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# THE CONTRIBUTION OF CLOTHING WATER VAPOUR RESISTANCE TO THE DEVELOPMENT OF THERMAL STRAIN IN CLOTHED INDIVIDUALS

by

**Patrick John Sullivan**

B.Sc., Kinesiology, Simon Fraser University, 1985

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THE CONTRIBUTION OF CLOTHING WATER VAPOUR
RESISTANCE TO THE DEVELOPMENT OF THERMAL
STRAIN IN CLOTHED INDIVIDUALS

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Jan - 2 1990
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# ABSTRACT

The present study investigates the water vapour resistance ($R_e$) of several thermal protective suit fabrics and examines its effect on the temperature, humidity and vapour pressure within the clothing microenvironment ($T_\mu$, $RH_\mu$ and $P_\mu$), and thus, its indirect contribution to the development of thermal strain. Four aircrew suits were utilized in the present investigation representing two different design concepts: A) wet-suit design allowing ventilation of the microenvironment volume of the suit ($V_\mu$) either through the fabric or through openings in the suit, and B) dry-suit design allowing ventilation of the $V_\mu$ through the fabric only. The former was represented by the suits constructed of Nomex/Insulite (N/I) and Nomex/Neoprene (N/N) whereas the later was represented by the suits constructed of Cotton Ventile (CV) and Gore-Tex (GT).

Determination of $R_e$ is dependent on the measurement of evaporative rate (E) and water vapour pressure gradients developed across the fabric ($\Delta P_f$), thus, for the purpose of monitoring local evaporative rate, a Vapour Flow Meter was developed and compared with the more common measurement of sweating rate (SR). Evaluation of the sensors was conducted during heating (exercise at approximately 50% of $VO_2max$ and immersion in 38°C water), and subsequent cooling in thermoneutral water (28°C). Results indicate that $E_{sk}$ was detected very early on in the heating phase and in many cases reached steady state levels minutes before similar sweat rate levels were measured, suggesting that a number of factors inherent in the technique of sweat rate measurement may artificially delay both the sweating response and its subsequent detection. These include the artificial drying of the skin surface and the inherent sensitivity of the SR monitor.

The assessment of the $R_e$ characteristics of the fabrics, incorporated in the above mentioned suits, was performed using a test apparatus incorporating the Vapour Flow Meters. The fabrics tested include Nomex (N), Gore-Tex and Cotton Ventile, the latter two of which are normally worn in combination with cotton underwear, (GT/U and CV/U). Fabric results indicate $R_e$ values for N, GT/U and

CV/U to be 40.1 ± 2.8, 67.9 ± 5.4 and 54.6 ± 4.2 $m^2 \cdot Pa \cdot W^{-1}$ respectively. In addition, since $R_e$ consists of the resistance of the fabric plus microenvironment air layers during normal wear, a separate assessment was made on two vapour permeable helicopter aircrew suits during a hot air exposure (GT/U and CV/U) showing an increased water vapour resistance.

Finally, the influence of $R_e$ of fabrics on the elevation of $T_\mu$, $RH_\mu$ and $P_\mu$ within the clothing microenvironment was also investigated. Temperature and relative humidity within the clothing microenvironment were monitored 8mm above the skin surface during the hot air exposures where ambient temperature and RH were varied 20 to 40°C. Throughout the exposure the N/I and N/N suits, both of which are constructed of impermeable fabrics (Insulite and Neoprene), consistently produced the highest $P_\mu$, achieving a final levels of 5.68 ± .12 and 5.83 ± .21 kPa respectively. In contrast, the GT/U and CV/U suits displayed progressively lower levels of water vapour within the suit microenvironment (5.11 ± .13 and 4.34 ± .23 kPa) which was consistent with their lower water vapour resistances. No significant differences existed in $T_\mu$ between suits. Of these suits only the N/I produced elevated rectal temperatures ($\Delta T_{re}$=1.2°C). This is explained in terms of suit design as the neoprene worn under the N/N suit did not fully cover the arms and legs, allowing sufficient evaporative heat loss from these areas.

*Those who are disciples of Buddha must wear clothing to protect the body from extremes of heat and cold and to hide its shame, but they should not wear it for decoration.*

Anonymous
From the teachings of Buddha
Duties of the Brotherhood
Tokyo: Bukkyo Dendo Kyokai
1966 page 406

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## GENERAL INTRODUCTION

Analysis of the thermal conditions of the working environment, and the assessment of hazards associated with acute and chronic exposures to either heat or cold have only been attempted in a methodical manner in this century. As a result of increasing awareness of the decrement to performance that exposures to hot or cold may instigate, numerous investigators have suggested the establishment of heat stress indices, determined empirically by establishing a tolerance limit of the thermal strain exhibited by the workers exposed to such environments. To date, such assessments have been limited to the measurements of ambient conditions in the workplace. However, as explained by Rodahl and Guthe (1988), a worker may, in the course of his regular eight hour shift, be exposed to a wide variety of ambient conditions. Thus, the overall stress of an environment may be the superposition of all such exposures. This has led to the suggestion of personal monitoring of individuals working in hot environments, such that the overall thermal status of a given worker may be determined. These methods range from projections of a ranking of the relative difficulty or stress based on a few subjective responses or symptoms, to the development of sensors for the continual monitoring of heart rate, sweat rate, skin humidity and body temperatures. Thus, not unlike radiation dosimetry, it has been suggested that the thermal stress experienced by the worker be assessed individually, and furthermore, that exposure be limited in the same manner as it is limited for workers in areas of radiation hazard. Personal monitoring may provide a viable, alternative approach to the establishment of of limits based solely on the measurement of environment conditions.

The main problem with the establishment of exposure limits however is the need to assess thermal strain. For acute exposure to hot environments, thermal strain for a given level of stress, has been assessed using a variety of methods which include the assessment of psychomotor performance, changes in skin and core temperature (or body heat storage), heart rate and the rate of sweat loss. In many studies, the analysis has solely involved a correlation of the observed strain for a range of stresses, including changes in both temperature and humidity. Ideally the level of strain should be determined by obtaining the thermal balance of the worker according to the heat balance equation, but this is of limited value, with present technology in field conditions. Thus, most assessments continue with the observation of the responses of the indices mentioned earlier. For the sake of this study, analysis of thermal strain was limited to the measurment of elevation in skin and body core (rectal) temperature.

Further complications to the determination of the relationship between stress and strain in hot environments arise with the utilization of different types of of clothing or protective garments. Clothing, essentially a thermal and moisture barrier, establishes by virtue of its characteristics and design concepts, an environment between the skin and the external environment. Thus, thermal exchanges do not occur directly between skin and ambient air, but rather indirectly via this clothing microenvironment (or microclimate). Similarly, the stress of an environment may either be dampened or enhanced, depending on the clothing properties. Assuming that work clothing covers 93% of the total surface area of the body (excluding the head), then the strain observed may result primarily from the stress of the microenvironment.

This thesis examines the microenvironment during exposure to hot air conditions as it is affected by the water vapour permeability (or resistance) of the fabrics and the design of the suit. Previous work (Sullivan *et al.*, 1987a,b) improved upon the method developed by Birnbaum and Crockford (1978) for determining the volume of the clothing microenvironment used in the assessment of the ventilation index of garments, which incorporates air exchange through the fabrics, as well as through the vents of the suit. The suits chosen for the present evaluation represent the range of suits worn by aircraft personnel during offshore flights. These suits are unique, as they must accomplish dual tasks: 1) they should offer substantial thermal protection and flotation in the event of sudden accidental ditching, and 2) they should not induce heat strain during normal flight conditions. The latter requirement becomes a significant design problem in view of the cold protection requirement and in summer conditions, where cockpit air temperatures may rise to high levels, due to the solar radiation.

The present investigation focuses on the thermal characteristics of such suits in hot air exposures. The main avenue of heat loss from subjects wearing such suits will be through sweat production and its subsequent evaporation. Chapter 1 outlines the instrumentation developed for the purpose of measuring these variables. Furthermore, typical measurements of both local evaporation and sweating rates are presented and discussed.

Utilizing the above instrumentation developed for measuring local evaporative rates, chapter 2 quantifies the water vapour resistance of fabrics utilized in the design of these suits. The device, which enables such evaluation, is detailed. In contrast to existing methods, the method developed assesses water vapour resistance over the entire anticipated range of water vapour pressure differences across the fabric. The data of water vapour resistance is compared to data obtained *in vivo*. During the protocol outlined in chapter 2, continuous assessment of $R_e$ was conducted, to determine the extent to which suit performance in simulated field conditions, could be assessed from analysis of fabric properties alone.

Finally, as the microenvironment conditions are a consequence of the water vapour permeability and the ventile properties of the garments, an assessment was made, in chapter 3, of the elevation in temperature and humidity within the suit microenvironment over a three hour period, during which the air temperature was elevated from 20°C to 40°C, representative of conditions experienced by aircraft personnel commuting to offshore installations by helicopters. The analysis compares the conditions developed within the suit microenvironment utilizing suits constructed of a variety of fabrics and designs.

The format of this thesis is such that it consists of a compendium of three independant studies dealing with; 1) the development and assessment of sensors utilized in the quantification of water vapour resistance of fabrics, 2) the assessment of fabric water vapour resistance of fabrics utilized in the construction of commercialy available helicopter pilot suits, and 3) the determination of thermal strain developed in individuals wearing these suits during a hot air exposure simulating the heat stress normally encountered during normal operations. The results of these studies are summarized in the general conclusions presented at the end of this thesis.

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# Comparison of the Methods Used in the Measurement of Local Sweat and Evaporative Rates

## ABSTRACT

*Comparison of the rates of local skin sweating and evaporation and the methods utilized in their measurement were made during conditions of exercise (EX) and hot water immersion (HW). Two subjects underwent body heating by exercise on a bicycle ergometer (50% $VO_2max$) or immersion in 38°C water with subsequent cooling in 28°C water. Forehead sweating rate (SR) was measured using a standard ventilated capsule and resistance hygrometry whereas forehead evaporative rate ($E_{sk}$) was determined using a Vapour Flow Meter (VFM) which measures the vapour density distribution within the boundary layer of the skin surface. Both exercise and hot water immersion produced an increase in esophageal temperature ($T_{es}$) of 0.97±0.28°C. Sweating rate varied linearly with esophageal temperature with the HW protocol producing a higher sweat rate for any given $T_{es}$ as compared to EX. In contrast, $E_{sk}$ was detected very early on in the heating phase and in many cases reached steady state levels of approximately 61.6 $mg \cdot m^{-2} \cdot sec^{-1}$ up to 7 minutes before similar SR levels were detected. It is suggested that this discrepancy was due to the influence of the apparatus on the responses in question. It is evident from this study that the responses and magnitude of sweat rate and evaporative rate from the forehead differ during generalized body heating. Sweat rate, measured using a ventilated capsule, reflects the activity of the sweat glands in response to the thermal status of the body, whereas evaporative rate, measured using a VFM, is a physical process dependent on environmental conditions. The detection of steady-state $E_{sk}$ values before a SR of equivalent magnitude suggests that local skin drying below the sweat capsule by forced evaporation may result in delayed detection. In addition, the influences of local skin temperature and perfusion may also play a role.*

# INTRODUCTION

During exercise and/or conditions of heat stress, the cutaneous circulation serves to dissipate metabolic heat to the environment. Dry heat transfer from the skin to the environment is mediated primarily by convection and radiation, and is enhanced by increases in the skin-to-air thermal gradient brought about by increases in skin temperature ($T_{sk}$). The magnitude of dry heat loss in hot ambient environments is limited, due to the low thermal gradient between the skin and ambient air. As such, the primary effector mechanism for heat dissipation under these conditions of thermal stress is through variations in the sweating rate (SR) with its subsequent evaporation from the skin surface ($E_{sk}$) so long as the vapour pressure gradient between the skin and environment is maintained.

Measurements of sweat rate are common in the literature as an effective means of assessing the response of the thermoregulatory system to elevations in body temperature. However, sweating rate is often considered synonymous with evaporative cooling. This is based on the assumption that all of the sweat secreted is completely evaporated. Evaporation however, depends to a large degree on the conditions of the ambient environment and may be significantly altered by the presence of clothing regardless of the rate of sweat production.

To date, a variety of techniques have been developed for the measurement of sweating rate (SR). The quantitative measurement of local sweat rates has traditionally involved either the collection and subsequent measurement of sweat produced, or the forced evaporation of sweat from skin within a capsule. In the collection of secreted sweat, regions of the body may be sealed with impermeable bags or capsules, the volume of sweat collected is measured and the rate of sweating determined by incorporating the time required for accumulation. Measurement of the volume of sweat produced is made by weight changes of either the encapsulating system (Boysen *et al.*, 1984) or of an absorbent substance contained within, such as filter paper (Takagi and Sakurai, 1950) or hygroscopic salts (Hattingh and Luck, 1973). In addition, the amount of sweat produced may also be estimated by measuring the changes in water content of air within the capsule using resistance hygrometry (Rosenburg *et al.*, 1962). These methods, in addition to restricting evaporative heat loss, and thus possibly imposing additional heat stress (if the surface area is sufficiently large), also create an artificial environment near the surface of the skin which may itself influence the sweating response. Collection techniques, although ideal for the purpose of analysing the components of sweat, are even less desirable in the study of the dynamic response as they only allow measurements intermittently.

Currently the most commonly used method for measuring local SR is that of the ventilated capsule. Dry air or Nitrogen gas is passed through an inverted capsule, which has been secured to the skin, at a rate which will ensure immediate evaporation of sweat as it is secreted onto the skin surface. In these forced-evaporation sweat capsules, the amount of sweat secreted is calculated by measuring the water content of air passing through the capsule. As the most popular method for determining local sweat rate, a variety of forced evaporation capsules have been developed. Although similar in principle, these devices differ only in the techniques utilized for water vapour detection. The water content of inlet and outlet air can be determined by a number of different methods: resistance hygrometry utilizing a number of different substrate humidity sensors (Nakayama and Takagi, 1959; Bullard, 1962; Gonzalez *et al.*, 1974; Kraning and Sturgeon, 1983), dew-point hygrometry (Brengelmann, 1975), thermal conductivity cells (Adams *et al.*, 1983) and infra-red analysis (Albert and Palmes, 1951).

Whereas methods utilizing sweat collection techniques may produce spurious results due to elevations in local temperature, vapour pressure and skin wettedness, the forced evaporation within the sweat capsule may also affect the rate of sweat secretion. In addition to the artificial drying of the skin surface by the dry air being flushed through the capsule, changes in local skin temperature (MacIntyre *et al.*, 1968 and Spruit, 1971) and pressure exerted by the edges of the capsule on the skin are factors, which remain to be assessed in terms of their significance in affecting sweat rate. In addition, the results of such methods are difficult to extrapolate to whole body sweat production and evaporative heat losses due to regional variations in sweat rate (Tam *et al.*, 1976). Regardless, the capsule technique has proved useful as an objective means of assessing the sweating response, and, due to the sweat capsule's simplicity, smallness of size, inexpensive design, and the ability to make measurements on exercising subjects, its use has gained popularity in studying the dynamics of the sweating response and the factors involved in its control.

In any attempt to quantify the amount of heat lost by evaporation, sole determination of sweat rate is inadequate. Whole body evaporative rate is commonly assessed by measuring body weight before and after the experimental condition. The change in body weight; corrected for water intake, respiratory water loss, metabolic weight loss, dripped sweat and water absorbed by clothing, is generally considered to accurately reflect skin evaporative losses. This technique, however, is not without its limitations. The accuracy of the method relies on the accuracy of the weight scale and unless continuous weight monitoring is feasible, the dynamics cannot be determined. Recently, continuous measurements of evaporative sweat losses at rest (Libert *et al.*, 1978) and during exercise (Alber-Wallerstrom and Holmer, 1985) have been made by suspending the subject (and bicycle ergometer) on a sensitive weight scale and placing a paraffin-filled tray below for the collection of dripping sweat. Although ideal for estimating whole body evaporation, it is often considered too slow and not sufficiently sensitive enough to determine small and rapid changes (Webb *et al.*, 1957; Belding and Hertig, 1962).

Until recently, accurate measurements of local $E_{sk}$ have, for the most part, alluded researchers. The use of a ventilated capsule is inadequate in determining normal $E_{sk}$, as the evaporative rate from the skin surface to the environment would be quite different from that under the sweat capsule, due to the absence of a constant flow of dry air. With the recent development of miniaturized humidity sensors, the continuous assessment of local evaporative rate has been made possible by measuring the vapour density distribution over the surface of the skin. This development was pioneered by Nilsson (1977) and has been used extensively in the study of cutaneous water loss from infants and burn patients. Improvements have since been made which increase the accuracy and allow measurements at multiple sites (Kakitsuba, 1982;

Kakitsuba *et al.*, 1988). Such an instrument can provide valuable information regarding local evaporative rates, and thus heat loss, a parameter which depends both on the sweating rate and environmental conditions. In addition, measurements of local evaporative rates, in combination with measurements of the water vapour pressure gradients would enhance the innovative *in vivo* measurements of the resistance of clothing to water vapour transfer as performed by Holmer and Elnas (1981) and Sommerville (1988).

To date, few studies have reported on continuous measurements of local evaporative rates and the underlying theory upon which it is based. For the present thesis, the purpose of this study is to outline the principles and methods of local evaporative rate measurements and to compare these with the common method of measuring local SR. To illustrate the differences, comparisons are made between local $E_{sk}$ and local SR during two types of heating maneuvers and these differences discussed.

## METHODS

In the following presentation of the theory and methods utilized in the measurement of sweating and evaporation, a distinction will be made between the rate at which sweat is secreted and that at which it is subsequently evaporated. The Glossary of Terms for Thermal Physiology (Bligh and Johnson, 1973 and Cabanac, 1987) does not emphasize this difference, and also does not give guidance as to the acceptable nomenclature and units for these measurements, thus a brief definition of these concepts is warranted.

Diffusion of water from the skin surface consists of two components: the transepidermal water loss (natural diffusion) through the skin ($E_d$), and the evaporation of secreted sweat from the skin surface ($E_{sk}$). Whereas natural diffusion through the skin constitutes a minor component of the total evaporation during heat stress and is a constant process under stable environmental conditions, evaporation of secreted sweat is primarily a function of skin wettedness. The total evaporation from the wet skin surface, whether the skin is wetted artificially or naturally by the secretion of sweat, contributes to heat loss from the body, as 0.58 kcal of thermal energy is dissipated in the process of evaporation of one gram of water.

Whereas the magnitude of heat loss due to $E_{sk}$ is important in the regulation of body temperature, it does not necessarily reflect the physiological response of sweating, the value of interest in the analysis of thermoregulatory effector responses. For this reason, the rate of sweat secretion and evaporation are measured separately. The nature of SR measurement, as discussed below, requires the artificial drying of skin to adequately quantify the secreted sweat over the entire physiological range of sweat secretion.

## Theory

In the present thesis, the assessment of both evaporation and sweat secretion relies on similar principles, those of resistance hygrometry. Evaporation is defined by the natural vapour density or vapour pressure gradient existing above the skin surface, sweating however, is derived by establishing an artificial environment in a capsule above an isolated skin surface area.

*Measurement of the rate of sweat secretion using resistance hygrometry:*

Measurement of sweating rate is based on the technique of passing dry air through a capsule which is sealed over an isolated area of the skin (Figure 1.1). By continuous monitoring of the temperature and relative humidity of inlet and outlet air and its rate of flow through the capsule, the determination of transient changes in sweat production can be made. Resistance humidity sensors are used to directly measure the relative humidities of the inlet and outlet air. Calculation of vapour density of the inlet and outlet air is based on measurements of the temperature and relative humidity of air entering and exiting the capsule, and is performed using the following regression equation adapted from the data presented by Weast (1983) for calculating saturation vapour density of air ($\rho H_2O_{sat}$):

$$\rho H_2O_{sat} = 5598.6 \cdot e^{(0.0565 \cdot \mathrm{Temp})} \qquad (\mathrm{mg \cdot m^{-3}}) \qquad [1.1]$$

The vapour pressure for outlet air is a function of the relative humidity and the saturation vapour pressure of outlet air:

$$\rho H_2O_{out} = \left(\frac{RH_{out}}{100}\right) \cdot \rho H_2O_{sat.\ out} \qquad (\mathrm{mg \cdot m^{-3}}) \qquad [1.2a]$$

Similarly, substituting the inlet air temperature and relative humidity into equations 1.1 and 1.2 above, the vapour density of the inlet air may be calculated.

$$\rho H_2O_{in} = \left(\frac{RH_{in}}{100}\right) \cdot \rho H_2O_{sat.\ in} \qquad (mg \cdot m^{-3}) \qquad [1.2b]$$

Sweating rate (SR', mg·sec$^{-1}$) may be determined by accounting for the differences in vapour densities ($\Delta\rho H_2O = \rho H_2O_{out} - \rho H_2O_{in}$, mg·m$^{-3}$) and the air flow rate through the capsule ($\dot{V}_s$ m$^3$·sec$^{-1}$).

$$SR' = \Delta\rho H_2O \cdot \dot{V}_s \qquad (mg \cdot sec^{-1}) \qquad [1.3]$$

The sweating rate thus determined is only for the surface area of skin covered by the capsule, therefore it should be adjusted for the capsule surface area ($A_{capsule}$, m$^2$) to yield SR in units of mg·m$^{-2}$·sec$^{-1}$.

$$SR = \frac{SR'}{A_{capsule}} \qquad (mg \cdot m^{-2} \cdot sec^{-1}) \qquad [1.4]$$

*Measurement of the rate of natural evaporation using a Vapour Flow Meter (VFM):*

The evaporation of water from a surface establishes a gradient of water vapour concentration or density ($\partial\rho$) above that surface. The rate of diffusion of water vapour ($m_w$) from a wet surface within the boundary layer of air in contact with the surface depends on the resultant component of random movement of water molecules and may be described as:

$$m_w = D_w \cdot \frac{\partial\rho}{\partial x} \qquad (mg \cdot m^{-2} \cdot sec^{-1}) \qquad [1.5]$$

where:

$D_w$ = mass diffusivity of water vapour in air ($m^2 \cdot sec^{-1}$)

$\frac{\partial \rho}{\partial x}$ = vapour density gradient ($mg \cdot m^{-3}$)

Although it is not possible to measure the gradient at a point within the boundary layer, the gradient is approximately proportional to the difference between the vapour density measured at two separate fixed points within the zone of diffusion. The VFM evaluated by Kakitsuba (1982), and Kakitsuba *et al.* (1988), incorporates a resistance humidity sensing element coated with a humidity sensing conducting polymer film whose resistance varies with the changes in relative humidity (Figure 1.2). By determining the local relative humidities and temperatures at two points in the diffusion boundary layer over the skin surface (assumed to be 1.0 to 2.0 centimeters) the local evaporative rate can be determined (Figure 1.3). Thus the diffusion process may be described by applying Fick's Law:

$$m_w = -D_w \cdot \frac{(\rho_1 - \rho_2)}{(x_1 - x_2)} \qquad (mg \cdot m^{-2} \cdot sec^{-1}) \quad [1.6]$$

Simplifying:

$$m_w = -D_w \cdot \frac{\Delta \rho H_2O}{\Delta x} \qquad (mg \cdot m^{-2} \cdot sec^{-1}) \quad [1.7]$$

where:

$m_w$ = rate of water diffusion from the surface of the skin ($mg \cdot m^{-2} \cdot sec^{-1}$)

$\Delta \rho H_2O$ = $\rho_1 - \rho_2$ = difference in water vapour density between the two measuring points ($mg \cdot m^{-3}$)

$\Delta x$ = $(x_1 - x_2)$ = distance between the two measuring points (0.003 m in the present study)

Mass diffusivity ($D_w$) of water into ambient gas is a function of ambient temperature, pressure, molecular volumes and molecular weights of water and air (Holman, 1976).

$$D_w = 0.04357 \cdot \left[ \frac{T_a^{3/2}}{P_B \cdot (V_{wv}^{1/3} + V_a^{1/3})^2} \right] \cdot \sqrt{\frac{1}{M_{wv}} + \frac{1}{M_a}} \qquad (m^2 \cdot sec^{-1}) \qquad [1.8]$$

where:

$T_a$ = ambient temperature (K)
$P_B$ = ambient pressure ($N \cdot m^{-2}$)
$V_{wv}$ = molecular volume of water vapour
$V_a$ = molecular volume of air
$M_{wv}$ = molecular weight of water vapour
$M_a$ = molecular weight of air

As in the calculations for SR, the vapour density at each measuring point ($\rho_1$ and $\rho_2$) is a function of the relative humidity and the vapour density of saturated air at that temperature, and as such, the equations for vapour density are identical to those of [1.1] and [1.2].

## Protocol and Instrumentation

Heat loss effector responses are normally assessed during alterations in core and skin temperatures. Since responses, such as the rate of sweating, may differ depending on whether body temperature is elevated by exogenous or endogenous heating, a comparison of SR and $E_{sk}$ was conducted on two unacclimatized male subjects using both protocols.

Following approval from the Simon Fraser University Ethics Commitee, subjects were instrumented for measurements of esophageal temperature ($T_{es}$, YSI 701, Yellow Springs Instruments), local sweating rate (SR) and local evaporative rate ($E_{sk}$). In addition, skin temperature (YSI 401, Yellow Springs Instruments) was represented by the temperature of the chest, and measured before heating and prior to the transfer to the cool bath. Subjects then underwent body heating by exogenous (hot water immersion) and endogenous (exercise) means on separate days ($T_{amb}$ = 24°C, $RH_{amb}$ = 50%). During hot water immersion (HW), subjects were immersed to the level of the sternal notch in 38°C water for approximately 25 minutes until the subject was clearly sweating as indicated by the beading of sweat on the forehead. Subjects were then cooled by subsequent immersion in cool (28°C) water until sweating had returned to pre-exposure levels. During immersions the water bath was covered with a polyvinyl sheet such that only the subjects head was exposed to the ambient air in an attempt to shield the VFM from water vapour emanating from the bath.

Endogenous heating was accomplished by cycling on a bicycle ergometer (EX) at a work rate equivalent to 50% of their $VO_2$ max as previously determined using an incremental load exercise protocol. During the exercise period, a polyvinyl cape was draped from the subjects' shoulders to impede evaporative heat loss and thus fascilitate body heating. As in the water immersion, body heating was continued until subjects were clearly sweating, following which subjects were cooled in a 28°C water bath.

In the measurement of SR, compressed air ($T_{air} = 24°C$, RH = 10%) was passed through a 250 ml plastic container, with a thermistor and relative humidity sensor mounted in its center (Figure 1.1). The air was directed from the container by means of a 4mm (o.d.) polyethylene tubing to the sweat capsule (surface area = $8.04 \times 10^{-3}$ $m^2$) which was positioned on the subject's forehead and secured firmly with an elastic head-band to prevent leakage. Air from the sweat capsule was further directed via another 4 mm polyethylene tubing to a 250 ml container similar to that on the inlet side also containing a thermistor and relative humidity sensor mounted internally. Thus, a comparison of outlet and inlet temperatures and relative humidities allowed calculation of the secretion of sweat from the skin encapsulated by the sweat capsule. Air flow through the system was maintained at 1 liter·min$^{-1}$ and monitored both on the inlet and outlet side with flow meters to ensure no leakage occurred.

The VFM (Shinyei Kaisha, Japan) was placed on the forehead next to the sweat capsule and held in place with an elastic headband and adhesive tape. The relative humidity sensors, VFM, and $T_{es}$ were sampled every 30 seconds with an HP 3497A (Hewlett Packard) Data Acquisition System and stored on an HP 85 (Hewlett Packard) computer. Calculation of SR, $E_{sk}$ and data analysis was performed using a MacIntosh 512KE (Apple). Calibration of the thermistors and relative humidity sensors was conducted, as described in Appendix A.

## RESULTS

Manufacturer's specifications indicate that the accuracy of the RH sensors was within ±1%. Air of approximately 10% relative humidity was passed through the sweat capsule in the determination of sweating rate. However, analysis of the sensors revealed that readings were unreliable below 20% RH. As such, calculated SR values below 44 $mg{\cdot}m^{-2}{\cdot}sec^{-1}$ are unreliable and thus not presented.

The nature of the esophageal temperature and sweating rates are similar during the heating phase for both the hot water immersion and exercise heating protocols (Figure 1.4). Heating was associated with a rise in $T_{es}$ of 0.97 ± 0.28°C, with the exercise protocol displaying a transient decline at the onset of cycling. Forehead sweating, as determined using resistance hygrometry, also tended to show a linear response to a maximal value of 108.1 ± 21.7 $mg{\cdot}m^{-2}{\cdot}sec^{-1}$. Upon cessation of the heating regime and entry into the thermoneutral water, $T_{es}$ began to decline, the rate of which appears to be dependent upon the nature of the heating stimulus, with the fastest decline seen following HW heating as compared to EX heating. Sweating also declined abruptly upon entry into the cool water bath. Skin temperatures ranged from resting values of 32.15 °C to final levels of 33.86 and 36.93 for the exercise and hot water conditions respectively.

For both HW and EX heating regimes, sweat rate varied linearly with esophageal temperature (Figure 1.5). Although the slopes were similar (90.5 $mg{\cdot}m^{-2}{\cdot}sec^{-1}{\cdot}{}^{\circ}C^{-1}$), the SR-$T_{es}$ relationship during HW immersion was shifted approximately 0.5°C to the left of that determined for EX.

In contrast to SR, evaporative rate from the forehead, as measured using the vapour flow meter, was detected very early on in the heating phase and in many cases reached steady state levels up to 5 minutes before similar SR levels were detected. Evaporative rate rose abruptly from an initial value of 8.3 ± 2.3 $mg{\cdot}m^{-2}{\cdot}sec^{-1}$ to a steady state value of 61.6 ± 4.4 $mg{\cdot}m^{-2}{\cdot}sec^{-1}$ within eight minutes from the onset of heating. Thereafter evaporative rate remained relatively constant throughout the remaining heating and cooling periods.

The onset in evaporation is associated with an increase in the vapour density gradient between the two measuring points within the VFM. The two points (1 and 2, Figure 1.3) were positioned 5 and 8 mm above the surface of the skin respectively. Figure 1.6 displays the results from one of the hot water immersion heating trials, and was typical for all trials. Prior to the apparent onset in evaporative rate, the vapour density at points 1 and 2 were approximately equivalent at 12 $g{\cdot}m^{-3}$. The measurable occurrence of evaporation is associated with both an increase in the vapour density of points 1 and 2, and an increase in the gradient between them (Figure 1.6a). Maximal $\rho H_2O$ for the conditions within this study was approximately 35 and 28 $g{\cdot}m^{-3}$ at five and eight millimeters from the skin respectively.

The measured temperatures within the diffusion boundary layer varied between 30.5 and 33.7°C with the region closest to the skin (5 mm) elevated 1.5°C above the more distant point (8 mm) when evaporative rate was maximum (Figure 1.6c). During the high sweat rates measured in this study, evaporation was associated with a rapid and near complete saturation of the air within 5 mm of the skin surface, whereas a maximum of only 80% saturation was seen at the more distant point (Figure 1.6b).

## DISCUSSION

From the present study it is evident, that there is a difference in the rate of increase, cessation and possibly the onset of measured sweating and evaporation. Although onset of SR cannot be assessed in the results of the present trials, differences in the responses of $E_{sk}$ and SR are evident and merit discussion. Since the thermistors and relative humidity sensors and their respective hardware were identical for both the sweating and evaporation measurements, it is unlikely that the discrepancies in the observations are due to differences in instrumentation (hardware). In addition, calibration procedures of the humidity sensors was conducted in the same manner (see appendix A for details of humidity sensor calibration). Therefore, to establish the cause of the differences in $E_{sk}$ and SR, both physiological and physical factors associated with both responses need to be examined.

### *Sweating Rate*:

The sweating results (Figure 1.5) confirm the previously observed pattern of a proportional response to $T_{es}$, as has been described by others (Hammel *et al.*, 1963; Cabanac and Massonnet, 1977; Mekjavic and Bligh, 1989). Above a threshold core temperature, a linear relationship exists between sweat rate and the rise in esophageal temperature (Nielsen, 1969; Nadel, 1971). The magnitude of the response is within the expected range reported elsewhere (Nadel *et al.*, 1971; McCaffrey *et al.*, 1979; Beaumont and Bullard, 1963) with a maximum attained of $108.1 \pm 21.7$ $\mathrm{mg \cdot m^{-2} \cdot sec^{-1}}$. Although the greatest sweating rates in this study are lower than maximums attained by others (Beaumont and Bullard, 1963), this is due to cooling initiated before maximal steady state sweating was attained, as only the dynamics of the response was of interest in this study.

In general, during HW immersion the SR-$T_{es}$ relationship appeared shifted to a lower level of Tes than during EX (eg: 36.5°C vs. 37.1°C, see Figure 1.5). Such a difference is predictable considering both the low initial $T_{es}$ in subjects prior to heating (36.46 ± 0.21°C) and the higher skin temperatures observed during hot water immersion, and as such, the elevated skin temperatures would be expected to shift the core temperature threshold for sweating lower (Nadel, 1971). Thus the data confirm the thermoregulatory nature of the sweating response.

*Evaporative Rate*:

Initial $E_{sk}$ values of 8.3 $mg \cdot m^{-2} \cdot sec^{-1}$ correspond to transepidermal water loss, as has been demonstrated by others. Maximal steady-state values obtained during body heating represent the evaporation of secreted sweat as, in the absence of sweating, maximal transepidermal water loss is in the order of 5-10 $mg \cdot m^{-2} \cdot sec^{-1}$. The maintenance of steady-state levels throughout heating and cooling (despite variations in SR), and the similarity between trials, confirms that evaporation is governed by physical processes and as such, is dependent on the ambient conditions. Once the skin is wet, evaporation should remain constant unless changes occur in either ambient temperature, relative humidity, air velocity or skin temperature. In addition, it is anticipated that $E_{sk}$ would be lower than maximal SR, as the vapour pressure gradient and coefficient of evaporation from the skin to the sweat capsule air are greater.

Local measurements are fairly new and as a result there have been few direct measurements of local $E_{sk}$ on man directly comparable to those obtained here and, fewer reporting the time course associated with body heating. Kakitsuba (1982) determined steady state local evaporative rates of subjects exposed for 1 hour at various ambient temperatures using an apparatus similar to that used in this study. He found steady-state evaporative rates in resting subjects varied from 5 to 41 $mg \cdot m^{-2} \cdot sec^{-1}$ when ambient temperature was raised from 26.1 to 35.8°C respectively ($RH_a = 40, 60\%$). In addition, Alber-Wallerstrom and Holmer (1980) measured evaporative rates between 3 and 39 $mg \cdot m^{-2} \cdot sec^{-1}$ with variations in ambient temperature from 27 to 40°C ($RH_a$ =30%). The lower levels detected in these studies likely reflect low levels of sweating with only partial wetting of the skin. In comparison, Alber-Wallerstrom and Holmer (1985) using changes in body weight, found steady-state evaporative rates up to 89.5 $mg \cdot m^{-2} \cdot sec^{-1}$ during cycle ergometry ($T_a$ = 36.4°C and $RH_a$ = 50%). Their rates are approximately 45% higher than those in this study and can be attributed to the higher vapour pressure gradient established due to elevated ambient temperature, and a higher expected coefficient of evaporation with limb movement during cycling. Overall, the differences observed between these studies may indicate that with low thermal stress, evaporative rate will vary with the rate of sweat production. However, with high levels of thermal stress and complete wetting of the skin, evaporative rates will depend on ambient conditions (T, RH and air velocity).

Werner (1983) has reported one of the few dynamic measurements of $E_{sk}$ (using an evaporimeter) with body heating. With instantaneous changes in $T_a$ from 10 - 50 °C, he demonstrated rapid elevations in $E_{sk}$ to steady state levels with only minor elevations in core temperature, similar to the responses observed in this study.

*Comparison of Sweating and Evaporative Rate Responses:*

Although measurements of local $E_{sk}$ are relatively new, they have been validated by comparison with measurements of weight loss from a dish of water (Nilsson, 1977; Kakitsuba, 1982; Kakitsuba *et al.*, 1988). It would then appear that the values obtained are valid and that any discrepancies with SR measures are due to inherent differences in the techniques used to measure sweating and evaporation and possibly the influence of the apparatus on the responses in question.

The most striking discrepancy in this study is the elevation in $E_{sk}$, prior to the observed changes in SR, and this may in part be attributable to a lower sensitivity of the ventilated capsule method for determining SR. Namely, during low levels of sweat production, a small volume of sweat is forcibly evaporated into a relatively large volume of air ventilating the capsule (flow rate in the present study was 1 liter·min$^{-1}$), producing only small changes in the relative humidity of the outlet air. In contrast, using the VFM, the air between the skin surface and the sensors is relatively still. Thus the evaporation of a small amount of sweat may produce larger changes in RH detected at the VFM than using the ventilated capsule. Though the increased sweating rate is not detected until air exiting the capsule has passed through the system of tubes to the container incorporating the humidity and temperature sensors, the system has been shown to respond quickly (within 10 seconds) to the positioning of the capsule over a completely wet surface. It is unlikelt then, that this contributed significantly to the observed discrepancy.

Beaumont and Bullard (1963) have clearly shown that alterations in SR can occur within 2 seconds of the onset of muscular work, and before any apparent changes in body temperature. In addition, they found that this was detectable only during general eccrine sweating, and that in relatively cool environments where the pre-exercise sweating rate is low, the latency for increased SR is much longer. This latter finding suggests either a synergistic influence of nonthermal input on the control of sweating or, possibly the effects of skin hydration on the observed latency. Support for the latter hypothesis may be obtained from Lloyd (1959) and more recently from Bullard (1970). Lloyd proposed an 'empty duct' theory based on visual changes in the latent period of SR onset and changes in skin impedance. In 1970, Bullard repeated Lloyd's experiments on humans using a more quantitative assessment of SR, mainly that of resistance hygrometry. Through direct stimulation of cutaneous nerves of the forearm, he demonstrated an initial latency for the onset of sweat secretion of 1 - 2 minutes, as detected using resistance hygrometry. However, upon second stimulation, this latency was greatly reduced (as low as 10 seconds), the degree of which was dependent upon the stimulus interval. This reduced latency was attributed to an increased level of ductal filling and thus epidermal hydration level due to prior sweating. The longer the stimulus interval, the greater the SR latency. Although both Lloyd (1959) and Bullard (1970) hypothesized reabsorption of sweat as the factor responsible for decreasing epidermal hydration, a factor unlikely considering the osmotic gradients, Sato (1977) has suggested that evaporation from the skin may be more likely. It is clear that at the onset of body heating in this study, that the skin under the capsule is under different conditions than that under the

VFM. The forced evaporation created by passing dry air over the skin may result in excess drying of the skin and prolonging latency, a factor less likely for skin beneath the VFM.

In addition to the forced drying of the epidermis, the sweat capsule may also influence the sweating response due to other alterations in the microclimate below the capsule. Both sweating rate and transepidermal water loss have been shown to be skin temperature dependent (MacIntyre *et al.*, 1968; Spruit, 1971) and, it is apparent that the forced evaporation of either secreted sweat or transepidermal water from the surface of the skin would lower skin temperature as heat is removed, as latent heat of evaporation. Few studies have looked at skin temperature below the sweat capsule except when it is being directly controlled. However, Kraning *et al.* (1978) showed fluctuations of only 1°C (33 - 32°C) accompanying transcutaneous electrical stimulation of sweating, although the degree of cooling would be influenced by the magnitude of sweating and the temperature of the air entering the capsule. Although local skin temperatures within a range of 20 and 40°C have been shown to influence SR, this has not been demonstrated with fluctuations in $T_{sk}$ as small as 1°C. In this study, air entering the capsule was at a temperature of 24°C and it is unlikely that this would have an influence on the amount of sweat secreted relative to that under the VFM, as ambient temperature was 25°C throughout the duration of the experiment.

One further factor which may be postulated as influencing the SR and $E_{sk}$ responses is the difference in pressure exerted on the skin with the different apparatus. In the measurement of sweat rate a significant amount of pressure is required to hold the capsule against the skin in order to prevent leakage of air, whereas measurement of evaporation does not. Local pressure of the edges of the capsule may decrease the blood perfusion of skin directly below the sweat capsule. Although a relationship between skin blood flow and sweating has been assumed, direct evidence is as yet not available. In addition, it is unclear as to whether the pressure of the capsule would decrease local skin blood flow. In contrast, Nilsson (1977) has demonstrated that transepidermal water loss increases approximately 10% for every 100 gram load exerted via a circular capsule (similar to the SR capsule in this study) on the skin, suggesting a possible increase in local skin blood flow.

It is evident from this study that the responses and magnitude of sweat rate and evaporative rate from the forehead differ during generalized body heating. Sweat rate, measured using a ventilated capsule, reflects the activity of the sweat glands in response to the thermal status of the body, whereas evaporative rate, measured using a VFM, is a physical process dependent on environmental conditions. The detection of steady-state $E_{sk}$ values before a SR of equivalent magnitude suggest that local skin drying below the sweat capsule by forced evaporation may result in delayed detection. In addition, the influences of local skin temperature and perfusion may also play a role, however, at present their effects remain unclear.

Although not demonstated by the present study, the ventilated capsule method has an additional advantage over the determination of $E_{sk}$, and that is the ability to alter its sensitivity. This is possible by varying the flow rate of air through the capsule. However, the system needs to be designed to minimize the delay time, as decreasing air flow will increase the delay time, the result however, is an increased sensitivity. The present study incorporated an air flow rate suggested by other workers (Cabanac and Massonnet, 1977; Mekjavic and Bligh, 1989) and it would appear from the comparison of the results with those obtained with the VFM, that sensitivity is compromised slightly.

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## FIGURE LEGENDS

Figure 1.1: Diagramatic representation of the experimental set-up used for measuring local sweating rate. Dry air is passed through a capsule which is sealed over an isolated area of the skin. Sweat rate is calculated from the difference in vapour density of the air (determined from measurements of $T_{air}$ and $RH_{air}$) before and after passing through the sweat capsule.

Figure 1.2: Diagramatic representation of the Vapour Flow Meter (VFM). Substrate relative humidity sensors and thermistors are located at two points (5 and 8 mm) within the diffusion boundary layer.

Figure 1.3: Principle in the measurement of local evaporative rate from the skin $E_{sk}$. Vapour density distribution is determined at two points of known distance within the diffusion boundary layer.

Figure 1.4: Esophageal temperature, forehead skin sweating rate (SR) and evaporative rate during body heating by A) exercise (EX, $T_a$ = 25°C), and B) hot water immersion (HW, 38°C). Following heating, subjects were cooled in 28°C water bath. Time zero indicates the onset of the heating regime.

Figure 1.5: Effect of esophageal temperature on forehead sweating rate of two subjects during heating by hot water immersion (HW) and moderate exercise (EX).

Figure 1.6 Vapour flow meter results from one subject. A) Vapour density distribution within the diffusion boundary layer at two points, 1 and 2, situated 5 and 8 mm from the skin surface respectively. B) Temperature and relative humidity at the two points (1 and 2) within the vapour flow meter.

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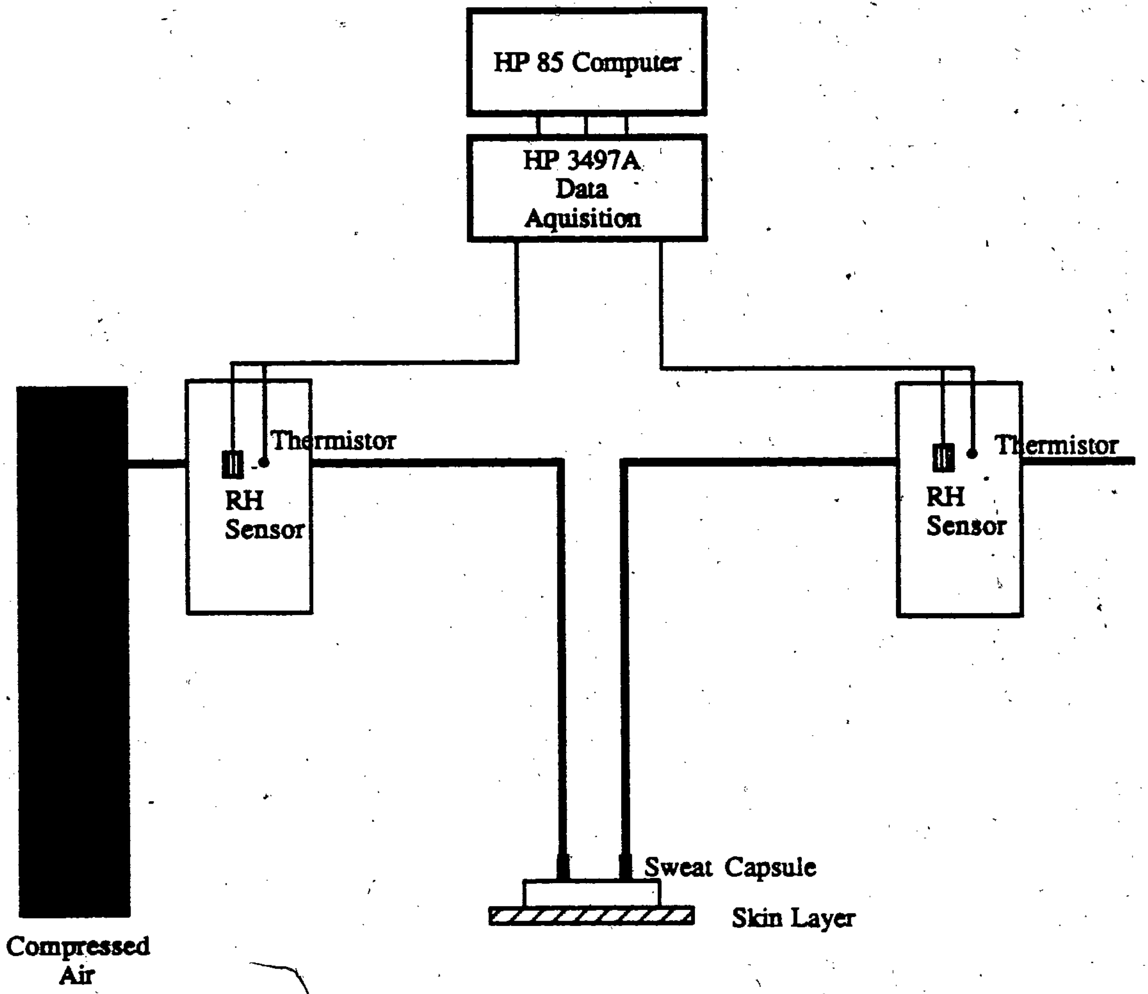

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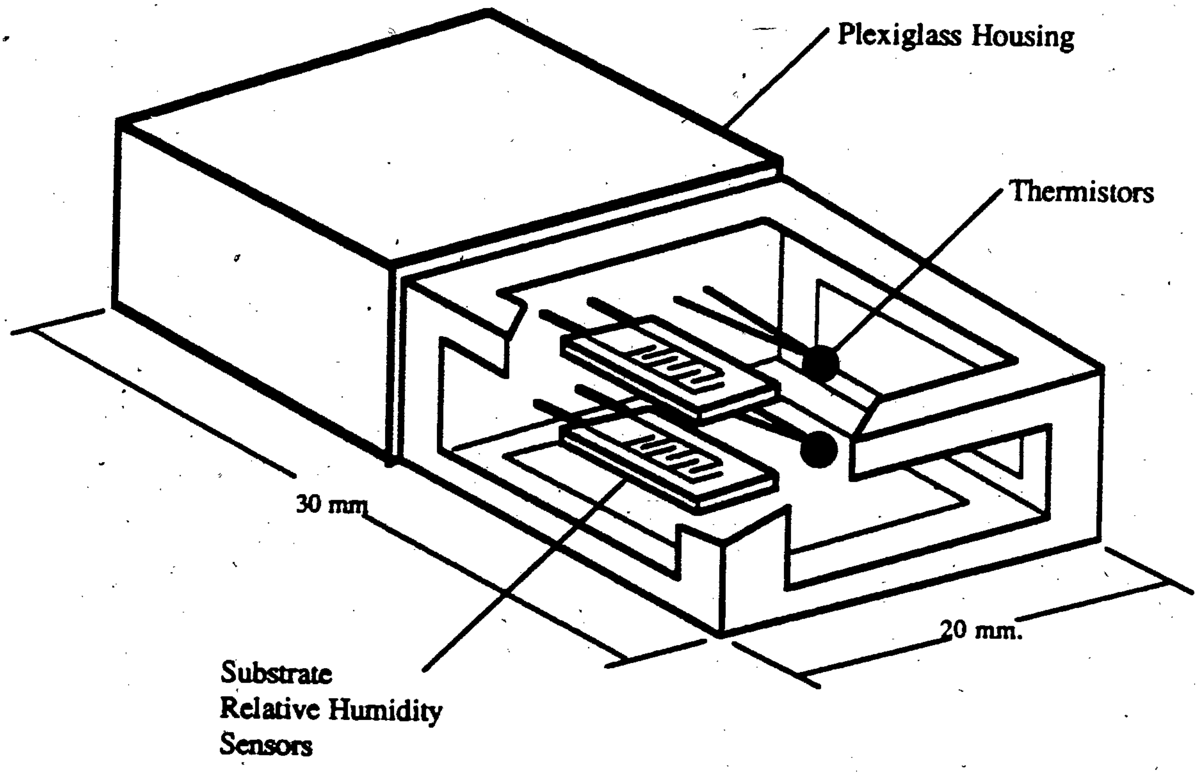

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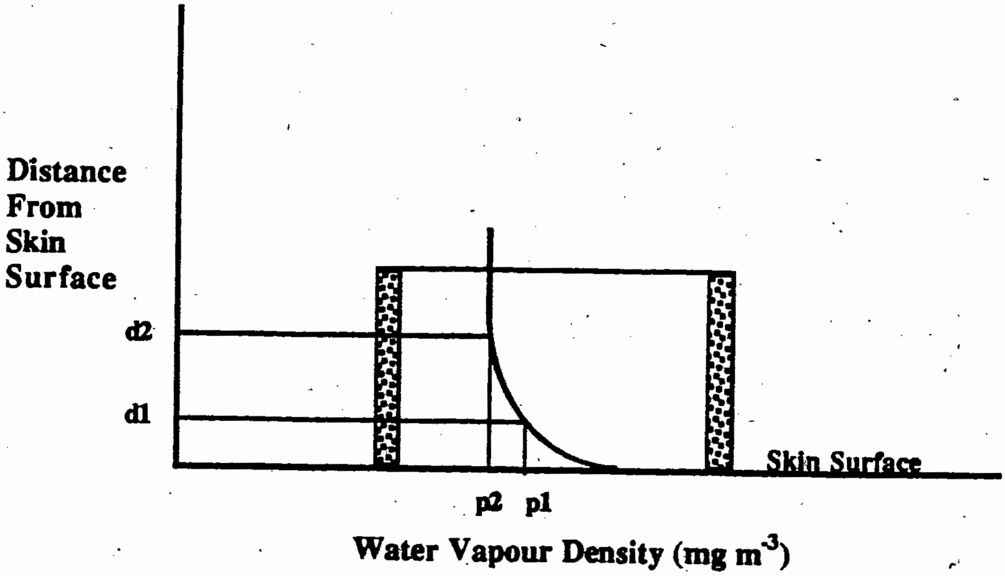

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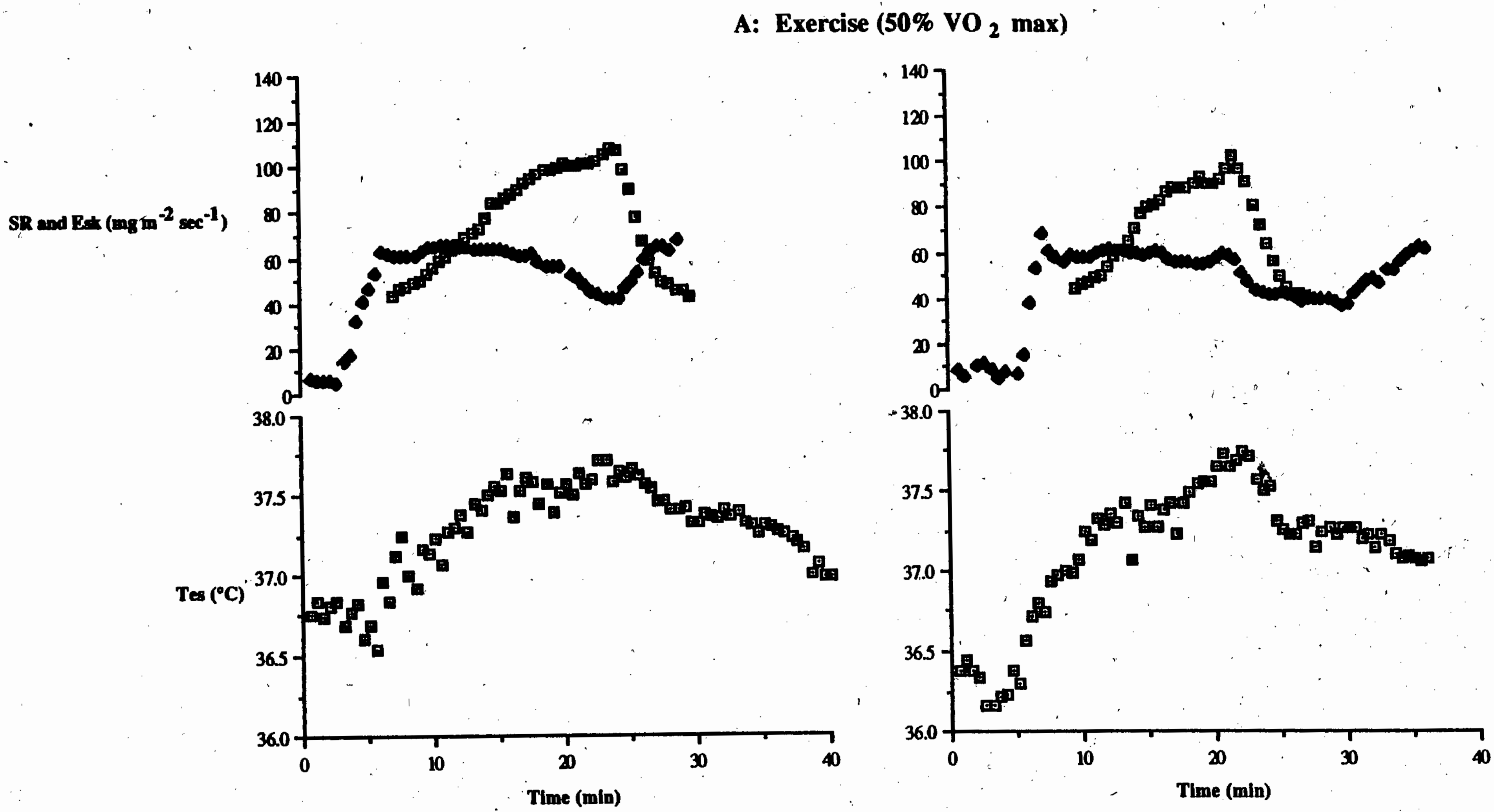
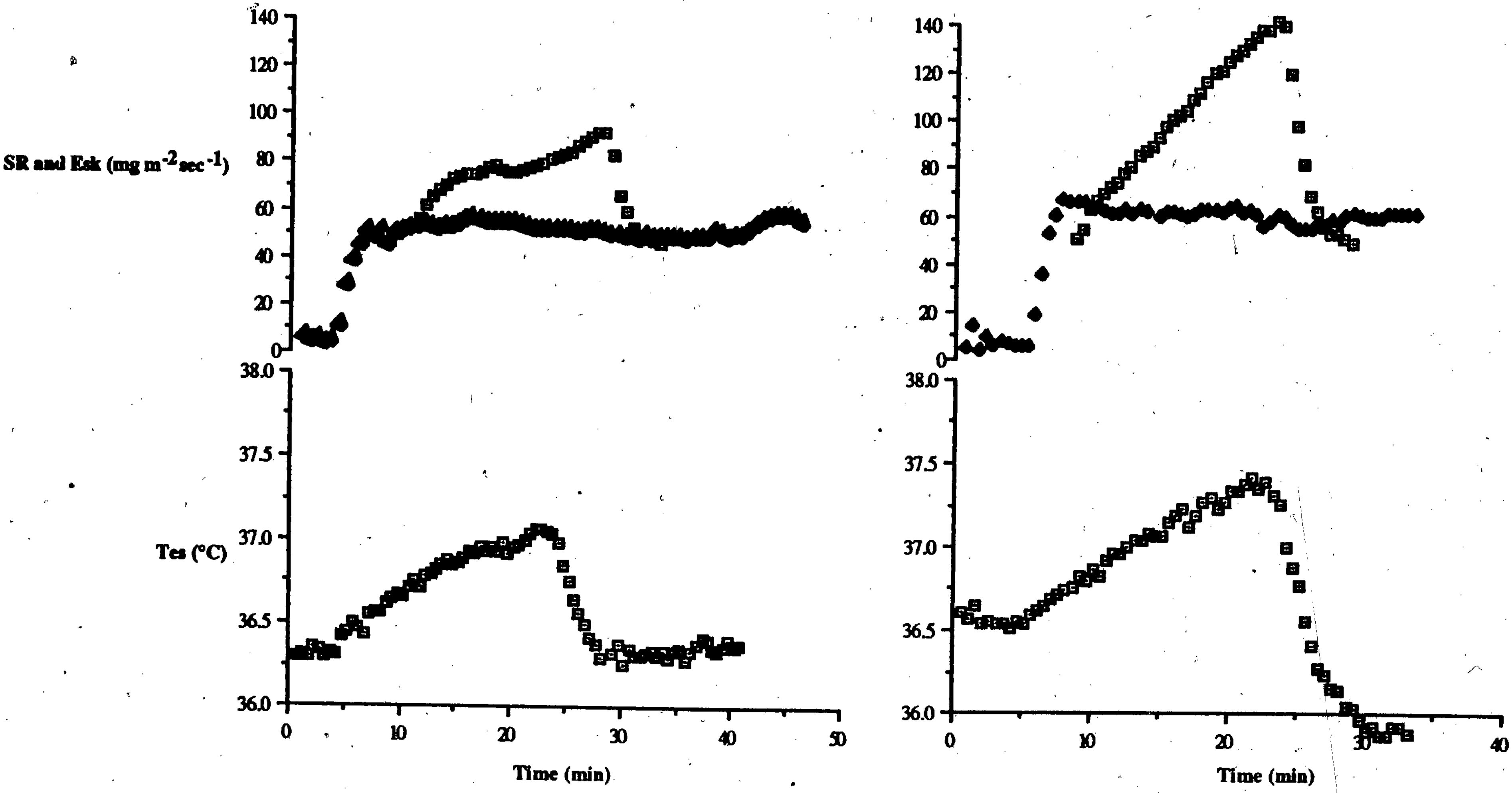


A: Exercise (50% $VO_2$ max)

## B: Hot Water Immersion



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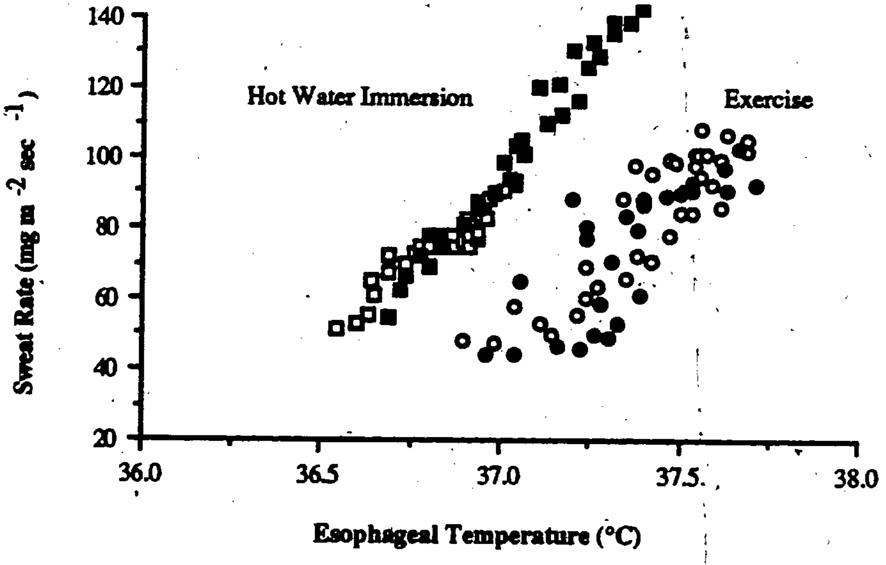

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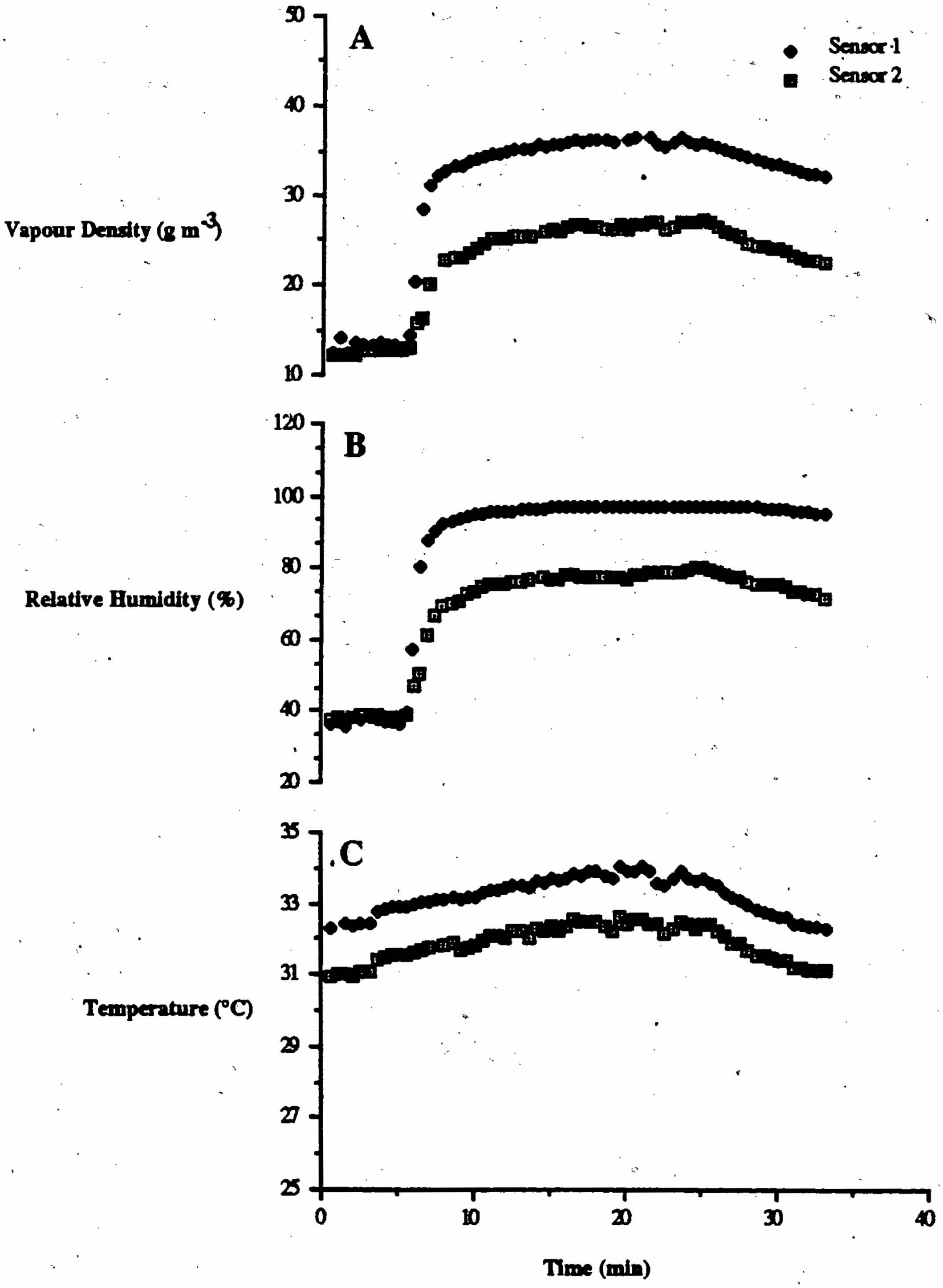

# Comparison of Water Vapour Resistances Determined From Fabric and Human Exposure Trials

## ABSTRACT

*In the present study, evaluation of the water vapour characteristics of fabrics is made utilizing a device for measuring local evaporative rates (Vapour Flow Meter, VFM), allowing similar assessments to be made both on a fabric model and* *<u>during</u>* *a simulated wear condition. Fabrics were assessed by means of a Water Vapour Resistance apparatus incorporating a temperature controlled water bath 15 cm below the fabric being studied by which heating of the water produces an increase in the water vapour pressure of the air directly below the fabric. In addition, the water vapour resistance of protective clothing fabrics was also performed during a hot air exposure in which five subjects were exposed to a linear increase in ambient temperature from 20-40°C over a 90 minute period and then remained at 40° C for an additional 90 minutes, for a total exposure time of 180 minutes. The fabric/fabric combinations studied include Nomex (N), Cotton Ventile, and Gore-Tex, the latter two of which were assessed in combination with cotton underwear (CV/U and GT/U).The water vapour resistance determined from results six trials performed on each fabric throughout the range of vapour pressure gradients were 67.9 ± 5.4, 54.6 ± 4.2 and 40.1 ± 2.8* $m^2 \cdot Pa \cdot W^{-1}$ *for the GT/U, CV/U and N fabrics, respectively. Resistances determined during the hot air exposure for the CV/U and GT/U combinations were 77.0 ± 10.4 and 91.4 ± 9.5* $m^2 \cdot Pa \cdot W^{-1}$ *respectively. Elevation in water vapour resistance may be attributed primarily to the added resistance of microenvironment air layers. In addition increased surface area of the garment through which evaporation may occur, hygroscopic absorption and possibly condensation may also influence water vapour resistance determined during normal wear conditions.*

## INTRODUCTION

An individual's well being depends upon the balance between energy production and the exchange of energy with the environment, so long as this balance is maintained within the limits of tolerance for heating and cooling of the body. This concept of balance is modified by the intervention of clothing, the intermediary between an individual and the surrounding environment. Clothing impedes the passage of both sensible and insensible heat due to the thermal insulation and the impedance to water vapour diffusion provided by the fabrics and trapped air layers (Gagge and Nishi, 1977).

Many industrial situations often require workers to perform in a variety of harsh environmental conditions. These potential hazards range from radiant heat, bacteria, chemicals and flames, to rain and cold water immersion. This has resulted in the development and provision of industrial protective clothing assemblies which attempt to minimize the hazards associated with the working environment. Unfortunately, while achieving this protection, various desirable attributes of clothing were sacrificed, the most important of which is the ability of the garment to allow the passage of water vapour, and thus insensible heat, away from the body, as the evaporation of sweat has the greatest capacity for the transfer of heat. Thus, in industrial situations where protective clothing assemblies are worn, comfort and performance will, to a great extent, be determined by a garment's ability to allow the transmission of water vapour. This is most evident in situations where the wearer is exposed to high environmental temperatures and/or is required to perform a moderate degree of physical activity.

In the past, the wearer has relied solely on the provision of garment design features such as full-length zippers, ventilation holes and covered flaps to improve the ventilation of the garments (Lomax, 1985). This is unacceptable for survival applications as time and space constraints in an emergency situation often preclude any suit adjustments particularly in aerospace applications (Brooks and Rowe, 1984). In recent years, manufacturers have attempted to alleviate this problem with the development of fabrics and fabric coatings which permit the transport of water vapour through the fabric layers while remaining resistant to the passage of liquid water (Taylor, 1975; Tanner, 1979).

Comprehensive testing of the thermal aspects of protective clothing assemblies often incorporate a variety of human exposure, manikin and fabric studies (Umbach, 1988). Human studies are attractive as a direct measure of the performance of clothing assemblies under simulated wear conditions, however determination of the vapour transfer characteristics is difficult during simulated wear conditions and the required methodology has only recently been developed (Holmer and Elnas, 1981; Gonzalez and Cena, 1985; Sommerville, 1988). Manikin studies eliminate some of these difficulties and provide the user with measures of the thermal and water vapour insulation characteristics for the total clothing system which can be inserted into predictive models used to simulate wear performance under a variety of climatic conditions and activity levels (Givoni and Goldman, 1974). In contrast, fabric studies offer the evaluation of specific fabric qualities which allow accurate selection among a number of textile items probably suited for a particular garment under specific applications. In addition, these studies also allow fabric manufacturers to determine the optimal fiber type, weave and/or coatings that will allow maximal transmission rates for water vapour.

The water vapour transmission rate (or the resistance to water vapour diffusion) of breathable fabrics is frequently the most difficult property to evaluate unambiguously, perhaps because there is no definitive test method yet available. There are currently a variety of simple methods utilized to determine water vapour transmission through fabrics, the most common of which is the control-dish method (CGSB-4.2-M77 Method 49). Ross (1987) lists a total of 10 different methods available for determining the transmission across a fabric layer (Table 2.1). In the majority of these tests the fabric under investigation is sealed over a dish of water and the rate of water vapour transmission is determined by measuring the weight loss from the dish over 24 hours. However, it should be noted that each method described by Ross, incorporates a specific combination of air temperatures and relative humidities on either side of the fabric such that the water vapour pressure gradient across the fabric is different for each test. The result of these dissimilar experimental conditions is, of course, an unfortunate difficulty in comparing results of the different methods unless the exact conditions under which the measurements were made are known. Recent innovative improvements in the assessment of water vapour characteristics of fabrics have been made by Watkins and Slater (1981), Farnworth and Dolham (1984), and Van Beest and Wittgen (1986) which allow fast and accurate assessments, and further, the ability to obtain absolute values for the water vapour resistance.

Although essential for the determination of the 'ideal' fabrics for use in the design of garments, fabric studies represent an optimal situation in which strict control of the fabric system and the prevailing ambient conditions is allowed. However, their extrapolation to normal wear situations is yet to be determined as similar techniques have not been used during wear conditions. Water vapour transmission through garments during normal wear, may be complicated by a number of factors, including; the added resistance of trapped air layers (Kakitsuba *et al.*, 1986), increased clothing surface area through which water vapour diffusion may occur (Haslam and Parsons, 1988), and the effects of condensation (Kaufman *et al.*, 1987), hygroscopic absorption (Nelbace and Herrington, 1942; Woodcock, 1962; Farnworth, 1986) and internal ventilation (Vokac *et al.*, 1973, 1976; Vogt *et al.*, 1983).

In the present study, evaluation of the water vapour characteristics of fabrics is made utilizing a device for measuring local evaporation (Vapour Flow Meter, VFM), allowing similar assessments to be made both on a fabric model and during a simulated wear condition. Comparison of these results with those of the fabric studies would provide information as to the water vapour-pressure gradients produced during normal-wear conditions and to give an indication as to the feasibility of utilizing fabric studies in the prediction of suit performance in hot environments. The present observations were made during the conduct of a larger study evaluating the thermal characteristics of protective clothing worn by helicopter personnel operating in Canadian coastal waters (Mekjavic and Sullivan, 1988).

## METHODS

The transmission of water vapour through a garment is often described by the following equation:

$$E = \frac{P_{sk} - P_a}{R_e} \qquad [2.1]$$

where:

$E$ = rate of water vapour transmission (often expressed as an equivalent evaporative heat loss, $W \cdot m^{-2}$)

$R_e$ = water vapour resistance of the fabric and air layers ($m^2 \cdot Pa \cdot W^{-1}$)

$P_{sk}$ = partial pressure of water vapour at the skin surface (Pa)

$P_a$ = partial pressure of water vapour of ambient air (Pa)

Thus, assessment of water vapour resistance ($R_e$) of the clothing system can be made from measurements of the evaporative rate and the vapour pressure gradient developed across the clothing ($P_{sk}$ - $P_a$). The design of the present study was such that the water vapour resistance measured was that of the complete fabric system (fabric plus air layers), as opposed to the intrinsic fabric water vapour resistance. In addition, the instrumentation utilized permitted identical measurements to be made on both a fabric model and during a simulated exposure. Sensor positioning ensured that the distance between the sensors and adjacent fabric were the same under all conditions such that the differences observed reflect the differences between fabrics and fabric/air layer combination.

## Fabric Studies

### Water Vapour Resistance Apparatus

Fabrics were assessed by means of a Water Vapour Resistance apparatus developed at Simon Fraser University. The present method incorporates a temperature controlled water bath 15 cm below the fabric being studied (Figure 2.1). Heating of the water produces an increase in the water vapour pressure of the air directly below the fabric, which is measured by means of a temperature and relative humidity sensor located 8 mm below the surface of the fabric. Water vapour pressure of ambient air is monitored by similar temperature and relative humidity sensors located in the room. By controlling the temperature of the water bath, with the whole apparatus in a constant environment, the water vapour pressure gradient ($\Delta P_f$) across the fabric can be varied so as to simulate gradients observed in the normal-wear condition. Vapour pressure gradients in protective clothing, in the order of 4.5 kPa, have been demonstrated in a previous study by Holmer and Elnas (1981).

Water vapour transmission through the fabric was evaluated by means of a Vapour Flow Meter (VFM) located on the surface of the fabric. The Vapour Flow Meter was used to determine the rate of water diffusion from the fabric surface by measuring the vapour pressure distribution over the diffusion surface. This is accomplished by measuring local humidity and temperature at two points in the diffusion boundary layer over the fabric surface, as shown in Figure 2.2. The diffusion process may be described by applying Fick's Law:

$$m_w = D_w \cdot \frac{\rho 1 - \rho 2}{d_1 - d_2} \qquad (\mathrm{mg \cdot m^{-2} \cdot sec^{-1}}) \qquad [2.2]$$

where:

$m_w$ = rate of water diffusion ($\mathrm{mg \cdot m^{-2} \cdot sec^{-1}}$)

$D_w$ = mass diffusivity of water into ambient gas ($m^2 \cdot sec^{-1}$)
$\rho$ = vapour density at measuring point ($mg \cdot m^{-3}$)
d = distance from diffusion surface to measuring point (m)

The rate of water diffusion through a fabric may be expressed as an evaporative rate ($E_f$, $W \cdot m^{-2}$) by incorporating the latent heat of vaporization ($0.58\ cal \cdot gm^{-1}$), in addition, vapour density is related to vapour pressure by the classical gas law. In this way the water vapour resistance for a particular fabric, expressed in $m^2 \cdot Pa \cdot W^{-1}$ was assessed throughout a range of water vapour density gradients as would be experienced with a variable sweating rate.

## Fabrics

Three fabric/fabric combinations were evaluated in this study which represent the range of water vapour permeable fabrics utilized in the assessment of microenvironment conditions in chapter 3 of this thesis. They consist of Gore-Tex/Underwear, Cotton Ventile/Underwear, and Nomex. Nomex/Insulite and Nomex/Neoprene combinations were eliminated due to the impermeable nature of the Insulite and Neoprene materials. Gore-tex, Nomex, and Cotton Ventile are all used in the construction of the commercially available helicopter pilot suits. Gore-tex is a polytetrafluoroethylene (PTFE) film which when stretched and annealed at high temperatures becomes permeable as a result of its reported 1.4 billion pores per square cm. These pores are large enough to allow the transmission of water vapour but too small to permit effective transmission of liquid water. Nomex is a loose weave aramid compound fiber whose very stable compound is commonly utilized as a flame retardant. Its looseness of weave allows rapid transmission of water vapour. Cotton Ventile is a double layered fabric constructed of Egyptian Cotton which allows water vapour transmission through its fairly large interfiber spacing. Once the fibers become wet they expand, decreasing the interfiber spacing providing an effective barrier to liquid water penetration. In conventional helicopter pilot suits both Cotton Ventile and Gore-Tex suits are worn in combination with long cotton underwear, thus comparisons with exposure studies were made using the Cotton Ventile/Underwear (CV/U) and Gore-Tex/Underwear (GT/U) combinations only. The Nomex fabric (N) was evaluated to allow comparison of the CV/U and GT/U with a fabric with a relatively low resistance to the transmission of water vapour. Fabric characteristics are listed in Table 2.2

## Protocol

Each fabric and fabric combination was assessed in a series of six trials, the combination of which produced a range of water vapour gradients across the fabric (from 1.0 to 5.0 kPa). A circular sample of each fabric (diameter = 9 cm) was placed in the apparatus such that an area of 19.63 $cm^3$ (diameter = 5 cm) was directly exposed to the microenvironment above the water bath. Ambient temperature and relative humidity were maintained at approximately 25°C and 30% respectively with a concomitant vapour pressure of 0.9 kPa. The water vapour pressure gradient was then controlled by means of changes in the temperature of the underlying water bath. During each trial, average $\Delta P_f$ and $E_f$ were determined and $R_{ef}$ calculated over a 30 minute period after a steady state had been achieved.

## Instrumentation

During the process of fabric assessment, water temperature ($T_w$), temperature and relative humidity 8mm below the fabric ($T_\mu$ and $RH_\mu$), ambient temperature ($T_a$) and relative humidity ($RH_a$) and evaporative rate through the fabric were monitored continuously. Water temperature was monitored by means of a copper-constantan thermocouple, whereas $T_a$, $RH_a$, $T_\mu$, $RH_\mu$ and water vapour diffusion were assessed using thermistors and substrate humidity sensors (Shinyei, Japan). The sensors were sampled every minute and the data stored by means of a Data Acquisition System (HP 3497A, Hewlett Packard) and a microcomputer (HP85, Hewlett Packard). After each test the data was transferred to a Macintosh 512KE computer (Apple) for analysis. Calibration procedures for the temperature and relative humidity sensors utilized in this study are outlined in Appendix A.

## Suit Exposure Studies

### Subjects

Five physically fit male university students volunteered to take part in this study. Following approval from the Simon Fraser University Ethics Review Commitee, all subjects underwent complete physical examinations by a qualified physician.

### Protocol

Before a suit was donned, subjects were instrumented with sensors to monitor temperature and relative humidity 8 mm from the skin surface, and evaporative rate from the surface of the suit fabric. Once the sensors were secured the subject donned a helicopter personnel suit over thermal underwear and entered the environmental chamber (Tenney), whereupon he assumed a seated position in a helicopter pilot seat (for complete description see chapter 3 of this thesis). The helicopter pilot seat used was supported above the floor in mid chamber by a metal frame constructed of steel tubing (Figure 2.3). The metal stucture with the subject seated within was then draped with 2 layers of cloth, an internal black cloth to absorb radiant heat emmited from the body and an external white cloth to reflect any radiant heat. Once positioned, the subject remained at an ambient temperature and relative humidity of approximately 22°C and 50% respectively for five minutes. Chamber temperature was then increased in a linear fashion to a temperature of 40°C (relative humidity uncontrolled) over a period of approximately 90 minutes. The subject then remained seated at this temperature for a further 90 minutes for a total duration of three hours (180 minutes).

## Suits

Garments utilized in this study consisted of commercially available helicopter suits constructed of the tested fabrics mentioned above during a simulated hot air exposure. The suits utilized for comparison this study are shown in Figure 2.4 and consist of; A) Gore-Tex and B) Cotton Ventile. Both the Gore-Tex and Cotton Ventile suits are of the dry-suit design with airtight seals at the ankles, wrists and neck such that the exchange of warm, moist microenvironment air with ambient air can only occur through the fabric. Both suits were worn over a pair of long cotton thermal underwear (C). During the exposure both leather gloves and heavy boots were worn.

## Instrumentation

Measurements of suit microenvironment temperatures and relative humidities were obtained by use of Vapour Flow Meters (VFM) secured to three sites on the skin: the upper arm, chest and thigh. Each VFM consists of two substrate relative humidity sensors and two temperature sensors (thermistors), thus the temperature and water content of the air within the microenvironment of the suit can be determined. Vapour Flow Meters located at three sites (arm, chest and thigh) on the surface of the fabric were utilized to determine the amount of water vapour transmission through the fabric layers as outlined in Equation 2.2. In this way instrumentation was identical to that in the fabric studies with exception of the source of water vapour (human sweat vs. temperature controlled water bath). The data was sampled by an HP3497 Data Acquisition System (Hewlett Packard) and stored on an HP9817 computer (Hewlett Packard). Calculations and analysis were performed on a MacIntosh 512KE (Apple).

## RESULTS

### Fabric Results

Prior to fabric assessment, the system was evaluated by producing step increases in $T_w$ and thus water vapour pressure gradients across the fabrics, an example of which is presented in Figure 2.5. Vapour pressure gradients ( $\Delta P_f$ ) and resultant evaporative heat loss through the fabric were monitored continuously at 2 minute intervals throughout the duration. Results indicated that for the system, the transmission of water vapour was linearly related to the water vapour pressure gradient developed across the fabric ($R^2$ = 0.99). Fluctuations were observed during transient changes in $\Delta P_f$ necessitating steady state determination of the water vapour resistance of fabrics as described in the methods.

The results of the six trials performed on each fabric are displayed in Table 2.3. The performance of several measurements of the water vapour resistance throughout the range of vapour pressure gradients tested, of each of the fabrics used in the construction of the suits, showed a distribution of resistances with means and standard deviations of 67.9 ± 5.4, 54.6 ± 4.2 and 40.1 ± 2.8 $m^2 \cdot Pa \cdot W^{-1}$ for the GT/U, CV/U and N fabrics, respectively.

## Suit Results

Determination of water vapour pressure near the skin of the subject is dependent on reliable data being obtained from both the thermistor and substrate humidity sensor located under the clothing. Similarly, accurate measurements of $E_{cl}$ is contingent on four measurements (two temperature and two relative humidity). Thus, errors obtained from any one of the six sensors would result in an inability to determine the $E_{cl}/\Delta P_{cl}$ relationship for the clothing of that particular site of measurement. Relative humidity sensors positioned 5 mm from the skin surface were very susceptible to wetting from dripping sweat. Due to wetting of the humidity sensors from dripping sweat during the exposure trials, erroneous values in at least one of the six sensors were detected in two subjects for the CV and GT suits. In addition, for the remaining three subjects, consistent errors were detected at the chest site. Thus for the Cotton Ventile and Gore-Tex suits, analysis will be restricted to two sites (arm and thigh) on each of three subjects allowing 6 determinations of the $E_{cl}/\Delta P_{cl}$ relationship for each suit.

Elevation in ambient temperature from 21.4 ± 0.5 to 39.8 ± 0.3 °C over a 90 minute period produced a decrease in relative humidity from initial to final values of 53.1 ± 1.1 to 28.1 ± 0.2% respectively. These changes in $T_a$ and $RH_a$ correspond to a slight overall increase in vapour pressure from 1.30 to 2.06 kPa. Figure 2.6 displays average $\Delta P_{cl}$ gradients developed across the suits throughout the 3 hour exposure. Gradients increased from initial values of 0.38 ± 0.15 and 0.47 ± 0.25 kPa to final values of 2.94 ± 0.25 and 3.26 ± 0.28 kPa for the CV and GT suits respectively. Vapour pressure gradients remained low for a period of 10 to 40 minutes following the increase in ambient temperature. A sudden increase in $\Delta P_{cl}$ was noted followed by an exponential rise which reached a steady state within 100 minutes of the duration of the exposure. Thereafter, $\Delta P_{cl}$ values remained relatively constant with only minor fluctuations. Variations in the onset and rate of rise of $\Delta P_{cl}$ were evident, however, initial and final levels remained fairly consistent.

Average evaporative rates of the six conditions are displayed in Figure 2.7. In general, $E_{cl}$ rose gradually following the elevation in ambient temperature, however, fluctuations in $E_{cl}$ throughout the last two thirds of the exposure in each condition as demonstrated in the representative graph of $E_{cl}$ for the CV/U suit shown in Figure 2.8.

A representative graph of the $E_{cl}/\Delta P_{cl}$ relationship is presented in Figure 2.9, and is typical of the hot air exposures. In addition, a line representing the predicted evaporative rate as determined from the fabric studies is also presented. It is evident from that, unlike the controlled fabric evaluation, a linear relationship does not exist between the vapour pressure gradients developed across the clothing system and the measured evaporative rates during transient increases in $\Delta P_{cl}$, and that evaporative rates are consistently lower than predicted from fabric assessments. This lack of linearity may be attributed to factors such as variations in the total thickness of the clothing system, condensation and hygroscopic absorption. Calculation of water vapour resistance for each condition was performed as in the fabric studies as the ratio of $\Delta P_{cl}$ over $E_{cl}$, both values of which were determined from the average of 30 minutes once steady state had been achieved, and are displayed in Table 2.3. Water vapour resistances for the CV/U and GT/U suits, determined during the hot air exposure, were 77.0 ± 10.4 and 91.4 ± 9.5 $m^2 \cdot Pa \cdot W^{-1}$ respectively. This represents a significant elevation in $R_e$ ($p<0.05$) during the suit exposure study as compared to the measurements made on the Water Vapour Resistance Apparatus, with the GT/U displaying consitently higher values as compared CV/U ($p<0.05$).

## DISCUSSION

The water vapour resistance of fabrics is of primary importance in the construction of protective clothing assemblies for use under conditions of elevated ambient temperatures, particularly when incorporated in the construction of dry suits, as the transfer of evaporated sweat is limited to passage through the fabric. Although many current methods used in the assessment of $R_f$ allow accurate determination of the intrinsic (minus air layers) water vapour resistance under steady state conditions, the present study illustrates the differences in water vapour resistances between fabric studies and simulated wear trials, and indicates that the relationship between the vapour pressure developed across the fabric and the transmission of water vapour through the fabric is not constant during elevations in sweat rate in normal wear conditions.

The Water Vapour Resistance Apparatus developed allows for the simulation of a varieity of different vapour pressure gradients developed across a garment during normal use. Of the fabric/fabric combinations studied, GT/U displayed the highest resistance to water vapour with the CV/U and N fabrics having progressively lower resistances. The magnitudes of the $R_{ef}$ values are large and reflect the added resistance of air layer. Although both Farnworth and Dolham (1984), and Van Beest and Wittgen (1986), have developed methods for determining the vapour resistance of fabrics in absolute terms, their values are reported in equivalent millimeters of still air making comparisons of $R_f$ values determined in this study with others difficult, however the relative differences between fabrics reported in this study are similar to those measured elsewhere (Farnworth, personal communication). Nomex is a loose weave fabric and has been shown to offer minimal resistance to the transmission of water vapour (Van Beest and Wittgen, 1986), thus much of the resistance measured in this study would be due to adhering air layers. Performing several measurements of resistance on each fabric/fabric combination yielded standard deviations as large as 5 $m^2 \cdot Pa \cdot W^{-1}$ and may be largely attributed to the sensitivity of the VFM. As a result, the present apparatus may be inadequate in the comparison of several highly permeable fabrics as the differences observed would likely fall within the range of accuracy of the apparatus.

Exposure to ambient temperatures of 40°C simulates the conditions observed within aircraft cockpits (Gribetz *et al.*, 1980). Elevation in ambient temperature was associated with a sudden increase in water vapour pressure gradient developed across the suit, which may be attributed to the onset of sweat secretion, followed by a gradual rise in the evaporative rate through the clothing. Elevated ambient temperature was characterized by steady state vapour pressure gradients which were larger for the GT/U suit (3.26 ± .28 kPa) than the CV/U suit (2.94 ± .25 kPa), however, $E_{cl}$, displayed some fluctuations around maximal values. Vapour Flow Meters enable calculation of evaporative rate by measuring the vapour pressure gradient within the diffusion boundary layer next to the clothing. Disturbance of this gradient by convective air currents would have resulted in variations in calculated $E_{cl}$. This was likely the case as fluctuations in $E_{cl}$ were characterized by variations in the measurement of RH, in particular the RH sensor furthest from the surface of the suit. The source of convection may be attributed to subject movement due to discomfort and unrest as the heat stress was imposed. Improved shielding of the VFM may aid in the development of steady-state $E_{cl}$, and thus improve the calculation of local water vapour resistance of the garment.

Throughout the first 80-100 minutes of exposure, the relationship between $E_{cl}$ and $\Delta P_{cl}$ differed from that of the fabrics assessed using the Water Vapour Apparatus indicating that for any given $\Delta P$, the evaporative rate through the clothing is less than that predicted from fabric studies under steady state conditions. In addition, steady state water vapour resistances were much larger than similar measurements made on the Water Vapour Resistance Apparatus. These discrepancies are likely due to the inherent differences in the clothing versus fabric studies, such as the volume of air between the skin and outer suit and the effective surface area through which water vapour transmission may occur.

Protective clothing systems typically contain a large volume of air between the skin and outer clothing (Crockfrod and Rosenblum, 1974; Sullivan *et al.*, 1987), termed the microenvironment volume ($V_\mu$), which effectively adds an increased resistance for the diffusion of water vapour. In fabric studies, this volume is minimal and is often limited to the thickness of the air within the fabric. In contrast, during normal wear, $V_\mu$ will depend to a large extent on the fit, drape, and posture, influencing the thickness of the air layer between suits and between locations within a suit. Suits with relatively small microenvironment volumes and areas where the clothing is close to the skin would likely display lower water vapour resistances than suits and regions where the thickness of the air layer is large. Performance of fabric tests with varying $V_\mu$ may lead to further understanding of this process, but would require some modification to the apparatus used in this study.

Large microenvironment volumes would also be associated with an increase in the surface area of the clothing ($A_{cl}$) through which water vapour may diffuse. Thus, the evaporative rate determined on fabric studies would overestimate $E_{cl}$. These factors ($V_\mu$, $A_{cl}$) may be accounted for by incorporating the ratio of skin area to clothing area (Lotens, 1988) and the average thickness of the clothing microenvironment ($V_\mu/A_{cl}$) as proposed by Kakitsuba *et al.* (1986).

Differences between fabric and clothing water vapour resistances may also be influenced, in part, by the processes of condensation and hygroscopic absorption. Water vapour permeability has been shown to decreased in colder environments, due to condensation, with most textiles becoming virtually impermeable to water vapour at -40°C (Meinander, 1986). However, condensation is an unlikely factor in the present study due to elevated environmental temperatures throughout most of the exposre. In contrast, hygroscopic absorption may have a similar, albeit much reduced, effect on measured water vapour resistance. Absorption of water vapour by the fabric layers may effectively reduce the water vapour available for diffusion through the clothing. The effects of absorption, however, are transient (Farnworth, 1986) and would likely only contribute to a reduced evaporative rate during transient increases in $\Delta P_{cl}$.

Both heat and mass transfer are influenced by wind and the pumping effect associated with movement (Vokac *et al.*, 1972; Vogt *et al.*, 1983), and their effect may be influenced through factors such as weight, stiffness, cut and fit of the garment. Although wind was not a factor in this study, it is unclear as to what influence the pumping effect may have had on the results of this study as the sensors utilized are dependant on the maintenance of a still air layer next to the clothing. Adequate assessment of wind and pumping effects on the resistance of clothing to water vapour may be restricted to direct measurements of heat exchange using human subjects (Holmer and Elnas, 1981; Gozalez and Cena, 1985).

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## TABLE LEGENDS

Table 2.1: Ten common methods of determining the water vapour transmission of fabrics.

Table 2.2: Insulative and air ventilation characteristics of suit fabrics utilized in the present study. Methods utilized are outlined in Appendix.

Table 2.3: Water vapour resistance of fabrics ($R_{ef}$, determined using the Water Vapour Resistance Apparatus), and suits ($R_{ecl}$) with associated average vapour pressure gradients ($\Delta P_{cl}$) and evaporative rates ($E_{cl}$) produced during hot air exposures.

Table 2.1: Ten common methods of determining the water vapour transmission of fabrics.

| Test Name | Method | Conditions | | Water Vapour Pressure Gradient (mm Hg) |
|---|---|---|---|---|
| | | Temperature (°C) | Relative Humidity (%) | |
| ASTM E96-80 | A (Desiccant) | 23.0 | 50 | 10.5 |
| ASTM E96-80 | B (water Method)* | 23.0 | 50 | 10.5 |
| ASTM E96-80 | C (Desiccant) | 32.2 | 50 | 18.0 |
| ASTM E96-80 | D (Water Method) | 32.2 | 50 | 18.0 |
| ASTM E96-80 | E (Desiccant) | 37.8 | 90 | 44.2 |
| JIS-Z-0208** | Dish (Desiccant) | 25.0 | 90 | 21.4 |
| JIS-Z-0208 | Dish (Desiccant) | 40.0 | 90 | 49.8 |
| British MOD*** | Dish (Water Method) | 35.0: outside 20.0 | 65 | 30.8 |
| B.S. 3177:1959 | Temperature (Desiccant) | 25.0 | 75 | 17.8 |
| B.S. 3177:1959 | Tropical (Desiccant) | 38.0 | 90 | 44.7 |

* This method currently used in most military specifications

** Japanese Industrial Standard

*** British Ministry of Defense

Table 2.2: Insulative and air ventilation characteristics of suit fabrics utilized in the present study. Methods utilized are outlined in Appendix.

| Suit | Fabric | Thermal Resistance (m2 K W-1) | Ventilation Index (liters/min) |
|---|---|---|---|
| CV | Cotton Ventile | 0.96 | 2.86 |
| GT | Goretex | 2.00 | 0.04 |
| N/I | Nomex shell<br>Insulite liner | 19.20 | 3.41<br>impermeable |
| N/N | Nomex Shell<br>Neoprene liner | 7.30 | 3.41<br>impermeable |

Table 2.3: Water vapour resistance of fabrics ($R_{ef}$, determined using the Water Vapour Resistance Apparatus), and suits ($R_{ecl}$) with associated average vapour pressure gradients ($\Delta P_{cl}$) and evaporative rates ($E_{cl}$) produced during hot air exposures.

| Fabric/Suit | Suit<br>$\Delta P_{cl}$ (kPascal) | Suit<br>$E_{cl}$ (W m-2) | Suit<br>$R_{e\,cl}$ (m2 Pa W-1) | Fabric<br>$R_{e\,f}$ (m2 Pa W-1) |
|---|---|---|---|---|
| GT/U | 3.26 ± .28 | 35.7 ± 10.4 | 91.4 ± 9.5 | 67.9 ± 5.4 |
| CV/U | 2.94 ± .25 | 38.2 ± 11.7 | 77.0 ± 10.4 | 54.6 ± 4.2 |
| N | | | | 40.1 ± 2.8 |

## FIGURE LEGENDS

Figure 2.1: Water Vapour Resistance Apparatus. Water vapour pressure gradient across the fabric/fabric combination was controlled through variation in water temperature, and assessed using temperature and relative humidity sensors below the fabric and in the ambient environment. Water vapour diffusion through the fabric was measured with a Vapour Flow Meter positioned on the surface of the fabric.

Figure 2.2: Principle of measurement of the amount of water vapour diffusing through a fabric layer. Vapour flow is determined by measuring the vapour density distribution above the surface of the fabric. The diffusion process may be described by applying Fick's Law.

Figure 2.3: Experimental set-up for the hot air exposure study. Subjects remained seated in a helicopter pilot seat suspended within an environmental chamber. Evaporative rate through the clothing was moitored by means of Vapour Flow Meters positioned on the arm, chest and thigh.

Figure 2.4: Helicopter aircrew personnel suits utilized in the comparison of water vapour resistance of fabrics and clothing. Suits consisted of: A) Gore-Tex and B) Cotton Ventile. Both suits are of the dry suit design (seals at the neck, wrist and ankles) and were worn over long cotton underwear (C).

Figure 2.5: Representative graph of the relationship between evaporative rate through the fabric ($E_f$) and water vapour pressure gradient developed across the fabric ($\Delta P_f$) during step changes in temperature of the water bath.

Figure 2.6: Average vapour pressure gradients ($\Delta P_{cl}$) developed across the Cotton Ventile/Underwear and Gore-Tex/Underwear suits throughout the duration of the hot air exposure. Data are presented at five minute intervals.

Figure 2.7: Average evaporative rates ($E_{cl}$) through the suits during the hot air exposure in, A) Cotton Ventile/Underwear, and B) Gore-Tex/Underwear suits. Data are displayed at five minute intervals.

Figure 2.8: Representative evaporative rate through the CV/U suit throughout the hot air exposure.

Figure 2.9: Typical $E_{cl}/\Delta P_{cl}$ relationship observed during the hot air exposure. The straight line represents the predicted evaporative rate as determined from steady state assessment of fabric water vapour resistance.

Figure 2.1: Water Vapour Resistance Apparatus. Water vapour pressure gradient across the fabric/fabric combination was controlled through variation in water temperature, and assessed using temperature and relative humidity sensors below the fabric and in the ambient environment. Water vapour diffusion through the fabric was measured with a Vapour Flow Meter positioned on the surface of the fabric.

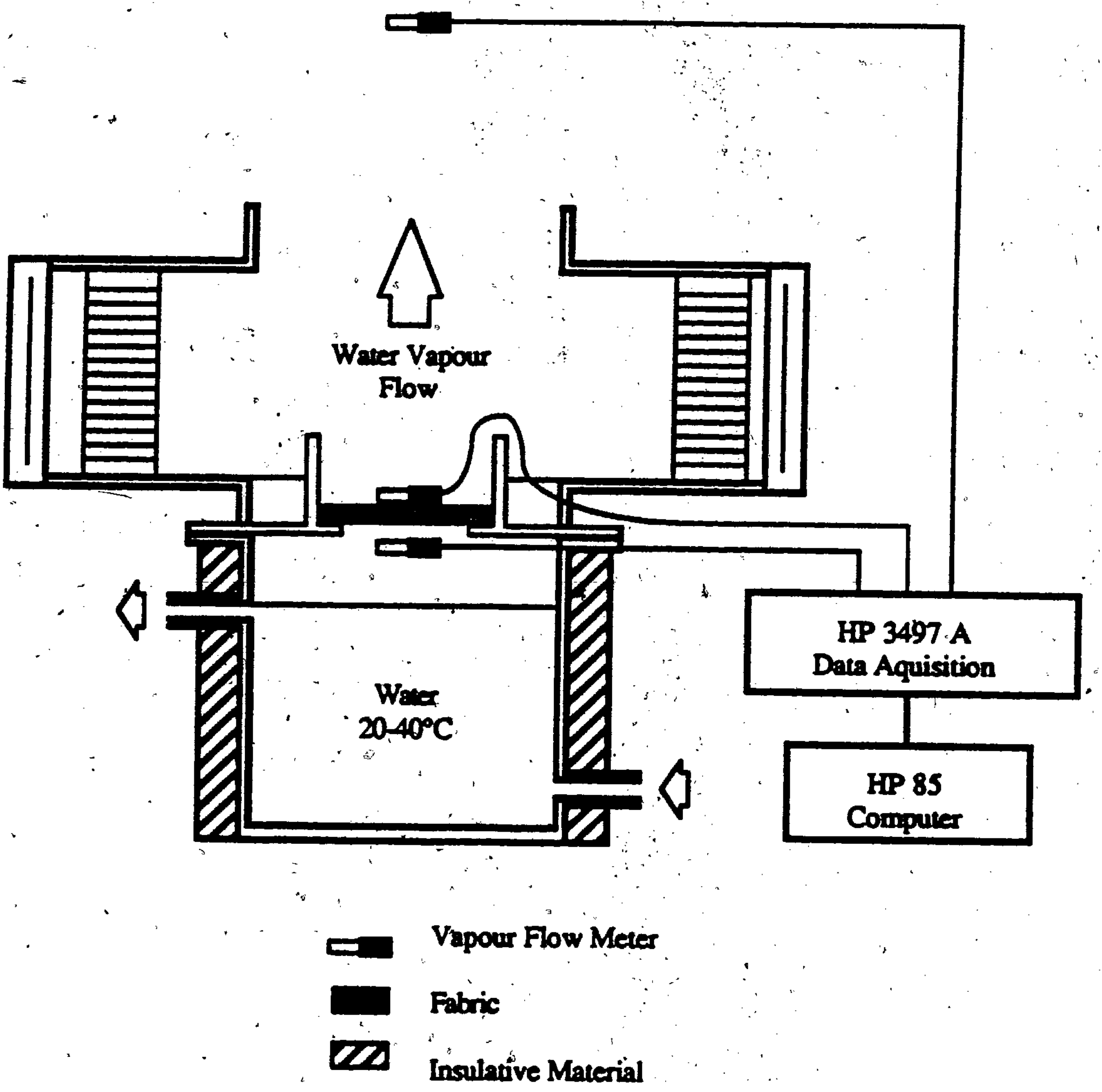


Figure 2.2: Principle of measurement of the amount of water vapour diffusing through a fabric layer. Vapour flow is determined by measuring the vapour density distribution above the surface of the fabric. The diffusion process may be described by applying Fick's Law.

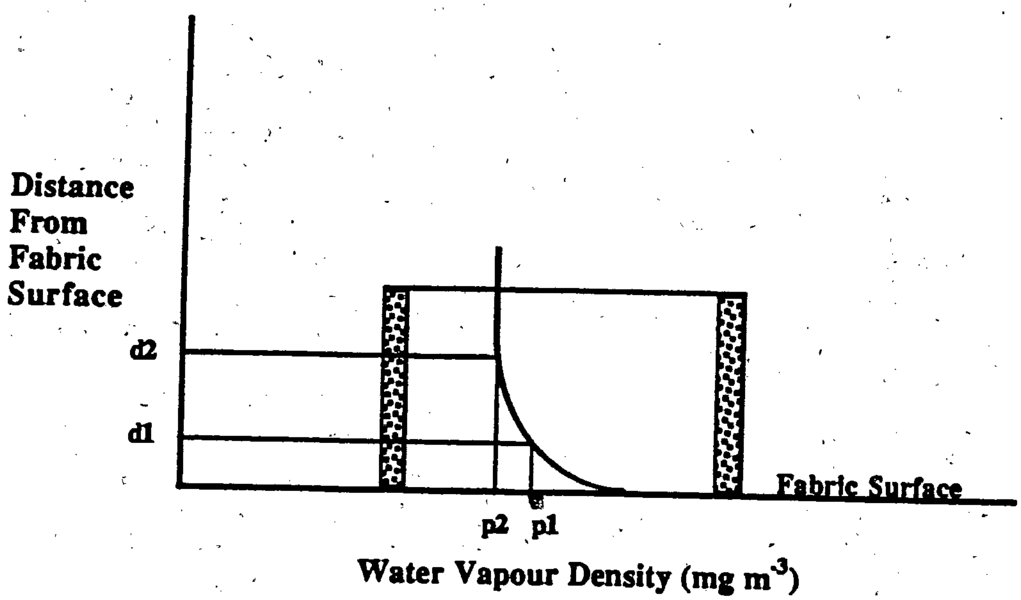


Figure 2.3: Experimental set-up for the hot air exposure study. Subjects remained seated in a helicopter pilot seat suspended within an environmental chamber. Evaporative rate through the clothing was moitored by means of Vapour Flow Meters positioned on the arm, chest and thigh.

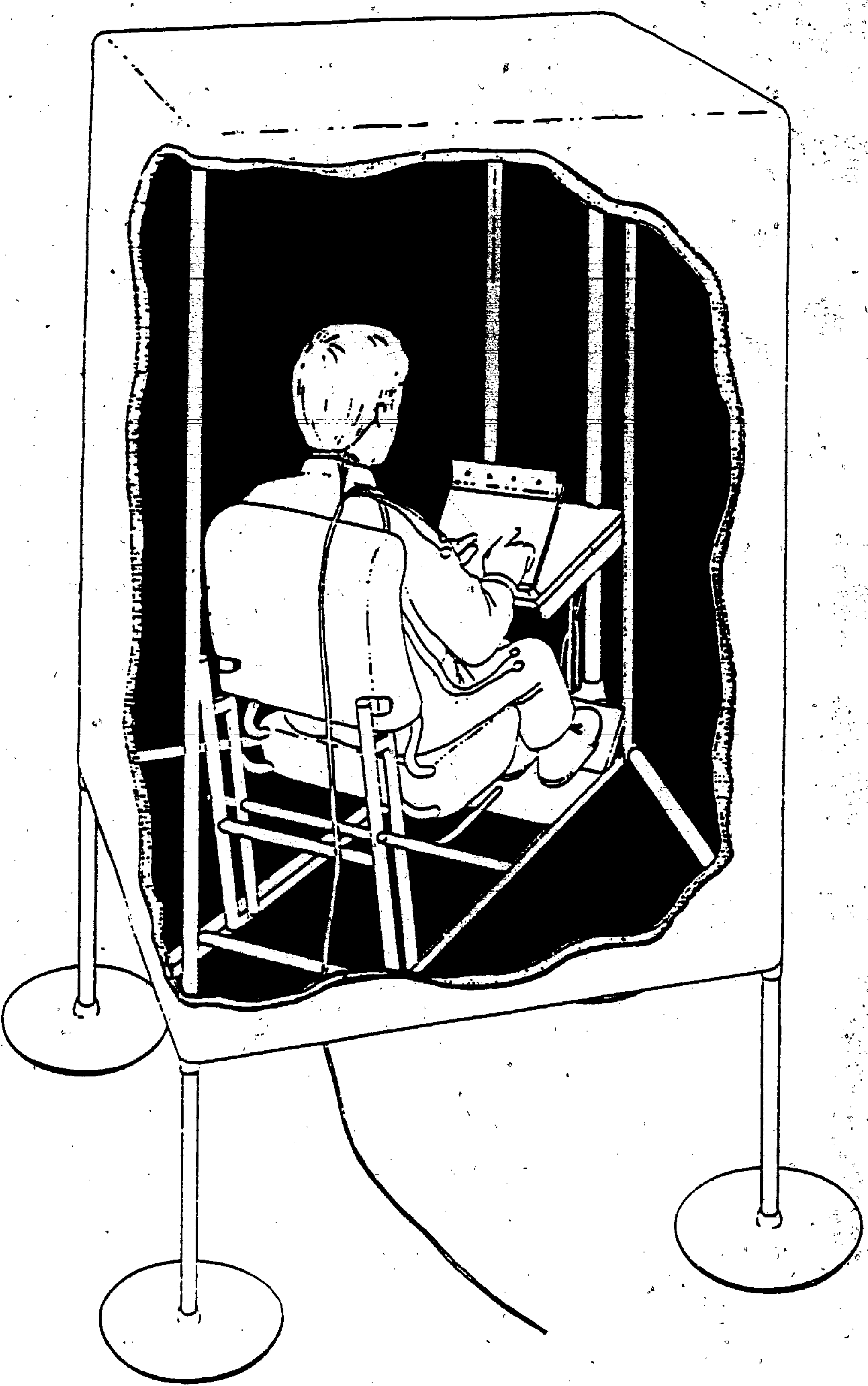


**Figure 2.4:** Helicopter aircrew personnel suits utilized in the comparison of water vapour resistance of fabrics and clothing. Suits consisted of: A) Gore-Tex and B) Cotton Ventile. Both suits are of the dry suit design (seals at the neck, wrist and ankles) and were worn over long cotton underwear (C).

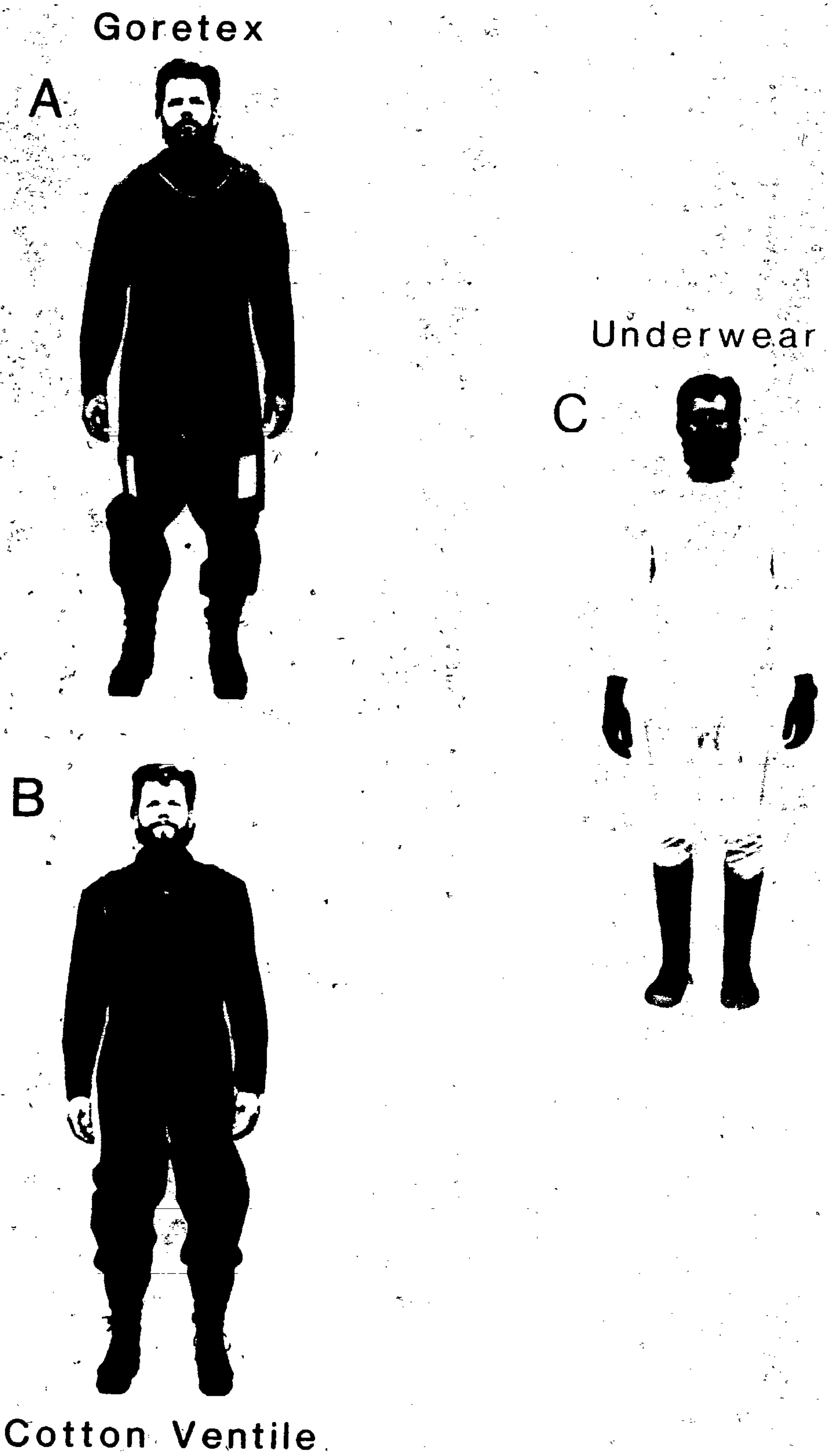


Figure 2.5: Representative graph of the relationship between evaporative rate through the fabric ($E_f$) and water vapour pressure gradient developed across the fabric ($\Delta P_f$) during step changes in temperature of the water bath.

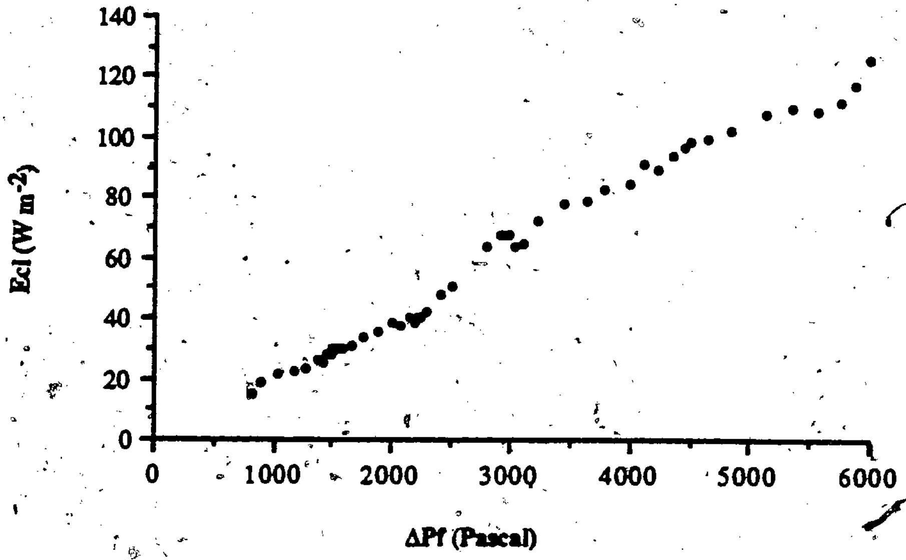


Figure 2.6: Average vapour pressure gradients ($\Delta P_{Cl}$) developed across the Cotton Ventile/Underwear and Gore-Tex/Underwear suits throughout the duration of the hot air exposure. Data are presented at five minute intervals.

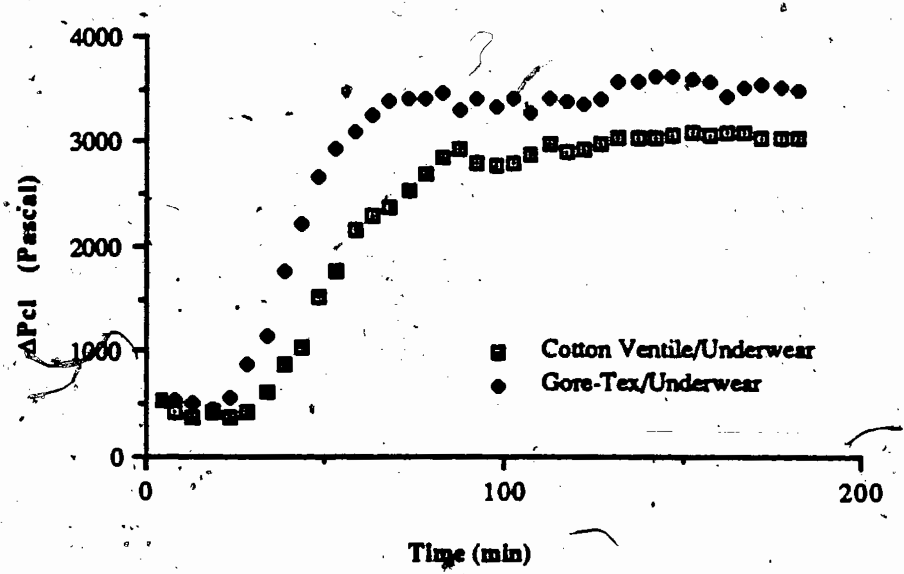


Figure 2.7: Average evaporative rates ($E_{cl}$) through the suits during the hot air exposure in, A) Cotton Ventile/Underwear, and B) Gore-Tex/Underwear suits. Data are displayed at five minute intervals.

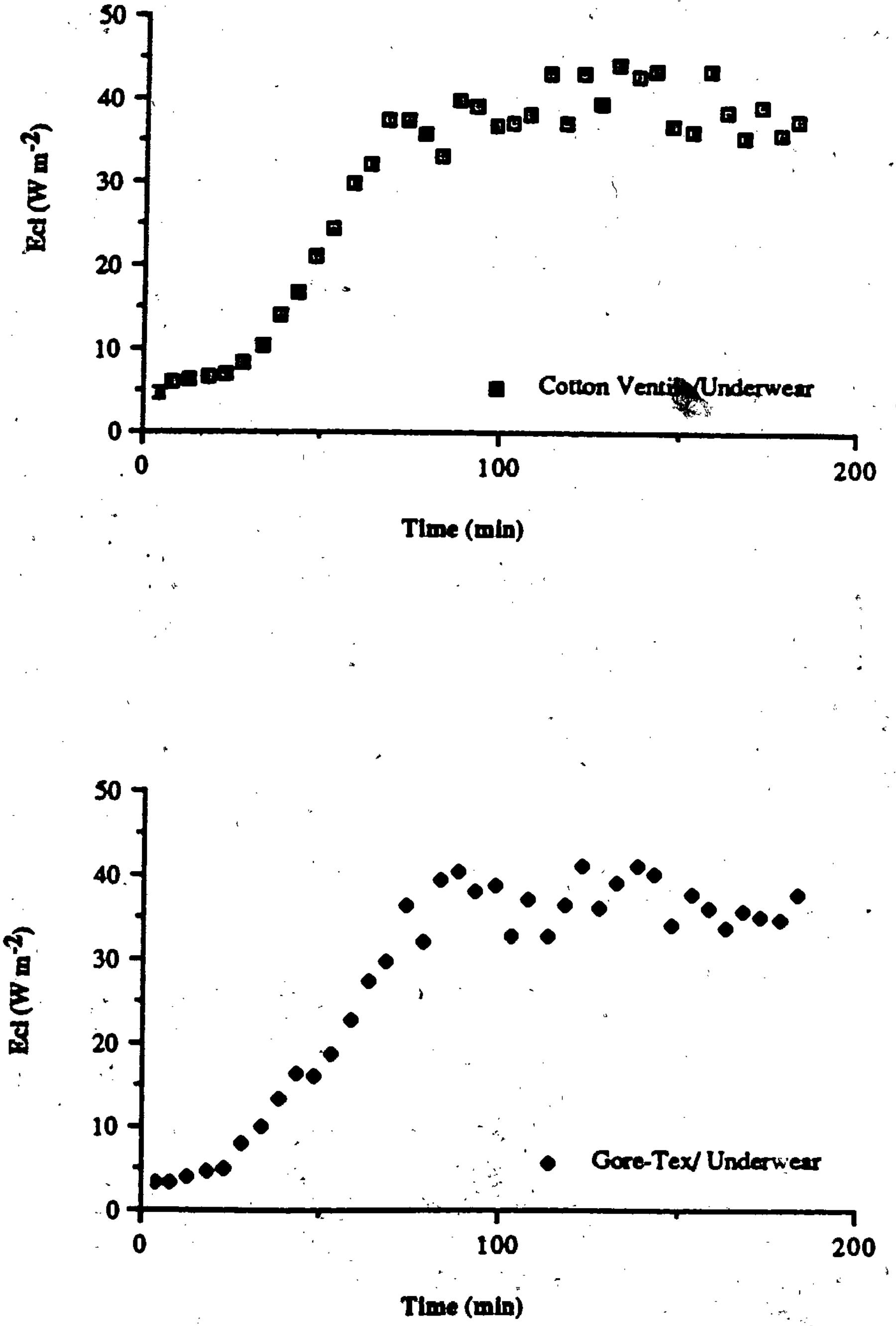


Figure 2.8: Representative evaporative rate through the CV/U suit throughout the hot air exposure.

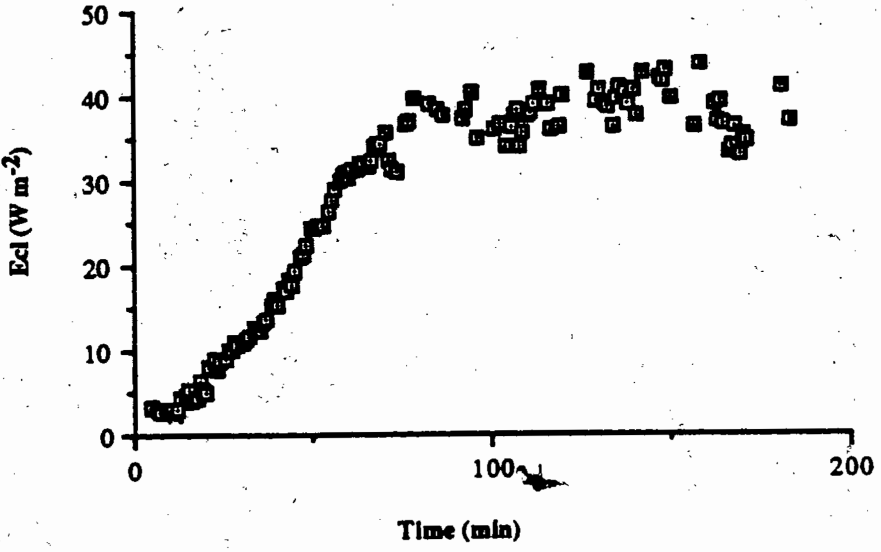
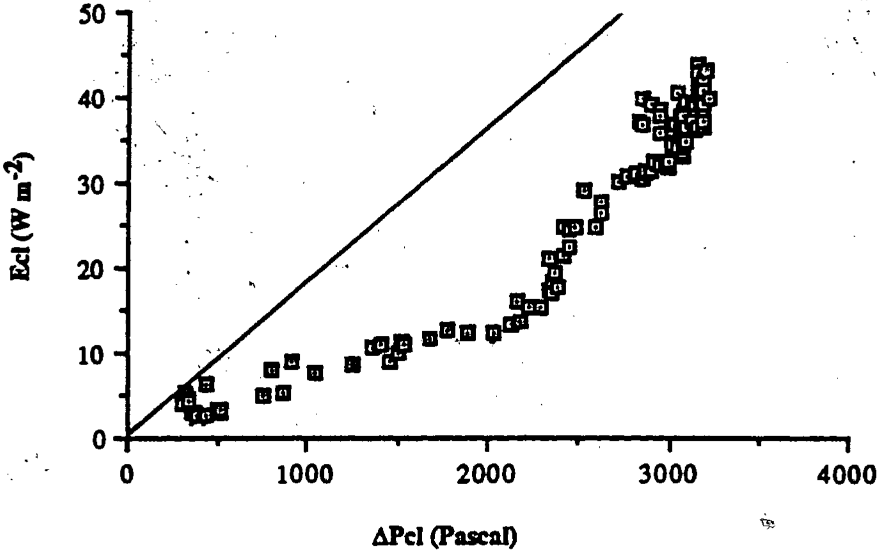


Figure 2.9: Typical $E_{cl}/\Delta P_{cl}$ relationship observed during the hot air exposure. The straight line represents the predicted evaporative rate as determined from steady state assessment of fabric water vapour resistance.



# Temperature and Humidity Within the Clothing Microenvironment: Determinants of Heat Strain

## ABSTRACT

*The thermal stress of a working environment is often defined by the dry-bulb temperature, radiant temperature, relative humidity and velocity of the ambient air. However, many occupations require workers to wear protective clothing, which creates a thermal and water vapour barrier between the skin and ambient. Thus, the temperature and humidity conditions of the clothing microenvironment ($T_{\mu}$ and $RH_{\mu}$), which is the true environment to which the worker is exposed, may be significantly higher than those of the ambient air resulting in decreased heat loss and thus a higher heat stress as would be predicted from ambient conditions. The present study investigates differences between ambient and microenvironment conditions that may develop during prolonged exposure of clothed workers to a hot environment. Five subjects were exposed to a linear increase in ambient temperature from 20-40°C over a 90 minute period and then remained at 40° C for an additional 90 minutes, for a total exposure time of 180 minutes. During the exposures subjects were clad in four types of helicopter personnel suits commonly used by helicopter pilots (Gore-Tex, Cotton Ventile, Nomex/Insulite and Nomex/Neoprene). These suits incorporated dry-suit and wet-suit designs and were constructed of a variety of different fabrics. During the exposure, continuous assessment was made of skin temperature and rectal temperature. Humidity and temperature sensors, positioned 8 mm from the surface of the skin, enabled assessment of $T_{\mu}$ and $RH_{\mu}$ and calculation of water vapour pressure ($P_{\mu}$). Results indicate that although microenvironment temperatures were similar amongst suits and slightly lower than that of the environment, the $RH_{\mu}$ and $P_{\mu}$ was much greater than that of the ambient air. In addition, the Nomex/Insulite and Nomex/Neoprene suits showed the highest $P_{\mu}$, of which only the Nomex/Insulite resulted in significantly greater increases in rectal temperature due to incomplete covering of the body with the impermeable neoprene component of the Nomex/Neoprene suit. Elevation of $T_{\mu}$ above that of the skin and clothing indicates heat production due to hygroscopic absorption. The present study obviates the need to discern between the ambient conditions and the conditions encountered next to the skin when protective clothing is worn. Since differing protective clothing assemblies will vary in their properties of insulation and water vapour permeability, it is proposed that conditions within the microenvironment of the suit would enable better prediction of heat strain than indices incorporating only ambient variables.*

## INTRODUCTION

For workers employed in occupations ranging from deep mining to aerospace industries, elevated environmental temperatures cannot be avoided as it is either impractical or impossible to remove all or part of the excessive heat from the workplace and the active worker. Low levels of heat stress produce discomfort and fatigue (Nunneley *et al.*, 1978), as the thermal load increases, performance becomes impaired (Grether, 1973) and eventually the health of the worker is jeopardized. It is both of practical and theoretical importance to determine a number of aspects of the effects of heat stress on the thermal strain experienced by the worker, including: what level of environmental heat load is associated with the onset of discomfort, performance degradation and physiological collapse; how each of these factors mentioned will vary with progressive thermal loads; what aspects of performance are affected by heat; and the physiological and/or morphological characteristics of those individuals able to resist such impairment as the tolerance limits are approached. An essential prerequisite for the elucidation of each of these questions is the ability to quantify the heat load or heat stress imposed upon individuals.

Since Houghton and Yaglou (1923a,b) developed the first index of heat stress termed the Effective Temperature (ET), there has been a plethora of studies aimed at either supporting their original concept, or developing new indices for specific working environments. To date the most commonly used indices of heat stress are (for review see Gagge and Nishi, 1976; Gonzalez *et al.*, 1978; Lee, 1980) the Predicted 4-hour Sweat Rate ($P_4SR$), Belding and Hatch's Heat Stress Index (HSI), Effective Temperature (ET), Corrected Effective Temperature (CET), Wet Bulb Globe Temperature (WBGT), Swedish Wet Bulb Globe Temperature Index (SWBGT), and the Wet Bulb Temperature (WBT). It is these indices of heat stress that researchers have used as estimates of the heat load on the individual for the purpose of predicting the heat strain experienced by the worker during a normal shift.

Indices of heat stress are based primarily on the physical measurements of air temperature ($T_{db}$, dry bulb), radiant temperature ($T_g$, globe), relative humidity ($T_{wb}$, wet bulb) and air velocity (v). An ideal index of heat stress is one that would include all the external factors which influence an individual's heat balance in addition to the inherent differences in individual responses. To this extent the above indices are inadequate as they do not fully account for duration of exposure, type of clothing worn, degree of acclimatization, level of fitness in relation to the physical work load, and physical work rate *per se*. Furthermore, in industry, work is performed under rather varied conditions. Most workers do not maintain a constant rate of physical work (and thus heat production) throughout their shift, and this varying physical work is often performed under varying levels of heat stress throughout the day.

Field studies in hot industries have demonstrated that there may be no universal index of heat stress, which would predict the heat strain of workers for a wide range of dry-bulb, wet-bulb, and globe temperatures (Goldman, 1988; Rodahl and Guthe, 1988). To a large degree, the ineffectiveness of the various studies is due to the variety of thermal protective clothing, which is currently being used in industrial environments. These clothing assemblies, although designed to protect the individual from specific environmental hazards such as chemicals, fire, cold or radiant heat, may prevent adequate dissipation of body heat, especially for active workers under conditions of elevated ambient temperatures. The clothing is constructed of fabrics which may vary in the resistance to heat and water vapour. In addition, the design of the clothing may vary, some allowing air movement within the microenvironment through openings in the wrists, ankles and neck and strategically placed vents, and others being restrictive in the amount of air movement through the suit. It is not surprising therefore, that current heat stress indices fail to predict the heat strain imposed on the worker.

Heat transfer from a clothed person can be described using a number of equations. These are commonly simplified into two general equations, one for dry heat transfer (DRY):

$$\mathrm{DRY} = \frac{(T_{sk} - T_a)}{R_c} \qquad (\mathrm{W \cdot m^{-2}}) \qquad [3.1]$$

and the other for evaporative heat transfer (EVAP):

$$\mathrm{EVAP} = \frac{(P_{sk} - P_a)}{R_e} \qquad (\mathrm{W \cdot m^{-2}}) \qquad [3.2]$$

Dry heat transfer, that of convection and radiation, is a function of of the temperature gradient ($T_{sk}$-$T_a$) and the combined resistance of the clothing and air layers to dry heat transfer ($R_c$), whereas evaporative heat transfer is a function of the vapour pressure or vapour density gradient ($P_{sk}$ - $P_a$) and the combined resistance of the clothing and air layers to the diffusion of water vapour ($R_e$). In general, the addition of clothing impedes both dry and evaporative heat transfer through an increase in the resistance of both the fabric and trapped air layers. Recent models predicting heat strain attempt to account for fabric and clothing characteristics, as determined using standard hot-plate or manikin techniques (Giovani and Goldman, 1972; Goldman, 1973; Breckenridge and Goldman, 1977; ISO/DIS, 1987; Mecheels and Umbach, 1979), however these models are often imprecise as the effects of air velocity and wearer activity on the resistance to heat and water vapour are often difficult to quantify (Holmer and Elnas, 1981; Haslam and Parsons, 1988). These factors will, to a large extent, be determined by garment weight, stiffness, cut, fit, and posture, and as such, a universal equation may be impossible (Breckenridge and Goldman, 1977). Adequate evaluation of clothing performance may be limited to actual wear conditions as models do not allow adequate simulation of the interaction between the human, clothing and environment (Fourt and Hollies, 1970; Holmer and Elnas, 1981)

For a fully suited worker with only the head exposed (relative surface area of the head is approximately 7%), 93% of the body surface area will be exposed to the suit microenvironment, that is, the volume of air above the surface of the skin but directly beneath the suit (Figure 3.1). For industrial protective garments this volume may be as high as 50 liters (Sullivan *et al.*, 1987). A reduction in the transfer of both heat and water vapour due to the addition of clothing may result in a build up of heat and water vapour within the clothing microenvironment, the level of which will depend on: 1) the characteristics of the fabric, and 2) the design of the garment (openings and ventilation).

In the past, conditions within the microenvironment have largely been ignored as researchers have concentrated on the measurement of skin temperature and vapour pressure in order to estimate the corresponding resistances to heat and water vapour flow (Nagata, 1978; Holmer and Elnas, 1981; Gonzalez and Cena, 1985; Sommerville, 1988). Recently however, Goldman (1988) has suggested evaluating microenvironmental conditions in assessing suit performance. This would be advantageous considering that the conditions within the microenvironment represent the true environment to which the individual is exposed. In contrast to ambient conditions, which may remain fairly stable throughout the industrial environment (independent of work place and time), the conditions of the suit microenvironment would vary with changes in activity level of the worker and possibly duration of exposure. However, few studies have documented measurements of the conditions within the clothing microenvironment. Vokac *et al.* (1973, 1976) have demonstrated the efficacy of such measurements in the assessment of the bellows ventilation of clothing and have indicated that microenvironment conditions may be dependant on the type of clothing worn.

The present study was designed to investigate the changes in the temperature and humidity of the microenvironment which may arise as a result of a heat exposure when wearing a variety of suits constructed of different fabrics types and design concepts. The present observations were made during the conduct of a larger study evaluating the thermal characteristics of protective clothing worn by helicopter personnel operating in Canadian coastal waters (Mekjavic and Sullivan, 1988). The suits are designed to provide thermal protection in the case of emergency ditching, but should not impair performance despite the possible elevations in cockpit temperatures as a result of the 'greenhouse effect' due to high radiant heat loads. The suits represent two different design concepts: the dry-suit and wet-suit principle, and incorporate different combinations of insulation and permeability. Thus the results demonstrate the range of heat stress which may be imposed on an individual exposed to the same environment, as a result of suit design and fabric composition.

## METHODS

### Subjects

Five physically active male university students volunteered to take part in this study, which was approved by the Simon Fraser University Ethics Review Committee. Their physical characteristics were (mean ± S.D.): age, 25.6 ± 2.1 years; height, 180 ± 5.1 cm; and weight, 77.8 ± 8.5 kg. All subjects underwent a complete physical examination prior to participating in this study.

### Protocol

Before donning a suit, subjects were instrumented for the measurement of rectal temperature ($T_{re}$), skin temperature ($T_{sk}$) and microenvironment temperature and relative humidity ($T_{\mu}$, and $RH_{\mu}$). In addition, the suits were instrumented for the measurement of clothing temperature ($T_{cl}$). Once the sensors were secured, the subject donned a helicopter personnel suit over thermal underwear and entered the environmental chamber (Tenney Engineering Inc.), whereupon a seated position was assumed in a helicopter pilot seat. The helicopter pilot seat was supported above the floor in mid-chamber by a metal frame (height = 180 cm, length = 72 cm, width = 72 cm) constructed of steel tubing (diameter = 38 mm). The metal cube shaped stucture, with the subject seated within its geometric center, was draped with 2 layers of cloth covering all six sides, an internal black cloth to absorb radiant heat emitted from the body and an external white cloth to reflect any external radiant heat. The set-up was designed to reduce air movement around the subject to a minimum, and to create a uniform radiation field (Figure 3.2). Once seated, the chamber conditions were maintained at an ambient temperature and relative humidity of approximately 22°C and 50% respectively for five minutes. Thereafter, the chamber temperature was increased to a temperature of 40°C over a period of approximately 90 minutes (relative humidity uncontrolled). The subject then remained seated at this temperature for a further 90 minutes for a total duration of three hours (180 minutes). Throughout the duration of the exposure $T_{sk}$, $T_{re}$, $T_{cl}$, $T_{\mu}$ and $RH_{\mu}$ were monitored continuously at one minute intervals.

## Suits

The suits utilized in this study were: Gore-Tex (GT), Cotton Ventile (CV), Nomex/Insulite (N/I) and Nomex/Neoprene (N/N). Both the Gore-Tex and Cotton Ventile suits were of the dry-suit design with airtight seals at the ankles, wrists and neck such that the exchange of warm moist microenvironment air with ambient air could only occur through the fabric. In contrast, the Nomex/Insulite and Nomex/Neoprene suits were of the wet-suit design thus allowing some measure of ventilation through openings in the garment. The Gore-Tex material is a polytetrafluroethylene film which, due to its small diametered 1.4 billion pores per $cm^2$, is reportedly able to resist the transmission of liquid water while maintaining a high degree of water vapour permeability. The Cotton Ventile suit was constructed of a double layer of Egyptian Cotton which, while dry, permits the transmission of water vapour, but once wetted, the fibers expand such that the interfiber space becomes reduced, thus becoming resistant to the transmission of liquid water. The Nomex/Insulite suit consisted of a 3-6 mm insulite layer sandwiched between two layers of Nomex material, preventing both liquid and water vapour transmission except through the openings of the suit. On the other hand, the Nomex/Neoprene suit consisted of a single layer of Nomex worn over a neoprene shorty. The thermal resistance, water vapour resistance, and air ventilation characteristics of each fabric are listed in Table 3.1. Thermal resistance was determined using a modified version of BS4745 (for details see Gilling *et al.*, 1972), water vapour resistance was assessed as described in chapter 2 of this thesis, and the rate of air exchange through the fabric was determined using the method described by Mekjavic and Sullivan (1988). All suits were worn over a pair of long cotton thermal underwear with the exception of the Nomex/Neoprene suit as indicated above. During the exposure, subjects wore wool socks and heavy leather boots.

## Instrumentation

Measurements of suit microenvironment temperatures and relative humidities were obtained with substrate humidity sensors (Shinyei Humient HPR-MQ) and thermistors positioned 8mm above the skin surface at three sites: the upper arm, chest, and thigh. With these sensors the temperature, relative humidity and vapour density of the air within the microenvironment of the suit could be determined and the vapour pressure (kPascals) calculated from the classical Gas Law. In addition an estimate of core temperature was made using a rectal thermistor (15 cm, YSI 701, Yellow Springs Instruments). Skin and clothing temperatures were measured at three sites (upper arm, chest and thigh) using heat flux transducers with embedded thermistors (Thermonetics Corporation). Ambient temperature and relative humidity were continuously measured by a thermistor (Yellow Springs Instruments) and a hygrometer (Shinyei Digital Hygrometer) respectively. The data was sampled by an HP3497A Data Aquisition System (Hewlett Packard), stored on a HP9817 computer (Hewlett Packard) and later analyzed using a Macintosh 512KE (Apple) computer.

## Analysis

Although continuous monitoring of all variables was conducted during each trial at one minute intervals, for the purpose of the present study, comparison of data was made during the last 60 minutes of the exposure when conditions within the microenvironment had stabilized. Average skin, clothing and microenvironment temperature and microenvironment relative humidity were calculated as unweighted means of the arm, chest and thigh sensors. In the event of a rare failure of a relative humidity sensor due to possible wetting from dripping sweat, average $RH_\mu$ was calculated as the mean of the two remaining sites. Comparisons of $T_\mu$, $RH_\mu$ and $P_\mu$ between suits were made by one way analysis of variance for repeated measures. In addition, heat strain was assessed by a one way ANOVA for repeated measures on the changes in mean skin temperature ($\Delta T_{sk}$) and rectal temperature ($\Delta T_{re}$)

## RESULTS

A representative plot of ambient and microenvironment temperature ($T_a$, $T_\mu$) and relative humidity ($RH_a$, $RH_\mu$) for one trial is shown in Figure 3.4. Following the collection of approximately five minutes of resting values the temperature within the climatic chamber was increased from 21.4 ± 0.5 °C to 39.8 ± 0.3 °C over a 90 minute period and thereafter held constant for the duration of the experiment. As only the temperature of the chamber was controlled, the increase in temperature was associated with a concomitant decrease in relative humidity from initial to final values of 53.1 ± 1.1 to 28.1 ± 0.2 % respectively. Changes in $T_a$ and $RH_a$ correspond to a slight overall increase in ambient vapour pressure ($P_a$) from 1.30 to 2.06 kPa possibly due to the addition of water vapour from the evaporation of water from the skin and respiratory tract of the subject and attendants. In general, the rise in $T_\mu$ followed that of ambient temperature, stabilizing at approximately 90 minutes, whereas $RH_\mu$ displayed an abrupt increase up to 40 minutes after the elevation in ambient temperature. The time at which $RH_\mu$ began to increase varied between subjects and locations and may be attributed to differences in the onset in sweating.

The increased environmental heat load is accompanied by increases in the temperature of the air within the clothing microenvironment (Figure 3.5A, Table 3.1). Average $T_\mu$ for all suits increased from 31.08 ± 0.22 °C to a maximum of 36.26 ± 5.56°C for the N/N suit. A one way analysis of variance indicated no observed difference in $T_\mu$ between the suits throughout the last 60 minutes of the exposure, rather microenvironment temperature appeared related to the temperature of the ambient air than to fabric type and garment design.

In contrast to $T_\mu$, the relative humidity of air within the clothing microenvironment increased despite a decrease in $RH_a$ and, the degree of rise appeared to be dependent on the type of suit worn (Figure 3.5B). Initial $RH_\mu$ for the CV (39.2 ± 5.1 %) and GT (38.0 ± 2.1 %) suits were much lower than that of N/I (56.9 ± 17.1 %) and N/N (69.8 ± 11.9 %) suits. Throughout the exposure the N/I and N/N suits consistently produced the highest $RH_\mu$, achieving near saturation levels of 96.1 ± 1.5% and 97.7 ± 0.7%

respectively. In contrast, the microenvironment air below the CV and GT suits achieved saturation levels of only 76.5 ± 6.6 and 88.4 ± 4.1 percent. Due to the similarity in $T_\mu$, water vapour pressures ($P_\mu$) reflect the degree of saturation of microenvironment air (Figure 3.5C). One way analysis of variance showed no differences in $P_\mu$ between the N/I and N/N suits, whereas the vapour pressures within the GT and CV suits were significantly lower ($p < 0.05$).

A representative graph of $T_{sk}$ and $T_{re}$ for the duration of the hot air exposure is displayed in Figure 3.6A. Initial skin temperature was similar for all four suits and began to increase in a linear fashion at the onset of the hot air exposure thereafter stabilizing a few degrees above the pre-exposure $T_{sk}$ with an overall profile similar to that of $T_a$ and $T_\mu$. In contrast, $T_{re}$ either remained near the pre-exposure level or dropped slightly for the first 30 to 60 minutes, rising thereafter. One way analysis of variance performed on the changes in $T_{sk}$ and $T_{re}$ ($\Delta T_{sk}$ and $\Delta T_{re}$) showed similar elevations in $T_{sk}$ for all four suits whereas rectal temperature increased significantly more (as much as 1.2°C, $p<0.05$) when subjects wore the N/I suit as compared to the CV (0.29°C), GT (0.23°C), and N/N (0.39°C) suits (Figure 3.6B).

# DISCUSSION

The experiments simulated, in a simplified manner, a typical situation in which the investigated clothing is worn, and serve to illustrate the differences between ambient and microenvironment conditions. During offshore helicopter flights, high radiant heat loads on clear days often result in cockpit temperatures becoming elevated as high as 40-50°C (for review see Gaul and Mekjavic, 1987) due to a lack of onboard cooling systems. Although it is common to estimate the heat stress on an individual (and thus predict heat strain) by incorporating measurements of ambient variables, an individual's thermal condition, when wearing industrial protective clothing, will ultimately be determined by factors which influence the rate at which heat can be dissipated to the environment, most notably the clothing assembly worn. Thus, even if a temperature and water vapour pressure gradient does exist between the skin and the ambient environment, a thermal or water vapour barrier will substantially affect the ability of an individual to dissipate metabolic heat, and as such, consideration of the characteristics of both the fabric type and the design of the suit is imperative when trying to predict the heat strain on an individual.

In the present study, cockpit conditions were simulated by elevating ambient temperature to 40°C within a structure designed to minimize air movement and to create a uniform radiant field. This increase in $T_a$ was associated with a decline in $RH_a$ from 53.1 to 28.1 %. However, regardless of the identical heat loads imposed, the true level of heat stress depended on the garments worn. This is evident in the significant elevation of $T_{re}$ by 1.2°C when subjects wore the N/I suit as compared to the other suits ($\Delta T_{re}$ = 0.3°C). Since $T_{sk}$ was similar in all conditions, and assuming that the skin was completely wet (a realistic assumption considering that most suits were completely saturated from sweat) then it would be reasonable to assume that under all conditions the gradients for the transfer of heat and water vapour were similar. However, the additional heat stress imposed by the N/I suit must be due to increased thermal or water vapour resistance of the garment. As such, it may be reasonable to expect elevated temperature and/or relative humidity within the microenvironment.

The concept of clothing microenvironment (or microclimate) was emphasized by Birnbaum and Crockford (1978) in an attempt to quantify the effects of clothing ventilation. Although the volume of this microenvironment may be insignificant in thin tight-fitting garments, in the case of outdoor recreational and industrial protective clothing assemblies it may be quite large (Birnbaum and Crockford, 1978; Sullivan *et al.*, 1987). Thus the exchange of heat and water vapour between the skin and environment does not occur directly, but rather indirectly via this microenvironment.

Despite the differences in suit design and construction, the temperature within the microenvironment was similar for all suits, suggesting that the resistance of the fabric and garment to dry heat transfer plays little role in the thermal status of the wearer during hot air exposures of this magnitude. However, analysis of the component thermal gradients indicates that the temperature of the microenvironment is greater than that of the skin and outer layer of the suit particularly during transient increases in $P_{\mu}$ (Figure 3.7). This indicates that the source of heat must be other than the skin or ambient air. In addition to the transfer of dry heat, temperature changes within a clothing system may also occur through the processes of evaporation, condensation, absorption and desorption. Thus the liberation of heat observed in this study may be attributed to either condensation or absorption. Condensation occurs when the vapour pressure ($P_{\mu}$) within the clothing system becomes equivalent to the saturation vapour pressure ($P_{sat}$) for that local temperature. This situation may occur if the resistance to water vapour of clothing is high, resulting in elevated $P_{\mu}$ and/or if $P_{sat}$ is reduced, as would be expected when ambient temperature is low (Farnworth, 1986). In this study the elevated $RH_{\mu}$ and thus $P_{\mu}$, developed initially within the N/I and N/N suits, may result in condensation and heat liberation considering the lower saturated vapour pressures at the lower suit temperatures.

Hygroscopic absorption can take place at all vapour pressures, and, in fabrics with high regain properties, such as the cotton underwear utilized in this study, the liberation of heat can be significant, as has been demonstrated for fabrics (Woodcock, 1962; Farnworth, 1986) and garments (Nelbach and

Herrington, 1942; Vokac *et al.*, 1973, 1976). It is clear that rising temperatures and relative humidities within the clothing microenvironemt would allow for appreciable hygroscopic absorption to take place throughout much of the duration of the exposure, thus contributing to the elevated microenvironment temperatures.

In contrast to microenvironment temperatures, the relative humidity and thus water vapour pressure of air within the microenvironment differed considerably between suits. Most interesting in this study was the effect of suit design and construction on the microenvironment conditions. The clothing assemblies incorporated a variety of suit designs (wet-suit and dry-suit) and fabric properties. Although suits of the dry-suit design would limit the path of diffusion of water vapour to that of the fabric only, the dry-suits utilized in this study were both constructed of a water vapour permeable fabric (Cotton and Gore-Tex). As a result of its high vapour permeability the CV suit tended to maintain the lowest $P_\mu$ throughout the duration of the exposure, indeed, the end-exposure $P_\mu$ was similar in magnitude to that produced after only 30 minutes of exposure in the impermeable N/I suit. Only the N/I suit, whose Insulite layer provides a water vapour barrier throughout the whole suit with exception of the neck, wrists and ankles, demonstrated a significant elevation in rectal temperature (1.2°C). This is in contrast to the N/N suit which had similar $P_\mu$ values as the N/I suit, however, the $\Delta T_{re}$ developed by the wearers of this suit was minimal (0.3°C). It is assumed that the areas of the body not covered by the neoprene in the N/N suit (legs, arms and head) were effective in permitting sufficient evaporative cooling to maintain body core temperature, as would be expected considering the relatively high regional sweating rates of these regions (Hertzman *et al.*, 1952), and, the lower water vapour resistance afforded by the Nomex fabric alone (Table 3.1). Similarly, the reported high water vapour permeability of the GT suit also allowed maintenance of acceptable levels of $P_\mu$. In contrast, the sitting position and the tight fit of the N/I garment may have impeded any potential evaporative and convective heat loss through the openings at the wrists, ankles and neck.

To date, few measurements have been made of the conditions within the clothing microenvironment. Both Holmer and Elnas (1981) and Sommerville (1988) determined the vapour density or pressure next to the skin while wearing a variety of protective clothing assemblies. In both cases measurements were made for the purposes of calculating the water vapour resistance of garments, although some comparisons based on vapour pressure were made. Holmer and Elnas (1981) determined vapour pressure next to the skin ($P_{sk}$) indirectly by measuring $PO_2$ and calculating $P_{sk}$ according to gas laws. In their measurements of a 2 piece garment (jacket and trousers) constructed of impermeable and Gore-Tex rainwear they demonstrated vapour pressures approximately 35% lower than in the present study with the impermeable suit producing a much greater build up of water vapour. Sommerville (1989), using mass spectroscopy also showed slightly lower values than those demonstated in this study with no differences between dry-suits constructed of Gore-Tex or Cotton Ventile. The lower values demonstrated in these studies are likely due to lower ambient temperatures, bellows action associated with the exercise performed, the low water vapour resistant fabrics utilized by Sommerville (1988), and the use of a 2 piece design of suit studied by Holmer and Elnas (1981) which would allow for greater ventilation of the clothing microenvironment.

Despite the differences in fabrics and designs utilized in the construction of the suits in this study, there were no differences between the microenvironment temperatures of the four suits and also no differences in $\Delta T_{sk}$. Such a similarity between suits emphasizes the importance of water vapour permeability as opposed to insulation in accounting for the higher degree of heat stress imposed on the wearers of the Nomex/Insulite suit. Although the present study has eliminated the effect of high radiant temperatures, it is anticipated that an increase in radiant heat load would have been reflected in further elevations of $T_\mu$ and $RH_\mu$.

It is apparent that in any attempt to evaluate and predict suit performance in hot environments, two approaches exist: 1) incorporate the fabric properties into indices of heat stress, and 2) directly determine the true environmental conditions to which an individual is exposed to, that of $T_\mu$ and $RH_\mu$. The incorporation of fabric properties into indices of heat stress is advantageous in that it would allow the development of sophisticated models with which manufacturers could predict the performance of a suit based strictly on fabric properties, expected environmental heat loads and the range of possible sweating responses. However, the complexity of designs currently being utilized in suit construction incorporating dry-suit designs, wet-suit designs, strategically placed vents, and regional variations in fabrics utilized would make such an attempt difficult. It would perhaps be more appropriate to determine suit performance by directly evaluating the conditions within the suit. There are a number of advantages to monitoring the conditions within the clothing microenvironment. The advances in miniature electrical hygrometry may allow the possibility of personal monitoring under actual working conditions. The effects of suit design and activity can be determined by actual measurements of regional variations in $T_{\mu}$ and $RH_{\mu}$. In addition the results from human studies may assist in the confirmation of accurate simulations in sweating manikin studies.

In conclusion, the present study emphasizes the need to discern between the ambient conditions and the conditions encountered next to the skin when protective clothing is worn. Since differing protective clothing assemblies will vary in their properties of insulation and water vapour permeability, it is proposed that conditions within the microenvironment of the suit would enable better prediction of heat strain than indices incorporating only ambient variables.

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## TABLE LEGENDS

Table 3.1: Thermal resistance, water vapour resistance and air ventilation of the fabric layers incorporated in the construction of the suits utilized in this study.

Table 3.2: Microenvironment, clothing and skin temperatures (°C), and microenvironment vapour pressure (kPa) determined utilizing the Cotton Ventile (CV), Gore-Tex (GT), Nomex/Insulite (N/I) and Nomex/Neoprene (N/N) suits (average of final 60 minutes). Change in skin and core temperature were determined as final values minus initial resting values.

Table 3.1: Thermal resistance, water vapour resistance and air ventilation of the fabric layers incorporated in the construction of the suits utilized in this study.

| Suit | Fabric | Thermal Resistance (m2 K W-1) | Water Vapour Resistance (m2 Pa W-1) | Ventilation Index (liters/min) |
|---|---|---|---|---|
| CV | Cotton Ventile | 0.96 | 54.6 | 2.86 |
| GT | Goretex | 2.00 | 67.90 | 0.04 |
| N/I | Nomex shell |  | 40.1 | 3.41 |
|  | Insulite liner | 19.20 | impermeable | impermeable |
| N/N | Nomex Shell |  | 40.1 |  |
|  | Neoprene liner | 7.30 | impermeable | impermeable |

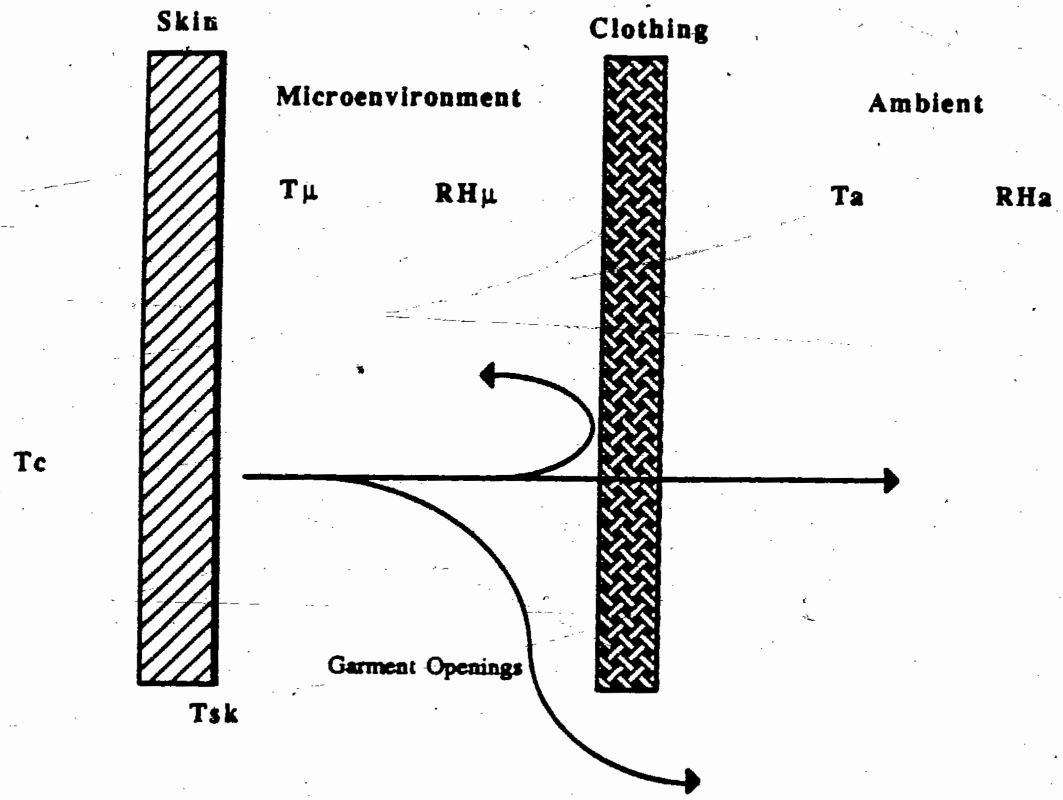
Table 3.2: Microenvironment, clothing and skin temperatures (°C), and microenvironment vapour pressure (kPa) determined utilizing the Cotton Ventile (CV), Gore-Tex (GT), Nomex/Insulite (N/I) and Nomex/Neoprene (N/N) suits (average of final 60 minutes). Change in skin and core temperature were determined as final values minus initial resting values.

| | | Suits (mean ± S.D.) | | | |
|---|---|---|---|---|---|
| | | **CV** | **GT** | **NI** | **NN** |
| **ΔTsk** | °C | 3.05 ± .87 | 2.85 ± .65 | 3.45 ± .50 | 3.26 ± .83 |
| **ΔTre** | °C | 0.29 ± .15 | 0.23 ± .18 | 1.21 ± .43 | 0.39 ± .39 |
| **Tsk** | °C | 34.17 ± .39 | 34.20 ± .17 | 34.73 ± .19 | 33.81 ± .63 |
| **Tcl** | °C | 35.13 ± .68 | 35.14 ± .66 | 35.71 ± .57 | 35.09 ± .44 |
| **Tμ** | °C | 35.46 ± .61 | 35.75 ± .61 | 36.10 ± .27 | 36.26 ± .56 |
| **Pμ** | kPa | 4.34 ± .23 | 5.11 ± .13 | 5.68 ± .12 | 5.83 ± .21 |

## FIGURE LEGENDS

| | |
|---|---|
| Figure 3.1: | Diagramatic representation of the skin-clothing-environment system indicating ambient and microenvironment conditions and the flow of heat and water vapour. |
| Figure 3.2 | Diagramatic representation of the experimental set-up utilized in the hot air exposures. Subjects were seated in a helicopter pilot suit suspended in mid-chamber by a metal frame. |
| Figure 3.3 | Helicopter pilot suits evaluated in this study. Suits were constucted of: A) Gore-Tex; B) Cotton Ventile; C) Nomex/Insulite; and D) Nomex suit worn over a neoprene shorty (F). Cotton Ventile, Gore-Tex and Nomex/Insulite suits were all worn over cotton thermal underwear (E). |
| Figure 3.4: | Typical response of both ambient and average microenvironment temperatures and relative humidities. Solid and open symbols represent ambient and microenvironment variables respectively. Squares represent temperature whereas circles represent relative humidity. |
| Figure 3.5 | Microenvironment conditions within the four protective suits studied: Cotton Ventile, Gore-Tex, Nomex/Insulite and Nomex/Neoprene. A) Temperature, B) Relative Humidity and C) Water Vapour Pressure. Asterisks represent statistical differences ($p<0.05$). Data are displayed at 5 minute intervals. |
| Figure 3.6: | a) Representative time series plot for skin and rectal temperatures during the 180 minute exposure. b) Change in skin temperatures and rectal temperature observed for subjects wearing the four helicopter pilot suits. |
| Figure 3.7: | Temperature gradients between the skin, microenvironment and outer suit layer during transient increases in ambient temperature. Microenvironment temperatures elevated above both skin and suit suggest the liberation of heat via condensation and hygroscopic absorption. |

Figure 3.1: Diagramatic representation of the skin-clothing-environment system indicating ambient and microenvironment conditions and the flow of heat and water vapour.



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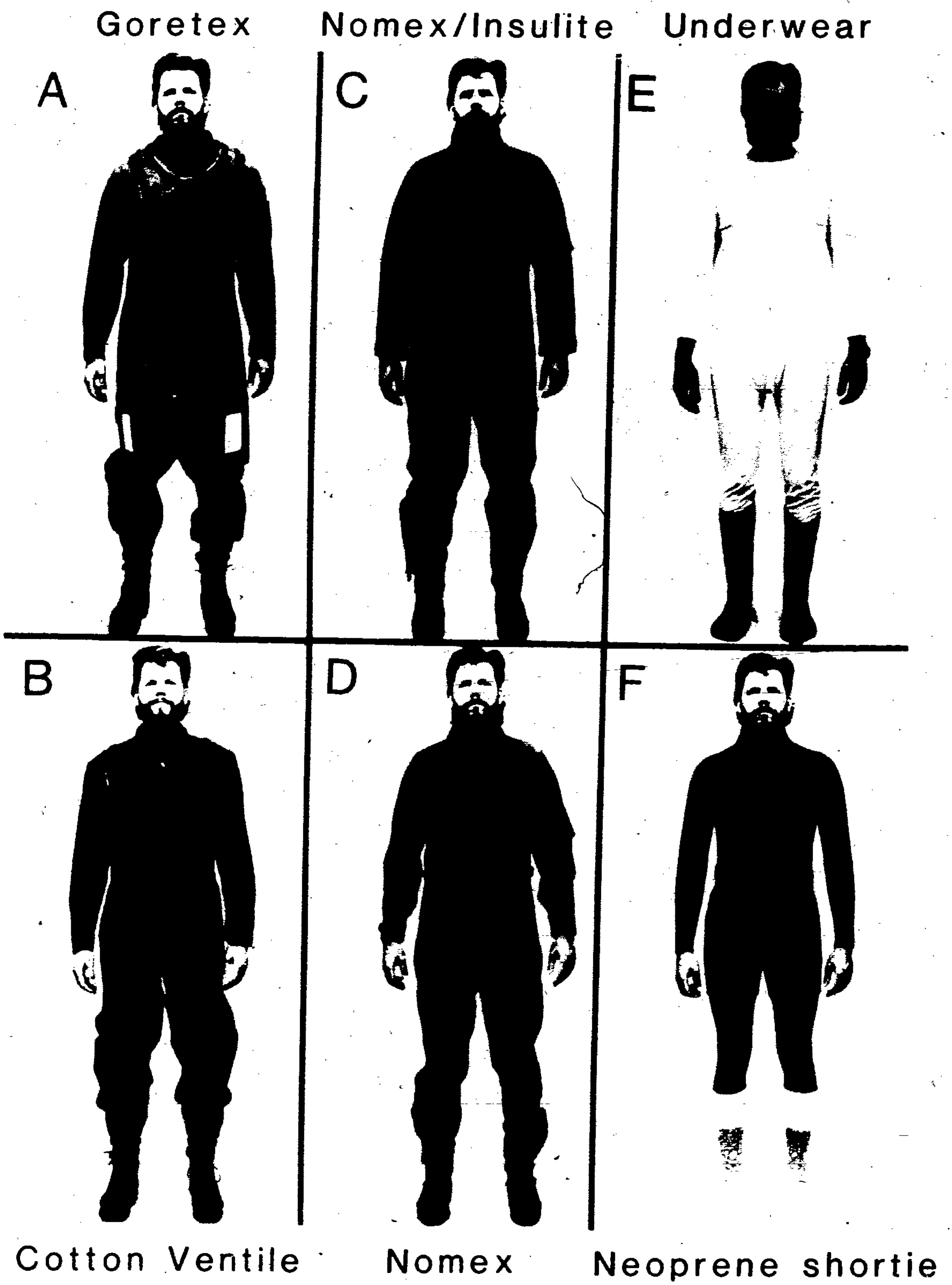

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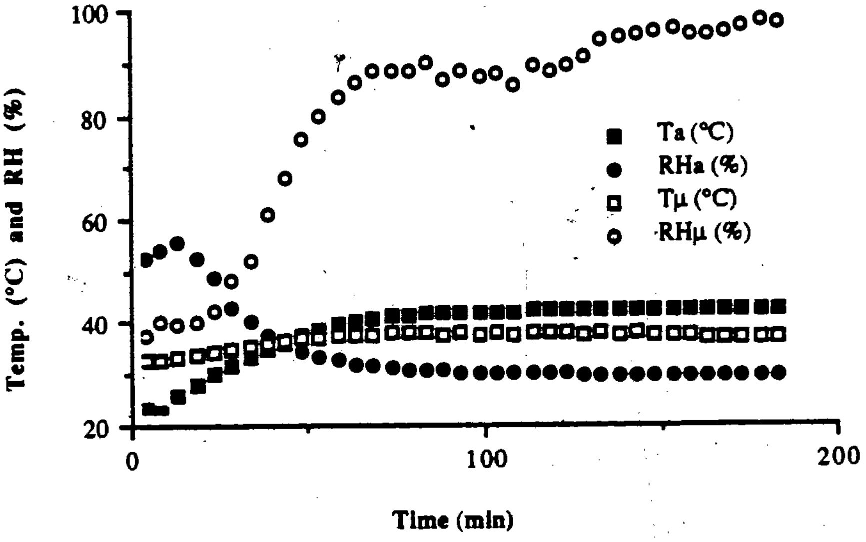
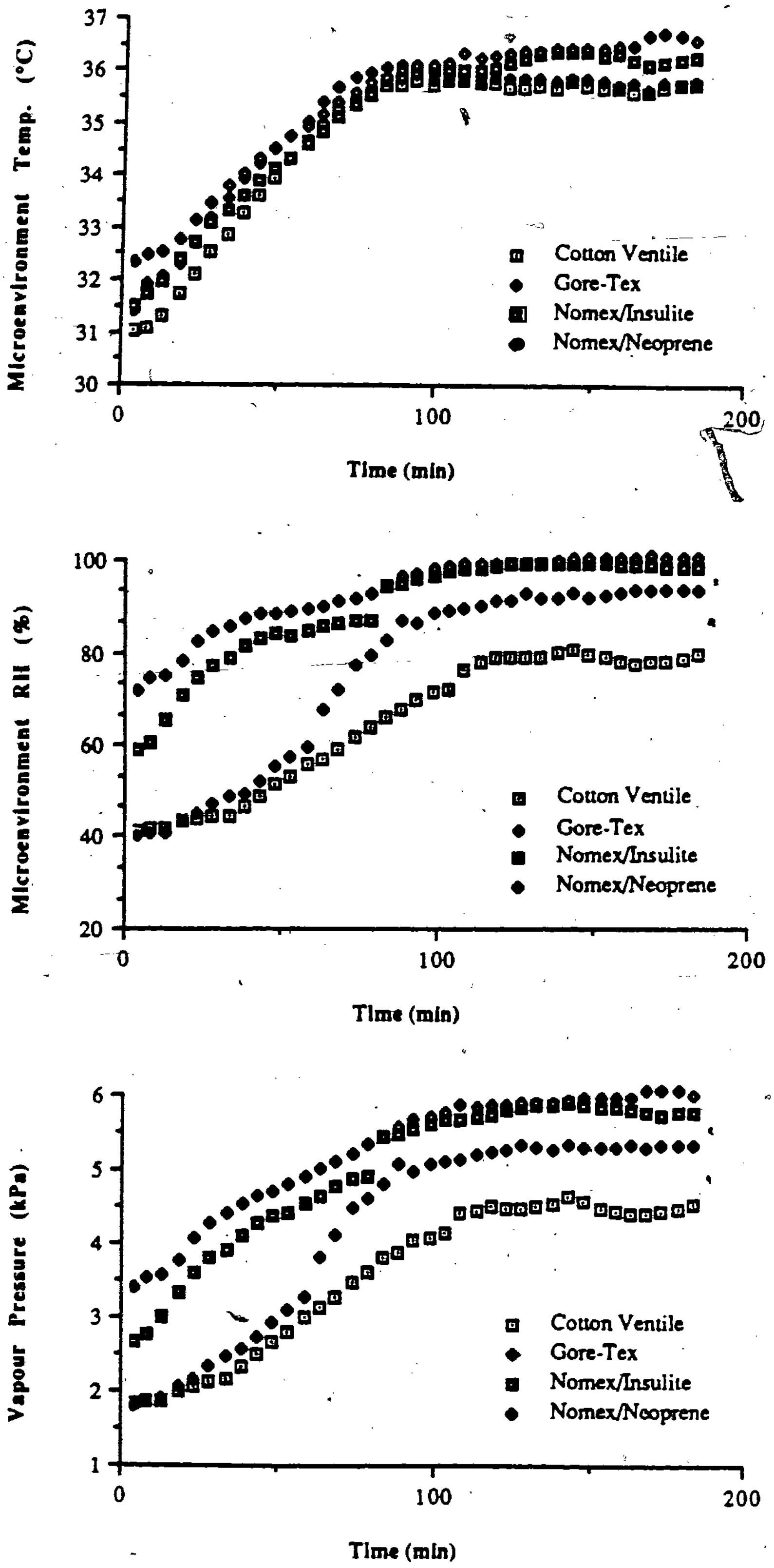


Figure 3.5 Microenvironment conditions within the four protective suits studied: Cotton Ventile, Gore-Tex, Nomex/Insulite and Nomex/Neoprene. A) Temperature, B) Relative Humidity and C) Water Vapour Pressure. Asterisks represent statistical differences ($p<0.05$). Data are displayed at 5 minute intervals.



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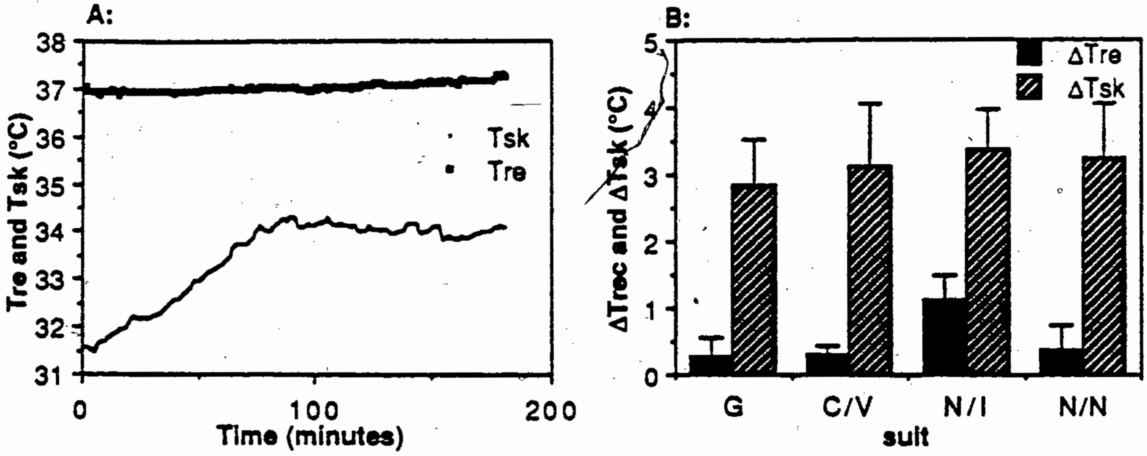
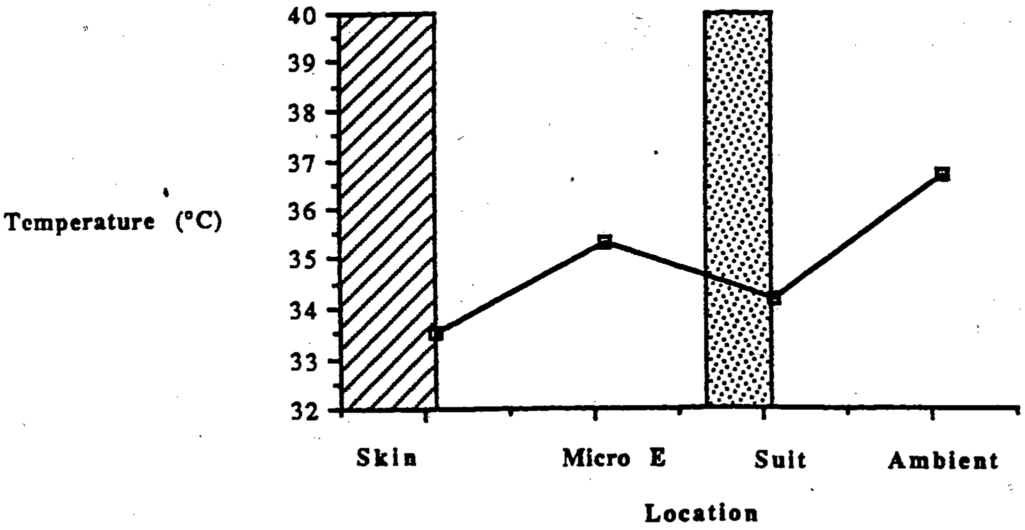


Figure 3.7: Temperature gradients between the skin, microenvironment and outer suit layer during transient increases in ambient temperature. Microenvironment temperatures elevated above both skin and suit suggest the liberation of heat via condensation and hygroscopic absorption.



## GENERAL CONCLUSIONS

In the past, indices, utilized for the quantification of heat stress in industry, have relied primarily on measures of ambient variables such as air temperature, vapour pressure, globe temperature and air velocity, and only in some instances are the characteristics of the clothing considered, usually in terms of a crude estimate of the resistance of the garment to dry heat transfer. However, the complex nature of industrial protective clothing has led many researchers to conclude that there may be no universal index of heat stress as these garments create a thermal and water vapour barrier between the skin and ambient air, creating conditions within the clothing microenvironment which may differ substantially from the ambient air, and which will depend on the garment design and the fabrics utilized in their construction. In many industrial applications, where elevated ambient temperatures cannot be avoided, heat loss from the body will be limited to the evaporation of sweat and its subsequent diffusion through the clothing layers, and as such, the microenvironment conditions will depend to a large extent on the water vapour resistance of the fabrics, a value which in the past has proven difficult to assess.

The present thesis represents one of the first attempts to assess the conditions within the clothing microenvironment when wearing a variety of commercialy available helicopter pilot suits incorporating a variety of design concepts in addition to a number of water vapour permeable fabrics. Evaluation was performed during a hot air exposure which simulated, in a simplified manner, the conditions encountered within a helicopter cockpit during a normal flight in summer conditions, and the water vapour resistance of fabrics was determined on an apparatus developed at Simon Fraser University which utilizes Vapour Flow Meters (VFM) developed in Japan.

Vapour Flow Meters allow calculation of local evaporative rates by measuring the water vapour density gradient within the diffusion boundary layer next to the skin or fabric layer. In contrast to sweating rate, a measure of the effector response to increased heat loads, evaporative rate is determined by the rate at which sweat is produced, the conditions of the ambient environment and the presence of clothing which, by virtue of its construction, provides a barrier to the diffusion of water vapour. Local sweating rates are normally assessed using a ventilated capsule technique whereby sweat is forcibly evaporated by passing dry air over the skin surface and measuring the resultant increase in water vapour density of the air. However, the presence of the sweat rate monitor, may delay the detection of secreted sweat due to the lower sensitivity of the system and forced drying of the skin. In contrast, due to the unique design of the Vapour Flow Meter, which minimizes interference with the normal sweating and evaporative processes, accurate determination of local evaporative rates can be made.

The small size and simplicity of Vapour Flow Meters enable their application in the evaluation of water vapour resistance of fabrics. The vapour permeable garments assessed in this study were constructed Nomex, Cotton Ventile and Gore-Tex, with the latter two suits worn in combination with cotton underwear (CV/U and GT/U). The water vapour resistance values determined in this study using a fabric model reflect similar differences between fabrics observed in other laboratories, with Nomex displaying relatively low resistance and the GT/U having the higher resistance of the samples studied. However, similar measurements made on the fabric during normal wear in the hot air exposure trials of this study revealed significant increases in water vapour resistance which may be primarily attributed to the additional resistance of still air layers of the microenvironment, the effects of which must be considered when attempting to extrapolate the results of fabric models to normal wear conditions.

In general the microenvironment vapour pressure, developed within the helicopter pilot suits during hot air exposure, reflects the water vapour resistance of the fabrics utilized in their construction, with the microenvironment air of the more impermeable suits (Nomex/Insulite and Nomex/Neoprene) displaying near complete saturation (close to saturation vapour pressure of the skin). However, the importance of suit design is evident as only in the Nomex/Insulite suit, whose impermeable insulite layer is incorporated throughout the entire suit, do significant elevations in rectal temperature occur, whereas because of the incomplete coverage of the neoprene layer in the Nomex/Neoprene suit, subjects do not experience undue thermal stress. Assessment of microenvironment conditions could be improved, particularly for suits like the Nomex/Neoprene which incorporate variable fabric types, by including measurement of microenvironment conditions throughout the entire suit and by weighting each measurement according to surface area.

For the purpose of this study, analysis of heat strain was made in terms of changes in core and skin temperatures, however, heat strain may also be evaluated by assessing psychomotor performance and perception of thermal comfort. Although thermal comfort votes were not administered, subjects were required, as part of another study, to perform a variety of psychomotor performance tests ranging from simple reaction time to computer controled tracking both prior to, and, during the final minutes of each exposure. For all suits analyzed in this study, there were no observed decrements in performance throughout the three hour exposure suggesting that despite the elevated core temperatures observed when wearing the Nomex/Insulite suit, pilot performance may not be impaired. However, conclusions to this effect would require assurance that the tests performed were sufficiently sensitive and that they adequately evaluate pilot performance.

In conclusion, the present study emphasizes the need to discern between ambient and microenvironment conditions, particularly when industrial protective clothing, which incorporates fabrics with relatively high resistance to the transmission of water vapour, is required.

# APPENDIX A: Calibration Procedures

The Vapour Flow Meters (VFM) utilized were constructed of two thermistors and two substrate relative humidity sensors housed within a plexiglass capsule (Figure A.1). The design of the VFM is based on the original work of Lamke *et al.* (1977), which has been improved for the purposes of this study by Kakitsuba (1982). The new design consists of an open construction in five faces of the plexiglass chamber in order to minimize the effect of the capsule height on the normal vapour density distribution above the surface of the skin (or clothing). In this thesis, the VFM was utilized for three purposes: 1) in the measurement of the evaporative rate from the surface of the skin ($E_{sk}$), clothing ($E_{cl}$) or fabric ($E_f$); 2) for the determination of water vapour pressure below and above the fabric (or garment) to be utilized in the calculation of the vapour pressure gradient across the fabric($\Delta P_f$) or garment ($\Delta P_{cl}$); and 3) for the assessment of conditions within the clothing microenvironment.

Vapour Flow Meter calibration consisted of individual calibration of the thermistors and relative humidity sensors within each VFM and finally comparing the evaporative rates measured with the VFM against the changes in weight loss observed from a petri dish of water. Initial calibrations for the thermistors and relative humidity sensors, prior to use in the hot air exposures, were performed by the manufacturer (Shinyei, Japan). For the purpose of the fabric studies (performed after the hot air exposures), the sensors were recalibrated at Simon Fraser University, the procedures of which are described here.

## Calibration of Thermistors

Thermistors were calibrated within the Environmental Chamber (Tenney) in the Environmental Physiology Unit at Simon Fraser University. Temperatures within the chamber were varied between 20 and 40°C, in 5°C increments, to ensure accuracy within the entire range encountered during the experimental procedures. The thermistors remained at each temperature for 30 minutes in order to allow for complete equilibration, and the output voltages were recorded within 0.1 millivolt by means of a Data Acquisition System (HP 3497A, Hewlett Packard) and a microcomputer (HP 85, Hewlett Packard). The voltages were subsequently compared to values recorded from a standard mercury thermometer (accuracy ± 0.1°C) located within 5 centimeters of the thermistors being calibrated. Linear least squares regression analysis was then performed by means of a Macintosh 512KE computer (Apple).

### Calibration of Relative Humidity Sensors

The relative humidity sensors (HPR-MQ, Shinyei Kaisha, Japan) incorporated in the VFM are composed of an electrode base-plate coated with a humidity sensitive material. The resistance value of the coated electrode varies with changes in relative humidity as an exponential function. Hardware provided by the manufacturer allows linearization and temperature compensation of the voltage signal obtained from the sensor. The relative humidity sensors have an operating range of 20% to 99.9 % with an accuracy of ± 1 % RH and display good stability in extreme conditions. The only major disadvantages of these sensors is the erroneous signal produced when the sensor is in contact with liquid water (eg. sweat dripping on the sensor), and the rather slow response to extremely rapid changes in relative humidity, as displayed in Figure A.2. In this figure the response time of the sensor is shown when relative humidity surrounding the sensor was either instantaneously increased from 30% - 90%, or decreased from 90% - 30%. The figure indicates that the sensor may not become stable at the new equilibrium relative humidity for at least 4 minutes for an instantaneous relative humidity change of 60%, and, that the response time for decreases in relative humidity are slightly greater than for similar increases.

The calibration method for the relative humidity sensors utilized in this study is similar to the one described by Brengelmann *et al.* (1975) and by Kraning and Sturgeon (1983). In this method, the desired relative humidity is obtained by controlled mixing of two gas streams, one dry and one 100% saturated

(Figure A.3). Nitrogen gas (5 liters·min.$^{-1}$) was dried by passing the gas through drierite after which it was directed to two branches. One gas stream was bubbled through a 500 ml erlenmyer flask filled with distilled water. To ensure that the gas was saturated, water within the bottle was held at a constant elevated temperature of 45°C. The gas was then passed through a 1 liter capacity buffer bottle which enabled cooling of the gas and dampened fluctuations in air flow, due to bubbling. The dry and saturated air, after passing through a flow meter (model 7262, Matheson), were merged in a plastic "Y" tube, and then passed directly to a container housing the relative humidity sensors. Relative humidity was then manipulated by varying the rates of dry and saturated gas flow, the effluent relative humidity being numerically equal to the percentage of saturated air flow in the mixed stream.

$$RH = \frac{\text{saturated flow rate}}{\text{total flow rate}} \cdot 100\% \qquad \text{(N.D.)} \qquad [A.1]$$

Following the calibration procedure, a linear least squares regression analysis was performed using a Macintosh 512KE computer.

### Comparison with weight loss from a dish of water

After calibration, the VFM's were mounted above a petri dish of water, positioned on a scale (model 50, Fisher) which measured mass to the nearest 0.0001 gram (Figure A.4). The scale, petri dish and VFM were placed within a cardboard protective housing to minimize errors due to the influence of air velocity. Values for calculated evaporative rates from the water ($E_W$, g·m$^{-2}$·min$^{-1}$) were compared to average weight loss per minute ($\Delta Wt$, g·m$^{-2}$·min$^{-1}$) to ensure that the calculated rates using the VFM were within an acceptable range.

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## APPENDIX B: Determination of the Thermal Resistance of Fabrics

The measurement of thermal resistance of a fabric ($R_t$) was determined using a guarded hot-plate technique (BS4745) modified from Gilling *et al.* (1972) according to current accepted standards.

### Apparatus

Water contained in a 31 x 36 cm rectangular container was heated and circulated through a copper cylinder (diameter = 15.4 cm) by a dynamic flow heating system (Heto, Denmark). Six rubber hoses (diameter = 4 cm) circulated water continuously between the supply container and the cylinder. Two hoses supplied water to inlet tubes located at opposite ends of the cylinder, 3 cm from its bottom. Four outlet tubes, situated at equidistant points around the cylinder, 5 cm from the material-cylinder interface, were connected by hoses to the water supply for recirculation (see Figure B.1). Control of the temperature of the water bath allowed maintenance of a constant hot-plate temperature necessary for accurate determination of thermal resistance.

Determination of thermal resistance involved placing the fabric sample (diameter = 15.4 cm), sandwiched between two layers of 5mm neoprene of known thermal resistance, above the guarded hot-plate. Copper-constantan thermocouples were placed centrally at each fabric interface and the temperature of the water bath was increased and subsequently held constant at 40°C. Thermocouple temperatures were recorded by means of a data aquisition system and microcomputer (HP 3497A and HP 85 respectively, Hewlett Packard) after 30 minutes to ensure that the system had reached equilibrium.

**Calculation of thermal resistance**

The equation for calculating the thermal resistance of a fabric is analogous to Ohm's Law:

$$HF_f = \frac{\Delta T_f}{R_f} \qquad (W \cdot m^{-2}) \qquad [B.1]$$

where:

$HF_f$ = heat flow across the fabric ($W \cdot m^{-2}$)

$\Delta T_f$ = temperature gradient across the fabric (K)

$R_f$ = thermal resistance of the fabric ($m^2 \cdot K \cdot W^{-1}$)

In this method, HF is not determined directly, but rather calculated from knowledge of the thermal resistance of Neoprene, the reference fabric ($R_{ref}$). Once the system has reached equilibrium it is assumed that heat flow through both the fabric under study and through the reference fabric are equal ($HF_f = HF_{ref}$) such that:

$$R_f = \frac{\Delta T_f \cdot R_{ref}}{\Delta T_{ref}} - R_{cont} \qquad (m^2 \cdot K \cdot W^{-1}) \qquad [B.2]$$

where:

$R_{ref}$ = thermal resistance of the neoprene (reference fabric) which has been previously measured to be 0.116 $m^2 \cdot K \cdot W^{-1}$.

$R_{cont}$ = contact resistance of the thermocouples which has previously been determined as $6.6 \times 10^{-3}$ $m^2 \cdot K \cdot W^{-1}$.

$\Delta T_{ref}$ = temperature gradient across the reference fabric (K)

## REFERENCES

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## APPENDIX C: Determination of the Ventilation Index of Fabrics

The measurement of Ventilation Index of clothing ($VI_{cl}$, liters·min$^{-1}$) was originally conceived and developed by Birnbaum and Crockford (1978). The index estimates the rate of air exchanged through the garment fabric and openings, utilizing measurements of suit microenvironment volume ($V_{\mu}$, liters) and the time constant (k, min$^{-1}$) for the exchange of a trace gas between the clothing microenvironment and ambient air. The contribution of each pathway of air exchange can be determined by evaluating separately, the ventilation index of the fabric alone ($VI_f$) and the garment ($VI_{cl}$).

For the assessment of $VI_f$, an apparatus was designed, based on the concept developed by Birnbaum and Crockford (1978), to allow the determination the air permeability of the fabric using oxygen as the trace gas (Figure C.1). A 15-cm diameter fabric sample was securely clamped on a cylindrical plexiglass container, the contents of which was then flushed with pure $N_2$ to eliminate all other gases within the container. Once the $N_2$ flushing was terminated, both the inlet and outlet valves were closed, and the $O_2$ fraction ($FO_2$) within the microenvironment of the chamber was then continuously sampled, and the rate of rise of $FO_2$ in the container determined. By knowing the volume of the plexiglass chamber ($V_{\mu}$), $VI_f$ can be determined by the algebraic combination of $V_{\mu}$ and the rate constant ($k_f$):

$$VI_f = V_{\mu} \cdot k_f \qquad \text{(liters·min}^{-1}\text{)} \qquad [C.1]$$

where:

$VI_f$ = ventilation index of the fabric (liters·min$^{-1}$)
$V_{\mu}$ = volume within the plexiglass chamber (liters)
$k_f$ = time constant for diffusion of $O_2$ through the fabric (min$^{-1}$)

It is expected that for dry-suits, in which exchange of the microenvironment air is limited to the pathway directly through the fabric, $VI_{cl}$ should be equivalent to $VI_f$ as has been shown to be the case (Mekjavic and Sullivan, 1988).

## REFERENCES

Birnbaum RR, Crockford GW. Measurement of clothing ventilation index. Appl. Ergonomics. 1978; 9: 194-200.

Mekjavic IB, Sullivan PJ. Constant wear thermal protection garments for helicopter personnel. In: Mekjavic IB, Banister EW, Morrison JB, eds. Environmental Ergonomics. London: Taylor & Francis, 1988.

## FIGURE LEGENDS

Figure A.1: Diagramatic representation of the Vapour Flow Meter showing the two thermistors and two substrate relative humidity sensors housed within a plexiglass capsule.

Figure A.2: Time course of the substrate relative humidity sensor in response to a step change in ambient relative humidity from 30 to 90% and additionally from 90 to 30%.

Figure A.3: Schematic representation of the equipment set-up utilized in the calibration of the substrate relative humidity sensors. Regulating the flow of dry and saturated nitrogen gas allowed for controlled variation in the relative humidity of air exposed to the sensor.

Figure A.4: Diagram of apparatus utilized in the comparison of evaporative rates calculated from the Vapour Flow Meters with evaporative rates as determined by the average rate of weight loss in the water filled petri dish.

Figure B.1: Apparatus used in the determination of thermal resistance of fabrics. A constant temperature of the hot plate was maintained through continuous circulation of heated water, allowing calculation of thermal resistance by measurment of the temperature drop across fabrics.

Figure C.1: Apparatus used in the determination of Ventilation Index of fabrics. The rate of air exchange is evaluated by continuous monitoring of the increase in Oxygen concentration within the plexiglass chamber following Nitrogen flushing.

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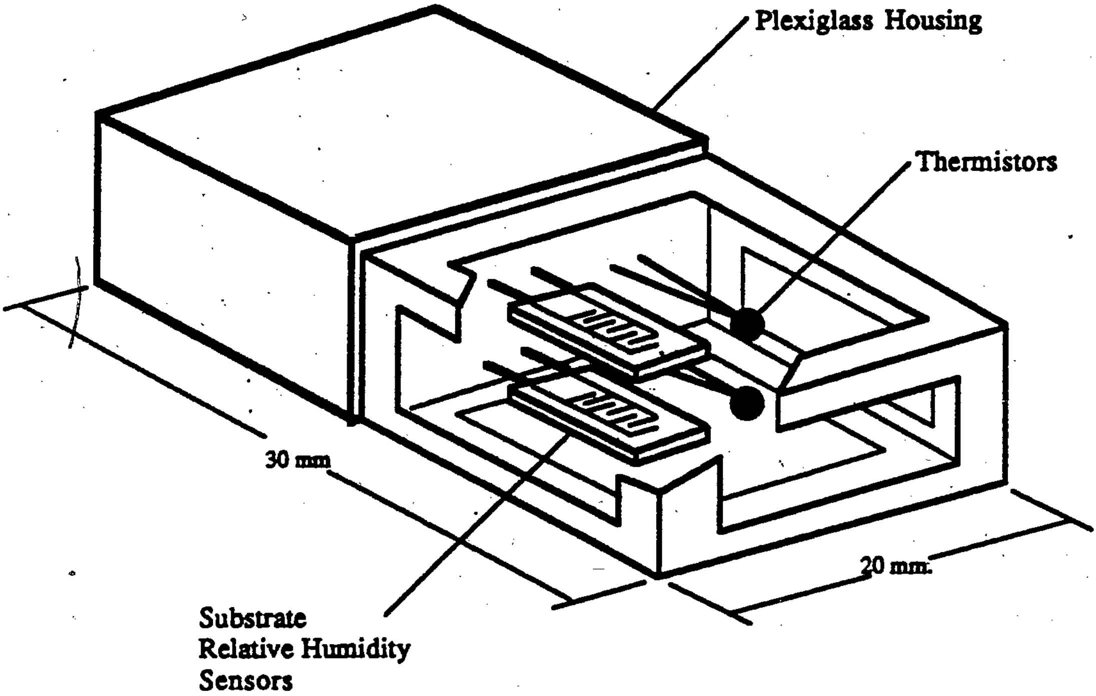


Figure A.2: Time course of the substrate relative humidity sensor in response to a step change in ambient relative humidity from 30 to 90% and additionally from 90 to 30%.

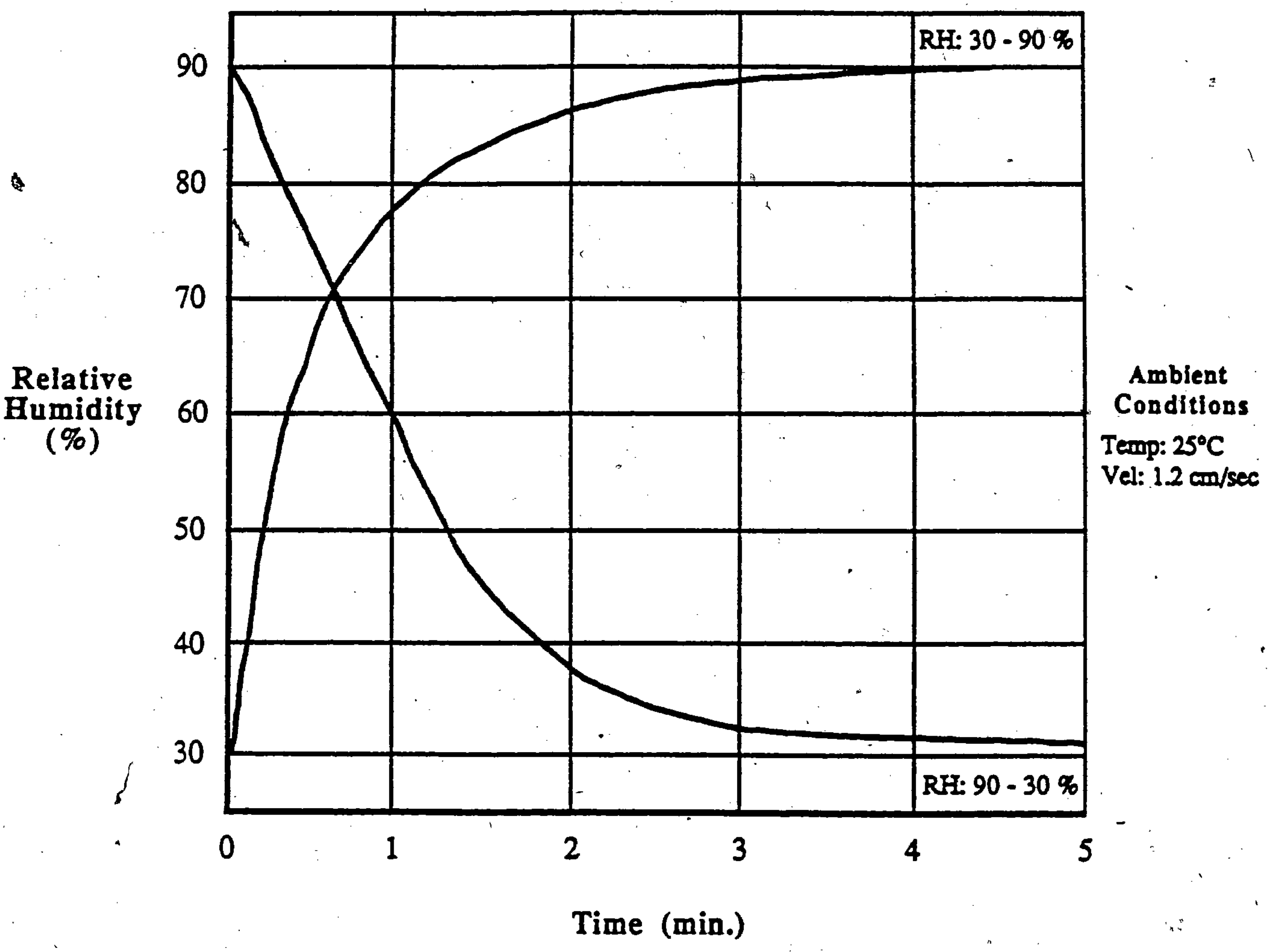
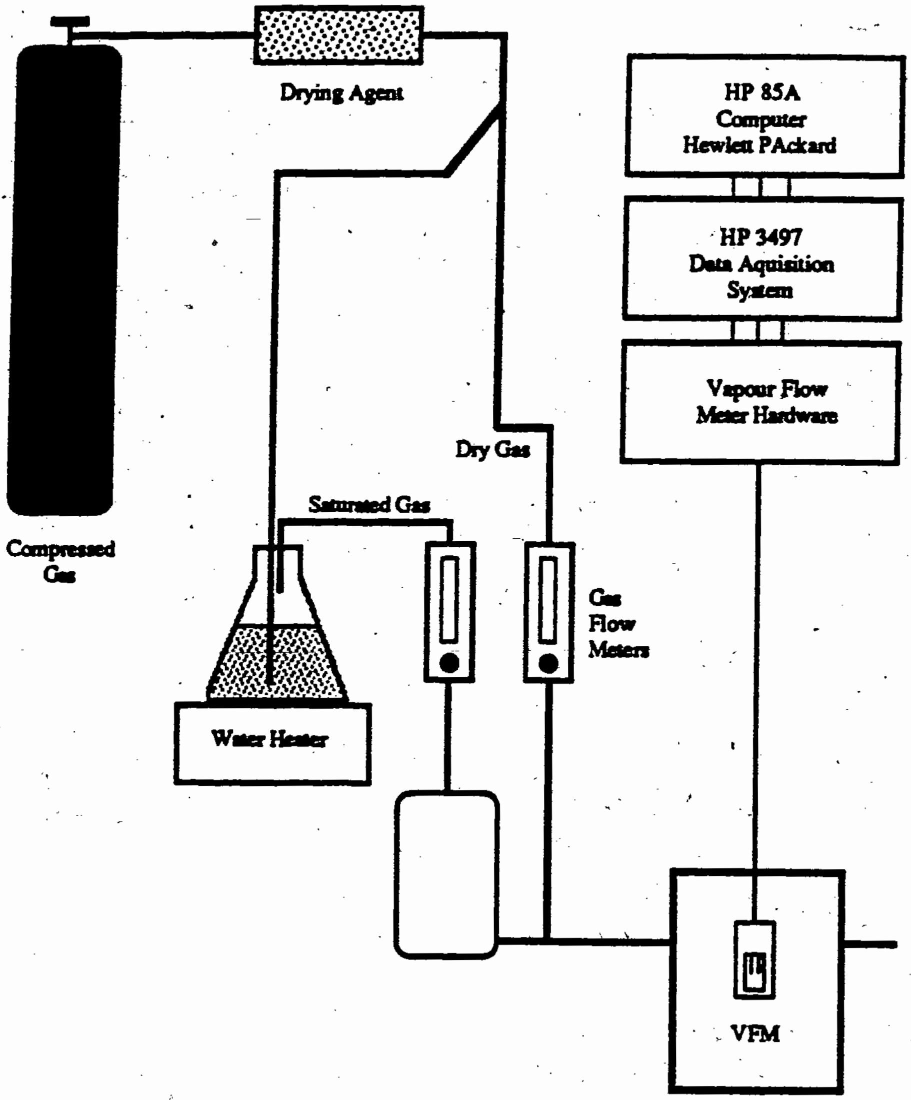


Figure A.3: Schematic representation of the equipment set-up utilized in the calibration of the substrate relative humidity sensors. Regulating the flow of dry and saturated nitrogen gas allowed for controlled variation in the relative humidity of air exposed to the sensor.



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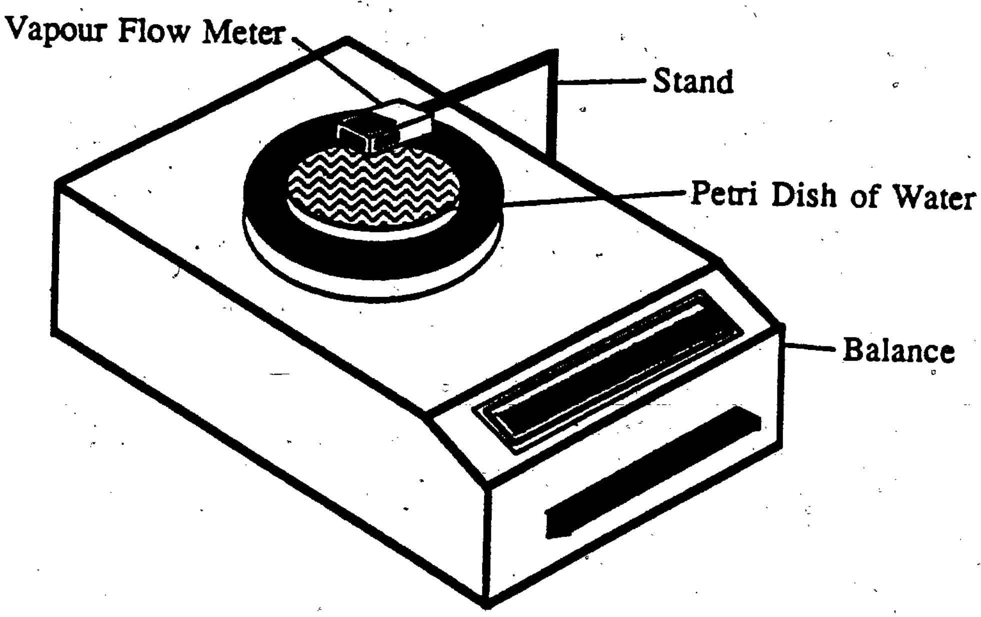

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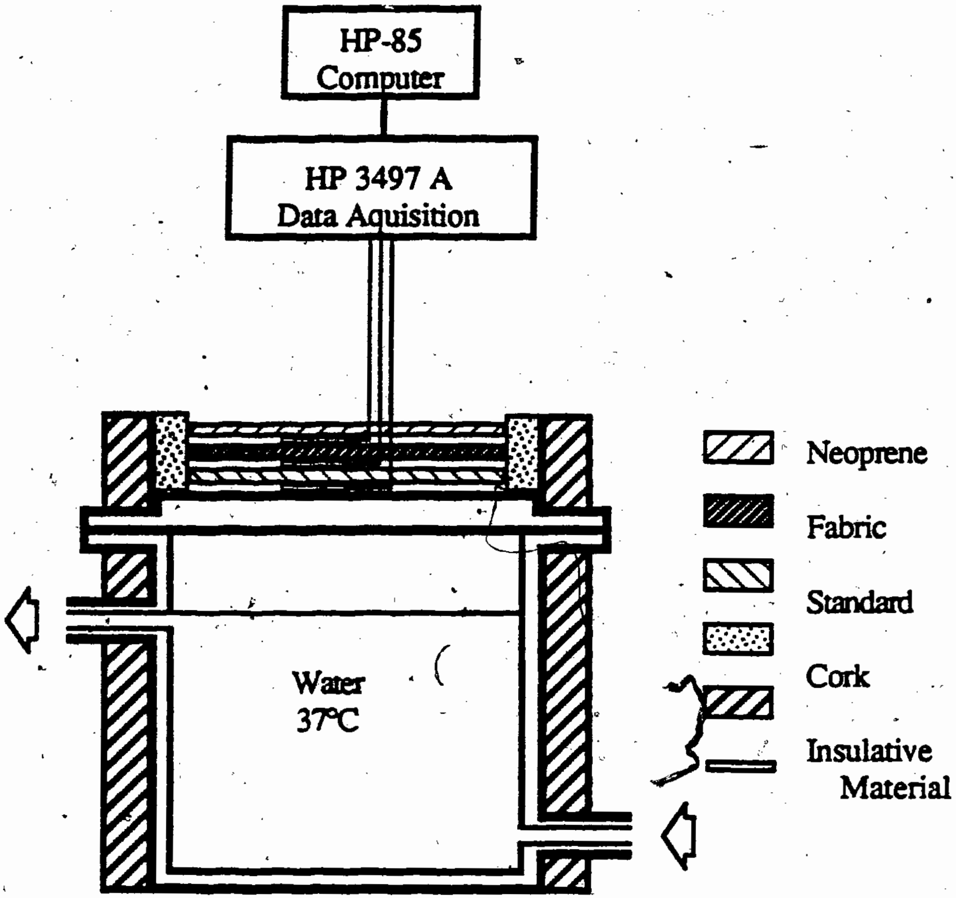

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