEN had only one comment of 'stickiness' and was classified as 'very comfortable' throughout. GOR seemed to allow sweating without any feeling of discomfort, the slight stiffness being the only undesirable feature.

NEO seemed to intensify sweating. It was observed in two cases that sweat was dripping on to the floor. Even the low sweating subject (HD) was sweating and felt clammy. In all cases, when wearing NEO, the subjects were too warm, very sweaty and uncomfortable. If this sweating continued and collected on the skin the sweat rate would decrease despite rising skin and core temperatures. This condition, hidromeiosis, could lead to heat stress and so removal of water from the skin is essential to eliminate heat stress (Kerslake 1972). This indicates that an impermeable outer could cause heat stress and is certainly unacceptable for wear during work involving continuous physical activity. As stated previously Fanger (1970) indicated that the subjects opinion was a better method of analysis of thermal comfort than was the monitoring of skin temperatures. NEO was disliked the most and VEN and GOR were equally approved of. This correlates with the findings after statistical analysis.

8.10 Final Selection of Jacket

The laboratory tests and wearer trials have allowed functional performance to be investigated and various conclusions drawn. However additional criteria have to be taken into consideration prior to manufacture. The cost per unit and final retail price is one of the main considerations included in the final analysis. The aspects of manufacture which contribute towards this final price are design development, ease of handling incorporating number and complexity of operations and marketing costs.

The design development and marketing costs would be similar whatever outer was used and therefore can be excluded from this analysis. The manufacturing operations are however partially influenced by the outer to be used. Both NEO and GOR are rather stiff to handle, needle damage occurred, great accuracy and longer time is required in machining, and all seams require to be taped thus the standard time and therefore cost per unit will be greater than VEN. The seams in VEN are not easy to tape and while this operation is excluded the garment cannot be classified as "waterproof". However with clever placement of seams the garment will perform well in wet conditions.

The cost per metre is also highly relevent in this analysis and GOR was by far the most expensive outer used. The fabric marketing costs in both VEN and GOR must be higher than with NEO as this is the traditionally accepted waterproof fabric. These costs are certainly greater with GOR than VEN as intensive marketing is done to promote this fabric. These promotion costs will raise the final cost price making GOR double the cost per metre of NEO and VEN. Should the performance of any fabric prove to be highly superior to any other then good performance will outweigh high constructional costs and provide an upmarket high performance garment. The conclusions drawn from the laboratory tests and wearer trials indicated that NEO was the least acceptable of the three outers tested. Its performance as far as moisture vapour transfer, uptake of moisture, drying time and unacceptability as far as comfort was concerned eliminated it as a desirable outer for cold, wet conditions. The fact that this fabric is still in common usage as waterproof clothing would indicate that manufacturers are ignorant of its disadvantages in wear or unknowledgable about alternatives.

The performance of both VEN and GOR was similar for drying out time and comfort; both being classified as highly acceptable and comfortable, VEN being only slightly superior to GOR. However GOR was highly superior to VEN in both the uptake of moisture and moisture vapour transfer tests and so GOR would be classified as the best in performance for active leisure wear for cold, wet conditions.

The inclusion of cost allows the VEN garment to gain ground in the analysis and the conclusion would be that GOR is superior at a much higher cost per unit. If price is not a consideration then GOR could be chosen; however, VEN is a much cheaper alternative.

8.11 Discussion on Wearer Trials

The difficulties relating to wearer trials in the laboratory are numerous thus indicating that alternative methods of analysis are desirable.

The fact that skin temperatures are of vital importance to man in his appreciation of thermal stress and that core temperature is not an instant indicator of these sensations seem to indicate the elimination of rectal monitoring. However this is not desirable as core temperature is the accepted method of monitoring subjects clinically during stress trials. The length of physiological trials, 2 hours being the longest anyone could work at 50% VO_2 maximum, was a limiting factor in any analysis.

If hidromeiosis did occur in NEO at exercise, 2 hours was too short a period for this to be monitored. The same will occur when examining for heat stress and hypothermia. These trials only indicate trends as the period of exposure was too short to give positive conclusions. These indications of suitability will allow informed projections to be made for performance over a longer time span.

The other limitation to this study was the small sample size, this indicating the practical difficulties of conducting research of this type. The physiological variations between individuals, due to the varying degrees of physical fitness amongst the participants, combined with the small sample size, tended to give results which masked the difference in performance of the jackets. This small sample can only be regarded as a pilot study and a positive conclusion cannot be drawn.

The problems encountered in running all physiological trials are numerous particularly in regard to studying enough people to allow the sample size to be large enough to be representative of the population. The subjects should be of the same sex, age and standard of fitness and this restricts choice and number of volunteers available. These tests had to be conducted for many weeks as consecutive days, trials were not possible due to exhaustion and over-exposure. In a civilian situation the subjects must be volunteers and/or receive payment. Inhospitable climatic conditions and the use of a rectal probe can deter many subjects. One experiment with each subject takes at least 3.1/2 hours and therefore any project is both expensive and time consuming. The apparatus and climatic chamber is expensive to acquire and running costs are high. Highly qualified medical staff are necessary during trials and at least 2 workers must be present throughout to carry out accurate weighing and analysis even when a computer programme is used. When any subjective assessment takes place, eg. comfort votes, inbuilt prejudice and personal attiudes are difficult to classify as reliable at all times. In this instance the fact in the sample we had a range of "sweating" and "low sweating" participants giving different quantities of moisture vapour within the assemblies demonstrates the large variation between individuals. This limited study showed that Mecheels (1981) statement that wearer trials were too expensive for clothing development and should be replaced by simpler cheaper systems of analysis was correct. However it remains true that the ultimate test is performance in wear and the reaction of the subject to the garment.

The close correlation between fabric performance in the laboratory and the physiological wearer trials would indicate that expensive time-consuming trials may not be necessary as a means of analysis. The method of monitoring moisture vapour transfer through the assemblies was highly successful on the permeable outers, however the fact that sweat dripped on the floor during the wearing of NEO caused an experimental error. The moisture transfer experiments would have been improved if the experiments could have been extended and perhaps a positive conclusion could have been achieved. The indications are that a user field trial over a longer time span would give adequate subjective analysis adequate to project customer reaction. Teamed with fabric laboratory performance trials this method of analysis would be adequate for the manufacturer and retailers needs. A longer time span and larger sample size would be necessary when objectively investigating physiological reactions to novel clothing assemblies.

It is obvious that more work needs to be done to understand insulation and moisture transfer systems within different clothing assemblies in varying environmental conditions.

The objective of the present study has been achieved, namely 1) to show links between objective laboratory measurements on fabrics with performance in wearer trials and 2) to examine the performance of outers, permeable and impermeable to the passage of moisture vapour, and the subsequent effect on both objective and subjective feelings of comfort.

Extensive physiological measurements of heat loss, skin temperature etc were not very informative within the timescale of these experiments and the weighing of clothes before and after the experiment was an adequate indicator of the outers performance. This, teamed with well designed questionnaires during the field trial would give enough information to assess the garment's performance. The way is open for designers to examine the performance level of the component parts of the clothing assembly in relation to optimum functionality, without recourse to time-consuming and expensive physiological testing. Perhaps Mecheels (1981) quantitative comfort calculations could also be employed in this area.

From the study, the following criteria were found to be desirable in clothing for cold conditions of high activity.

Sustained fabric handle in cold.
Permeabiity to moisture vapour.
Good washability and drying rates.
Aesthetic appeal and good fit.
Commercially viable garment giving good continued performance.

8.12 Summary of Conclusions

The investigations which have been carried out permit a number of conclusions and observations to be made.

a) A definite correlation was found to exist between fabric performance in laboratory conditions and the performance of the corresponding garments during wearer trials.

b) The analysis made by individual subjects of their thermal comfort at any time during an experiment is closely related to actual conditions of skin temperature and skin wetness.

c) Fabric handle, i.e. the immediate subjective analysis made by a subject of how a fabric feels to the touch, its sound when moved and its flexibility when worn, has a positive but not necessarily beneficial effect on an individuals' assessment of the implied comfort of an article of clothing.

d) If physiological testing is to be used as a means of monitoring garment performance, then the use of a large number of subjects is required in order that the reactions of as large a spectrum of physical, physiological and psychological types as possible, can be obtained. It is also advisable that the experiments be carried out over as long a time-span as possible. It is essential that a statistician be involved as a member of the monitoring team at the design stage of the experiments.

e) Physiological trials, which by their very nature are extremely expensive and time-consuming could possibly be replaced by a combination of laboratory testing of fabric properties together with wearer trials carried out in the field by experimental evaluators, suitably briefed and trained in this type of experimental technique, reinforced and monitored by the use of well-designed questionnaires.

f) The study has shown that further investigations are necessary and essential on the qualities of drape, stiffness and fabric handle in relation to clothing comfort in wear. The properties involved in moisture vapour transfer between the component parts of different types of a clothing assembly requires examination in greater depth.

REFERENCES

ABBAS, MSE & BURNIP, MS (1981). The production and properties of sliver-knitted fabrics. 65th Textile Inst. Annual Conference, York.

ANGUS, T C (1935). The heat retaining properties of clothing computed on a physiological basis. J. Textile Inst. 26, 83-86.

ALON, G & POURYAN A (1981). Knitted garments in relation to the energy crisis. Knitting International 2, 85-88.

ASTRAND, P & RODELL, K (1966). Textbook of Work Physiology.

A.S.H.R.A.E. (1972). Handbook of Fundamentals, New York.

BEDFORD, T (1936). The warmth factor in comfort at work. Industrial Health Research Report No.76 HMSO.

BLACK, C P & MATTHEW, J A (1934). Physical properties of fabrics in relation to clothing. J. Textile Inst. 25, 197-224.

BLACKMAN, W I (1930). Clothing - heat retaining power. Bull. Hygiene 5, 663.

BOOTH, J E (1968). Principles of Textile Testing, Heywood, London.

BRECKENRIDGE, J R & WOODCOCK, A H (1950). Effects of wind on insulation of Arctic Clothing. Environmental Protection Section, Quartermaster Climatic Research Laboratory; Report No.164.

BROOK, D B & KEIGHLEY, J H (1980). The application of pile fabric in outdoor clothing. Clothing Research J. 8,3, 193-144.

BSI HANDBOOK (1974). 11 Methods of test for textiles. British Standards Institution.

BURNIP, M S & ABBAS, M E S (1975). Production and properties of sliver-knit fabrics. Proceedings Int. Wool Text. Research Conference, Aachen.

BURTON, A C & EDHOLM, O G (1955). Man in a Cold Environment. London. Edward Arnold.

CARLSON, L D & HSIEH, A C L (1965). Cold, In The Physiology of Human

Survival, Ed. Edholm, O G & Bacharach A L. pp.15-51. London, Academic Press.

CARLSON, L D & HSIEH A C L (1974). Temperature and Humidity in Environmental Physiology, ed. Slonim N B. pp.61-118. St Louis, Mosby Co.

CARROLL D P & VISSER J (1966). Director measurement of convective heat loss from the human subject. Rev. Sc. Inst. 37, pp. 565-591.

CASSIE (1962). J. Text. Inst. 53, 739.

CLARK, R P, GOFF, M R & MULLAN, B J (1977). Heat loss studies beneath hovering helicopters. J. Physiol. 267, 6-7P.

CLULOW, E E (1974). Permeability and Textiles. Textiles 1-4 19-27

CLULOW, E E & REES, W H (1968). The transmission of heat through textile fabrics Part III. A new thermal - transmission apparatus. J.Text.Inst.59, 285-294.

COOK, K B (1942). Warmth and wearing qualities of spun rayon and wool blended fabrics. Text. World 92, No.9. 113-114.

COOPER, (1981). Textiles as protection against extreme wintry weather. Textiles 8, 72-83.

COULIER, P J (1858). Hygiene du Soldat. Experiences sur les Etoffes gui servant a confectionner les Vetements du Soldat, Comp. Rend. Acad. Sc. 45, 1002.

DAVID, H G & REDDIE, R N (1965). Some observations on the regain of "All-Wool" suits. Tex.Res. J. 35, 956-957.

Du BOIS, D & Du BOIS, E (1916). Clinical calorimetry: A formula to estimate the approximate surface area if height and weight be known. Archs intern. Med. 17, 863-871.

EDHOLM, O G (1978). Man - Hot and Cold. Camelot Press. No.97.

ERIKSON, H, KROG, J, ANDERSON, K L & SCHOLANDER, P F, (1956). Critical temperature in naked man. Acta physiol. scand. 37, 35-39.

FAHMY, S M A & SLATER, K (1976). A New apparatus to measure the resistance of textiles to water-vapour diffusion. J.Tex. Inst.67, 273-276.

FALCONER, S M & keighley, J H (1981). The Study of Clothing Comfort Factors in Cold Conditions. Sheffield Research Conference, 1981.

FANGER, P O (1970). Thermal Comfort. McGraw-Hill.

FANGER, P O (1970). Conditions of thermal comfort: introduction of a general comfort equation. In Physiological and Behavioural Temperature Regulation, ed. Hardy, J D, Gagge, A P & Stolwijk, J A J, pp.152-176. Springfield, Illinois: Thomas.

FANGER, P O (1973). Assessment of man's thermal comfort in practice. Brt. J. of Ind. Med. 30, 313-324.

FROESE, G & BURTON, A C (1957). Heat losses from the human head. J. Appl. Physiol. 10, 235-241.

FOURT et al (1951). Tex. Res. J. 21, 26.

FOURT, L & HOLLIES, N R S (1970). Clothing comfort and function. Fiber Science. M Dekker In. New York.

GAGGE, A P, BURTON, A C & BAZETT, H C (1941). A practical system of units for the descriptions of the heat exchange of man with his environment. Science, 94, 428-430.

GAGGE, A P, STOLWIJK, J A J & HARDY, J D (1967). Comfort and thermal sensations and associated responses at various ambient temperatures. Environ.Res. 1, 1-20.

GOLDMAN, R F, BRECKENRIDGE, B S, REEVES, E & BECKMAN, E L (1966). "Wet" versus "dry" suit approaches to water immersion protective clothing. Aerospace Med. 37, 348-357.

GOLDMAN, R F (1977). Establishment of the Boundaries to Comfort by analysing Discomfort. National Bureau of Standards Washington D.C. Feb.

GOLDEN, F.St.C. (1976). Hypothermia: A Problem for North Sea Industries. J.Soc.Occup.Med. 26, 85-88.

GIBSON, M G (1980), Repeated Measurements Experiments - Some models and analysis. MSc Thesis University of Dundee.

GILLING, D R, DICKENS T L, SAMUEL, G D, Physiological Evaluation of an experimental Poromeric Waterproof Fabric in Cold/Wet Conditions. APRE Report 1/77.

HAVEN, G B (1918). Bureau of Standard Misc Publications, No.19.

HALL (1930). PhD University of Leeds.

HAUSER, E R (1980). A survey of possible approaches to garment warmth evaluation.

HEPWORTH, B & LEAF, G A V, (1976). Studies in modern fabrics. Ed. P W Harrison. Textile Institute, Manchester.

HERVEY, G R (1973). Physiological changes encountered in hypothermia. Proc. R. Soc. Med. 66, 1053-1057.

HOLLIES, N R S & GOLDMAN, R F (1977). Clothing comfort. Ann Arbor Science Pub. Ann Arbor Mich.

HOLLIES, N R S, CUSTER A G, MORIN C J, HOWARD M E, (1979). A human perception approach to clothing comfort. Tex. Res. J. 10, 557-564.

HORVATH, S M, SPURR, B G, HUTT, B K and HAMILTON, L H (1956). Metabolic cost of shivering. J. Appl. Physiol. 8, 595-602.

JAKSIC, D (1975). The method of calculation of the effect of wind on the total thermal resistance of clothing. J. Text. inst. 3, 129-133.

KASWELL, BARISH & LAMOND (1961). J. Text. Inst. 52, 508.

KEATINGE, W R (1969). Survival in cold water. Oxford, Blackwell.

KEATINGE, W R, HAYWARD, M G & McIVER, N K I (1980). Hypothermia during saturation diving in the North Sea. Br. Med. J. i, 291.

KEIGHLEY, J H (1980). A comparison of the properties and performance in use of a number of mountain rescue bags. Clothing Research Journal 8, 46-56.

KERSLAKE, D, McK (1972). Physiological aspects of comfort. University Press Cambridge, Cambridge.

KERSLAKE, D, McK (1982). Effects of climate, Body at Work ed Singleton W T, Cambridge University Press, Cambridge.

KRUGER, D (1936). The warmth retaining properties of textile fabrics. Klepzig Text 2, 39, 593-5.

LAROSE, P (1947). The effect of wind on the thermal resistance of clothing with special reference to the protection given by coverall fabrics of various permeabilities. Can. J. Res. 25, 169-190.

LATHAM, B J (1969). The structure of shirting fabrics and shirts in relation to comfort in wear. MPhil Thesis University of Leeds.

LEBLANC, J (1975). Man in the cold. Charles Thomas Springfield Ill.

LIGHT, I M (1980). Prevention and Management of cold exposure in remote locations. PhD Thesis University of Aberdeen.

McKIE, N (1978). Physiological requirements for foul weather clothing. Textiles in the Oil Industry. Shirley Inst. Publ. S32. 1-11.

McINTYRE, D A & GOZALEZ, R R (1976) Man's thermal sensitivity during temperature changes at two levels of clothing insulation and activity. ASHRAE Transactions. 82, 2, 219-247.

McINTYRE, D A (1980). Indoor Climate. Applied Science Pub. London.

McINTYRE, D A (1978), Seven Scales of Warmth. Building Services Engineer, 45, 12, 215-226.

MACPHERSON, R K (1958). Acclimatization status of temperate zone man. Nature Land 182, 1240-1241.

MARCUS, P, ROBERTSON, D & LANGFORD, R (1977). Metalised plastic Sheeting for use in Survival. Aviat. Spac. Envitn. Mod. 48, 50-52.

MARSH, M C (1931). Thermal insulating properties of textile fabrics. J. Text. Inst. 22, 245-73.

MECHEELS, O (1938). Clothing fabrics - insulating power. Mellian Textilber, 19, 422-424.

MECHEELS, J (1971). The measurement of the functional effect of clothing on the Human body. Melliand 52, 7, 843-849, 8, 967-974, 10, 1215-1221.

MECHEELS, J (1981). Laboratory development of clothing systems using quantitative comfort calculations. Design for Survival. WIRA Leeds.

MECHEELS, J, IMBACH, K H (1977). Thermo physiological properties of clothing systems. Melliand Textilberichte 57, 1029-1032.

MEHTA, P N (1984). The requirements of moisture transport in underwear. Part III Wool Sc. Review 60, 23-46.

MONCRIEFF, R W (1967). The Chemical Senses. International Textbook Co. London (2nd ed).

MORRIS, G J (1953). Thermal properties of textile materials. J. Text. Inst. 44, 449-476.

MORTON, W E, HEARLE, J W S (1975). Physical properties of textile fibres. Man-Made Textiles 40, Nov. 75. Heinemann for Textile Inst. London.

MUNDEN, D L (1959). The geometry and dimensional properties of plain-knit fabrics. J.Tex.Inst. 50, T448-T471.

MUNDEN, D L (1962). Specification of construction of knitted fabrics. J.Tex.Inst. 53, 628-630.

NAKA, S & KAMATA, Y (1976). Thermal conductivity of wet fabrics. J.Tex.Machinery Soc. Japan 29, 7, 100-106.

NEILSEN, B & NEILSEN M (1965). On the regulation of sweat secretion in exercise. Acta Physiologica Scandinavia 64, 314-22.

NISHI, Y, GONZALEZ, R, NIVENS, R & GAGGE, A P (1976). Moisture penetration of clothing - a factor governing thermal equilibrium and comfort. ASHRE 76, (1), 137-45.

NISHI, Y & GAGGE, A P (1970). Field measurement of clothing thermal insulation. ASHRE Tranbslations 82, 2, 2418.

NIVEN, C D & BABBITT J D (1938). Heat transmission of textile fabrics. J. Text. Inst. 29, 161-72.

O'CALLAGHAN, P W & PROBERT, S D (1976), Thermal insulation provided by dry, single layer clothing materials. Applied Energy 2, 269-277.

O'CALLAGHAN, P W & PROBERT, S D (1977). Thermal resistance behaviour of single and multiple layers of clothing fabrics under mechanical load. Applied Energy 3, 3-12.

O'CALLAGHAN, P W & PROBERT, S D (1976). Thermal insulation properties of clothing fabrics. Building Services Engineer 44, 4 61-70.

OPEN UNIVERSITY (1979). System Behaviour ed. Beishon, J & Peters G. Open Univ. Press. 245-253.

PARKES, E A (1864). A Manual of Practical Hygiene for Use in the Medical Services of the Army, London.

PIERCE, F T & REES, W H (1946). The transmission of heat through textiles fabrics. J.Text.Inst. 37, Part II 181-204.

PIERCE, F T (1930). The handle of cloth as a measurable quantity.

PONTRELLI, G J (1977). Cloth Comfort Du Pont Research Report.

PUGH, L G C E (1966). Clothing insulation and accidental hypothermia in youth. Nature, 209, 1281-1285.

PUGH, L G C E (1969). Thermal, metabolic, blood and circulatory adjustments in prolonged outdoor exercise. Br.Med.J. 2, 657-662.

REES, W H (1946) J.Text.Inst. 37, 132.

REES, W H (1964). Lightweight warmth. Textile Institute & Industry, 2, 29-31.

REES, W H & OGDEN L W, (1947). Some observations upon the effect of colour on the absorption and emission of radiation by a textile fabric. J. Text. Inst. 37, 4, T113-120.

REISCHL, U & STANSKY, A (1980). Vapour barriers in a Firefighter Turn-out coat. Textile Research J. 11, 643-647.

REINBERG, A, et al. (1980). Oral temperature, ageing and tolerance to shiftwork. Ergonomics, 23, 55-64.

RENBOURNE, E T (1972). Materials and clothing in health and disease. London H K Lewis.

RODAHL, K (1952). Basal metabolism of the Eskimo. J. Nutr. 48, 359-368.

ROHLES, F H (1974). The measurement and prediction of thermal comfort. ASHRAE Trans. 98-113.

RUBNER, M (1907). Lehrbuch der Hygiene Leipzig.

SCHOLANDER, P F (1955). Evolution of climatic adaptation in homeotherms. Evolution, 9, 15-20.

SEPPEMAN, O, McNALL, P E, MUNSON, O M & SPRAGUE, C H (1972). Thermal Insulating Values for Typical Clothing Ensembles ASHRAE Trans. 78, 120-130.

SINGLETON, W T (Ed) (1982). The body at work, biological ergonomics. Cambridge University Press.

SIPLE, P A & PASSEL, C F (1945). Dry atmospheric cooling in sub-freezing temperatures. Proc.Am.Phil.Soc. 89, 177-179.

SMITHSON, P A & BALDWIN, H (1978). Windchill - A climatic hazard on the hills. Climber and Rambler, 10, 24-26.

SMITH, F M (1976). Survival at sea. MRC Report.

SPENCER-SMITH, J L (1976). The physical basis of clothing comfort.

Part 1. General Review. Clothing Reseach Journal 4, (3) 126-138.

Part 2. Heat transfer through dry clothing assemblies. Clothing Research Journal, 5,(1) 3-17.

Part 3. Water vapour transfer through dry clothing assemblies. 5, 82-100.

Part 4. The passage of heat and water through damp clothing assemblies. Clothing Research Journal 5, (3) 116-128.

Part 5. The behaviour of clothing in transient conditions. Clothing Research Journal 6, (1) 21-30.

Part 6. Application of the principles of the design of clothing for special conditions. Clothing Research Journal 6, (2) 61-67.

Part 7. Assessment of the comfort properties of clothing. Clothing Research Journal 6, (3) 39-48.

SPRAGNE, C H, MUNSON, D M (1974). A composite ensemble method for estimating thermal insulation value of clothing. ASHRAE Transactions 80, 1, 120-129.

STEADMAN, R G (1971). Indices of wind chill of clothed persons. J.App.Met. 10, 674-683.

STOLWIJK, J A J (1970). Mathematical model of thermo regulation. In Physiological and Behavioural Temperature Regulation, ed. Hardy, J D, Gagge, A P and Stolwijk, J A J. Illinois: Charles C Thomas.

TAYLOR, M A (1982). Fabrics and garments for rainwear. Textiles 11 25-28.

TANNER, J C (1979). Breathability, comfort and Gore-tex laminates. Journal of Coated Fabrics 8, 312-322.

TURKEY, J W (1953). The problem of multiple comparisons. Dittoed manuscript 396 pp. Princeton University.

VERNON, H M & WARNER, C G (1932). The influence of the humidity of the air on capacity for work at high temperatures. J.Hyg.Camb. 32, 431-462.

VICKROY, S C, SHAW, J B & FISHER, C D (1982). Effects of temperature clothing and task complexity on task performance and satisfaction. J.App.Psych. 67, 97-102.

VOKAC, Z, KOPKE, V & KEUL, P (1972). Evaluation of the properties and clothing comfort of the Scandinavian ski dress in wear trials. Text. Res. J. 42, 2, 125-134.

WALLENBERGER, F T (1982). What's new in man-made fibres: Fibre-dependent comfort factors. Textile Chemist & Colorist 14, 33-37.

WEINER, L I (1970). The relationship of moisture vapour transmission to the structure of textile fabrics. Textile Chemist and Colorist 2, 22. 378-385.

WEINER, L I (1971). Moisture vapour transmission in textile fabrics. Textiles for Comfort.

WEIR, J B de V (1949). New methods of calculating metabolic rate with special reference to protein metabolism. J. Physiol. 109, 1-9.

WHELEN, M E, MACHATTIE, L E, GOODINGS, A C & TURL, L H (1955). The diffusion of water vapour through laminae with particular reference to textile fabrics. Tex. Res, J. 25, 3, 197-222.

WOODCOCK, A H (1962). Moisture transfer in textile systems. Tex. Res. J. 32, 628-633.

WYNDHAM, C H & MORRISON, J F (1958). Adjustment to cold of Bushman in the Kalahari Desert. J. Appl. Physiol. 13, 219-225.

ADDENDUM. OPEN UNIVERSITY (1979) System Behaviour ed. Beishon, J & Peters G, Open.Univ.Press. 245-253.

APPENDIX A

1) Body Surface Area

The subjects' height H(cm) and nude body weight W(kg) were measured and body surface area calculated from Du Bois' Formula (Du Bois & Du Bois 1916) thus:-

$$\text{Body Surface area} = (W^{2.425} \times H^{0.725} \times 0.007184)m^2$$

2) Mean Skin Temperature (Tsk)

Tsk was calculated in accordance with the technique of QREC (Mitchell & Wyndham 1969). Skin temperatures were measured at those sites listed below and multiplied by the weighted coefficients. The products were then summated to yield the mean skin temperature.

Site	Weighted Coefficient
Slightly below right nipple	0.125
Lateral surface left upper arm	0.07
Mid forearm left	0.07
Lateral aspect of left calf	0.15
Mid upper thigh	0.125
Above iliac chest left side	0.125

3) Mean Body Temperature (Tb)

Tb was calculated using the weighted coefficients for rectal (Tre) and mean skin temperature (Tsk) of the Burton Formula (1935) thus:-

$$Tb = 2/3\ Tre. + 1/3\ Tsk.$$

4) Substrate

The substrate was calculated thus:-

$$Cge = Vo_2\ (1.977\ R - 1.429)$$

where Cge = weight loss in g/min due to respiratory gas exchange

Vo_2 = oxygen uptake in litres/min STPD

R = respiratory quotient

1.977 = weight in g of 1 litre Co_2 STPD

1.429 = weight in g of 1 litres 0_2 STPD

5) Change in Heat Storage

The change in heat storage was calculated thus:-

$$S = (M \times SH \times \quad MBT) \text{ kcal}$$

where M = Body weight in kg.

SH = 0.83 kcal.