

BIOPHYSICAL AND PHYSIOLOGICAL INTEGRATION OF PROPER
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BIOPHYSICAL AND PHYSIOLOGICAL INTEGRATION
OF PROPER CLOTHING FOR EXERCISE

Richard R. Gonzalez, Ph.D.

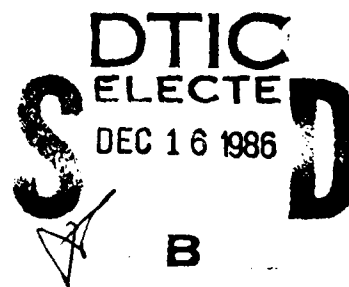
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This review is a discussion of current biophysical and thermal advances in clothing properties. Among the topics covered are effects of exercise in buffering clothing insulation, effects of modern day fiber techniques (polypropylene, etc.) in allowance or adjustments to water vapor and thermal exchange and special advantages (aids) used in fostering optimal heat exchange for athletes. *Kennedy*

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ABSTRACT

This review is a discussion of current biophysical and thermal advances in clothing properties. Among the topics covered are effects of exercise in buffering clothing insulation, effects of modern day fiber techniques (polypropylene, etc.) in allowance or adjustments to water vapor and thermal exchange and special advantages (aids) used in fostering optimal heat exchange for athletes.

Key words: clothing; exercise; temperature; protective fibers; insensible heat loss



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When first asked to contribute a chapter on clothing properties as they affect exercise, I hesitated. In my mind, clothing poses no real threat to the athlete: essentially each person exercises with limited intrusion by clothing and in reality it poses more of a hinderance than an aid. However, after thinking about the advances in polymer chemistry with development of new fibers being used for sports clothing, extended ranges into cold-wet environments or hot-humid and hot-dry environments, multiple sports programs that persons engage in not restricted to jogging (as my mind first reacted), I realized that we really do not know too much about the integration of the environment with exercise and clothing.

There have been many excellent reviews detailing clothing properties; some of these relate to one aspect of the problem centered on evaporation (13,14) and others to the physics of the environment (18). Several books and chapters have discussed mechanisms involved in clothing biophysics. (30,48,51,71). Their emphasis however has been either to solve particular fundamental questions (31,64,65,66) or are related to specific needs concerned with military or civilian clothing. One reason for another review is to clarify concepts (or misconceptions) in thermal biophysics attributed to different sports clothing. How is heat and water dissipated through a permeable or impermeable suit? Is running without a shirt in the heat better in reducing heat stress (in a pragmatic sense) than with one? To what extent can one buffer effects of cold environments by metabolism and clothing? Can I decrease my time in a marathon by decreasing clothing weight? These questions are but a few often asked by students and others who are not familiar with basic concepts or new developments in the field.

The purposes of this chapter are threefold: (a) to introduce some concepts of thermal biophysics which will be useful and applicable to the reader regardless

of the sport he/she engages in; (b) to critique methods used in the evaluation of thermal insulation that those active in a particular sports program can further apply to better their thermal comfort and well being; and, finally (c) to introduce suitable clothing aids for exercise which becomes almost "second nature" to the user.

HISTORICAL PERSPECTIVE

There has always been a direct association between clothing and the thermal environment in humans. Early accounts note that "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" (3).

Apparently for early man the use of clothing as a means of adapting to a hostile environment may have served as a stronger incentive than the other customs (sexual attractiveness, modesty) attributed for its use as noted above. (51,59,64,71,72). Possibly with the discovery of fire and movement into shelters the other attributes of clothing gained dominance. Goldman (31) points out that in modern man the design of clothing is presently associated with qualities related to fashion (and fiber techniques by industry) rather than actual scientific inquiry of heat exchange properties. We will focus on the latter in this chapter.

Renbourn (59) points out that "As early as 1620, Francis Bacon suspected that the warmth of wool, skin, and feathers and the like was due to the confinement and separation of air.." This is an amazing observation considering that the efficacy of clothing as an insulator is related to the amount of entrapped air regardless of the type of fiber. Renbourn also notes that Robert Hook by 1664 had envisioned use of artificial fibers which could function much like natural fibers as insulators. Sanctorious, also an early 17th century physician, had already developed a platform balance for measuring weight loss

and he recognized the importance of clothing properties in evaporative heat transfer (71).

The greatest impetus to development of clothing measurements and its usage occurred during the second World War when answers were needed to diverse problems related to heat exchange properties of clothing (16,29,71). There was an effort to standardize units of heat insulation which would be readily appreciated by a layman but also easily converted to common units used by scientists and engineers. Gagge, Burton, and Bazett (29) first introduced the term "clo". This unit of thermal insulation was arbitrarily set as the clothing necessary to allow a resting subject to be in a comfortable state when the ambient temperature is 70°F (21.1°C), with relative humidity less than 50% and air movement at 20 ft/min (0.10 m·s⁻¹). Along with this unit they introduced a standard value for metabolic activity for the above criteria as 50 kcal·m⁻²·h⁻¹ (58.2 W·m⁻²) termed one "met". No real cause and effect relationship was set between the met and clo. The two generally correspond to multiples of average resting heat production and an average comfortable clothing for the period in the 1940's.

One advantage to such a standardization even now is that the clo unit is easily understood in terms of dry heat flow in the heat balance equation. For this, Gagge et al (29) utilized the experimental work of Winslow et. al. (70) in which the non-evaporative heat flow (R+C) was 0.76 of the metabolism (50 kcal·h⁻¹·m⁻²) and comfortable skin temperature was 33°C. The insulation of the air (I_a) and clothing (I_{cl}) were thus determined from:

$$\begin{aligned} I_a + I_{cl} &= (\bar{T}_{sk} - T_a) / (R+C) \\ &= (33-21) / 38 \\ &= 0.32 \text{ } ^\circ\text{C} / (\text{kcal} \cdot \text{h}^{-1} \cdot \text{m}^{-2}). \end{aligned}$$

By estimating the insulation of air as $1/(h_r+h_c)$ or $0.14 \text{ }^\circ\text{C}/(\text{kcal}\cdot\text{h}^{-1}\cdot\text{m}^{-2})$ the difference or insulation of clothing equal to the original definition of 1 clo becomes $0.18 \text{ }^\circ\text{C}/(\text{kcal}\cdot\text{h}^{-1}\cdot\text{m}^{-2})$.

This value, or rather its equivalent $0.155 \text{ m}^2\cdot^\circ\text{C}/\text{W}$, has been the standard resistance unit for clothing insulation. In this paper the clo unit (I_{clo}) or the resistance unit ($I_{\text{cl}}=0.155\cdot I_{\text{clo}}, \text{ m}^2\cdot^\circ\text{C}/\text{W}$) will be used.

It's important to realize that one clo at the time it was developed corresponded to the insulation provided by a normal male business suit and as such is an arbitrary unit. It does have an appreciation as a standard of measure which one can apply to sports clothing. Historically, (71,72) the Chinese have used a similar index to judge weather on the basis of suits to wear. Warm or comfortable days (probably $18\text{--}20^\circ\text{C}$) are "one-suit days" and increasing cold weather refer to two suit and up to "twelve suits" for severe weather. Typically, the clo value necessary to maintain a comfortable level is dependent on activity level (since the required dry heat flux is changed) and air movement. We will see later that the concept of clothing insulation applied first to dry heat exchange was also extended to evaluation of water vapor transfer by Woodcock (65,66,68,69).

BASICS OF HEAT PRODUCTION AND HEAT GAIN

For homeotherms, a constant internal temperature (T_c) is prevalent whenever sources of heat gain are matched by avenues of heat loss; this balance occurs with no changes in heat content. Typically, thermal steady state occurs when metabolism (the source of heat produced) is balanced by one or more effective avenues of heat exchange (Fig. 1).

Fig. 1 here

In describing human heat exchange with the environment, nine independent variables can be considered: metabolic energy production M , the positive (or negative) work accomplished W , the dry bulb temperature T_a , the dew point

temperature T_{dp} , the mean radiant temperature \bar{T}_r , the linear radiation transfer coefficient h_r , the convective heat transfer coefficient h_c , which includes the effect of air movement, the thermal insulation of the clothing worn I_{cl} and, finally, the time of exposure (t) to the environment concerned. The dependent variables in the heat balance equation are the evaporative heat loss from the skin surface E_{sk} , the mean skin temperature \bar{T}_{sk} and the rate of change in mean body temperature $\Delta \bar{T}_b / \Delta t$, when there is no thermal equilibrium (30,32).

In physical terms, humans generate heat by metabolic activity. This heat is primarily dissipated at the skin surface although some energy is utilized in doing mechanical work and some loss occurs via the lungs. Increased exercise intensity can be detrimental for establishing heat balance in warm and heat stress conditions but can be a benefit in achieving energy balance during cold stress. Active heat production results from voluntary exercise or involuntary shivering. Shivering can generate a rate of heat production almost as high as a fast walk or jog. If the amount of heat generated is greater than that lost from the skin, the body becomes warmer; if it is less than that generated, the body cools. The physiological strain, in engineering terms, will depend to a great extent on the degree of warming or cooling (Fig. 1) (17).

HEAT LOSS AND HEAT EXCHANGE

Heat loss is achieved through four mechanisms: - conduction, convection, radiation and evaporation. Conduction (K) occurs when heat from within the body flows through the skin and into cooler objects in contact with it. This occurs when fast-moving (warm) molecules hit slower (cooler) molecules and transfer energy to them, producing heat: there is no transfer of material, just a net transfer of energy. Convection (C) is defined as the exchange of heat between hot and cold objects by physical movement in a liquid or gas. This type of heat loss is most readily apparent with elevations in wind speed. It has been

found that when wind is involved in heat loss, also known as forced convection, (Fig. 2) the heat exchange increases approximately in proportion to with the increase in the square root of air velocity (9,13,16,18,19,20,51).

Fig. 2 here

Heat transfer by radiation (R) is the exchange of thermal energy between objects, through a process that depends only on the radiating objects. The energy is in the form of electromagnetic waves. Surfaces that are good radiators are typically poor reflectors. Skin is typically a poor reflector (18,27,34).

The amount of heat loss by thermal radiation depends on the amount of exposed surface which is altered both by clothing and by posture (Fig. 1). Heat gain can also occur from radiation and becomes an important variable when exercising outdoors whereby full solar radiation adds the equivalent of 8 to 10°C to T_a .

Evaporative heat loss (E) occurs at the skin's surface when liquid sweat passes into vapor, thus producing a cooling effect on the skin's surface. About 25% of the heat lost from the body at rest is carried away in water evaporated from the skin and expired from the lungs; the former is generally more important from a heat loss standpoint. Water vapor diffusion through the skin, as part of insensible perspiration, is not wholly subject to active thermoregulatory control but responds passively to changes in interstitial fluid pressure and ambient water vapor pressure (P_a) (26).

Most of the burden of maintaining heat balance in the body is carried out by the circulatory system (1,16,51). The blood and tissue fluids are composed largely of water and so can speed up heat exchange with the outside air by conduction and convection of heat to the skin's surface.

The major link between human energy exchange and the environment begins at the skin surface. Clothing in this chapter is considered as a part of the environment. Typically, homeotherms must balance any heat gain through metabolism by a subsequent heat loss through skin and respiratory passages. Body temperature regulation also adjusts vasomotor action. This alters conditions of heat exchange similar to alterations apparent in changes in resistance to clothing. The skin of the human body is supplied by a rich network of blood vessels and also responds to adrenergic (acral regions) drives as well as to thermal changes. With cold stress, blood flow to the skin is greatly reduced but transient heat flow to extremities may occur by the mechanism of cold-induced vasodilation (CIVD) (17,63) which is modified to a great extent by body heat content. Heat flux through the cold skin must pass variable insulation barriers that are often higher than the fixed resistance typically seen at full dilation (1 to 1.5 cm of fatty tissue) (16,51,71). Burton (16) first estimated the clo values for variations in resistance shown in Table 1.

Table 1 here

Variations in cutaneous blood flow distribution thereby allow skin to alter its resistance in order to attenuate thermal gains derived from metabolic heat production as well as from heat gains from the environment. In the cold, the outer layers of the body (described as a 'shell') offer a fixed resistance through fat, muscle layer, and skin thickness (16,17).

Table 2 here

Table 2 shows various levels of exercise corresponding to the appropriate heat production. During exercise changes in heat flow a) provide an increased blood flow to muscles for a given intensity of exercise; b) provide a system for the dissipation of the extra heat produced while actually working, and c) are sensitive to higher central nervous system commands which offer the ability to

stop this heat dissipation during periods of low exercise, primarily to avoid rapid cooling of the body, especially in cold weather. If cold weather conditions are encountered during exercise, the body heat production alone is not able to maintain the proper heat balance. Appropriate clothing, therefore, as an added factor to skin resistance becomes a vital requirement for maintaining heat balance not only for comfort, but also for health. One method the body uses in circumstances where the outside weather conditions are too cold, or the clothing inadequate for maintaining a heat balance for the total body, is to sequester the warm blood in toward the vital organs and, in effect, limit the body heat flow to such extremities as hands, feet and ears. Extremity protection thus becomes a vital determinant for cold weather clothing ensembles. During extreme conditions hypothermia can occur, and the body's core temperature can be lowered excessively to the point of death. Clothing must also, therefore, prevent excessive heat loss from the body as a whole. One rough estimate of the interaction of clothing and exercise level during constant exposures to various ambient temperatures is given in Fig. 3.

Fig. 3 here

Since clothing adds another layer of insulation to human skin, as such it imposes a barrier to heat transfer by all three avenues (16,30,68). Interference with air motion across the skin decreases transfer by convection and the consequent potential to lose heat by evaporation. During exercise the decrease in the boundary layer immediately surrounding the shell by wind becomes an aid to heat loss when air temperatures are lower than skin temperature; the boundary layer is a buffer against solar load when air temperature is higher than skin temperature. The properties of clothing affect the evaporative potential primarily when ambient water vapor pressure is high (7,19) particularly while exercising in wet tropics (dew point $> 15^{\circ}\text{C}$) or if the clothing type is

especially impermeable. In such humidity zones the decrease in convective coefficient and maximum possible latent heat loss attributed to a normal porous track suit (60% cotton; 40% man-made fibers) can amount to some 30% (7,19).

In the presence of clear days while walking in desert heat, clothing can also decrease heat transfer by thermal radiation but affects the evaporative process as shown in Fig. 4 (17,27).

Fig. 4 here

Typical decreases in the amount of radiant heat on the skin, for example, can be about 30-40% with ordinary working clothes near industrial furnaces (7). Early work by Adolph et. al (2) showed that solar load on semi-nude men walking in the desert was about 233 watts. When clothing of light color was worn, demand on evaporative (sweating) heat transfer was lessened by some 116 Watts (roughly 50% of solar load) which drops the effective thermal load on an individual by 4 to 5 °C (28,32). Logically, the thick, loose fitting, light colored clothing used in the hot-dry zones of the Middle East by natives offers a guard for thermal extremes spanning excessive heat by solar gain in the day and rapid cold spells at night (7). In coastal areas of such zones, bellows activity allows some evaporation, but in humid zones where air temperature stays at about 32-33°C with humidities in the 90% rh range, clothing is more of an impediment since the effective ambient water vapor pressure gradient is so small (7,14,18,31).

Although it is true that the water content of artificial fibers and natural fibers varies widely over relative humidity from 0 to 100%, the changes in enthalpy (58) with the transient wetting and drying processes are negligible compared to the net heat flux from metabolic heat production at steady-state (18,19,21,58). Comparison of rates of diffusion of water vapor through sheets of fiberglass wool with that through normal garments indicated that for either

samples resistance to diffusion was similar to that for still air (18). Therefore, diffusion resistances for water vapor of sports clothing composed of artificial, but porous, fibers are similar to those garments made with natural fibers. The critical property is amount of entrapped air (10,16,21,41,46,59,71). The rates of evaporation from the exercising person are a function of metabolism and any decreases noted generally would vary as a function of the clothing thickness. A general rule of thumb is that the thermal resistance of fabrics is proportional to both thickness and volume of air per unit area of fabric. For regular fabrics (i.e. cotton, polyester) one estimate deduced by regression analysis is that about 0.16 clo insulation is gained per mm thickness of different layers (roughly 4 clo per inch) (31,41,46). Another important quality is that the garment weave not be too tightly constructed so as to give a marked resistance to vapor transfer (not greater than that of an equivalent layer of air I_a) so that effective evaporative heat transfer is inhibited. For example, the effects of thermoregulation may be excessive using completely vapor impermeable garments. Studies (14,19,31) indicated that while wearing protective clothing, impermeable to both liquid and water vapor, a large proportion (over 50%) of soldiers suffered from heat exhaustion because they were not able to dissipate metabolic heat rapidly enough.

The techniques applied to measuring clothing insulation of sports garments (natural fiber) are in general equally applicable to a study on quantification of heat transfer in garments made of artificial fibers. The amount of clothing insulation, in clo units, and its distribution over the body affects radiative and convective heat loss from the skin to the environment. The permeability of the particular fabric matrix and any so-called pumping coefficient (31) affect the evaporative heat loss (transfer of water vapor, as a gas) through the fabric.

THE THERMAL INSULATION OF CLOTHING

As detailed before, the thermal insulation of a clothing ensemble or a single garment was first designated by the empirical "clo" unit introduced by Gagge et al. (29). The clo in resistance units is defined as $1 \text{ clo} = 0.155 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$.

The total insulation (I_T) is typically the insulation (13,22,46,56) from the skin surface to the environment, which includes the property of the increased surface area (f_{cl}) and the added resistance at the surface of the clothed body (I_a).

$$I_T = 6.45 (\bar{T}_{sk} - T_o) / H_s \quad (1)$$

where

I_T = total insulation, clo units

H_s = dry heat loss per m^2 skin area, W/m^2

\bar{T}_{sk} = mean skin temperature, $^{\circ}\text{C}$

T_o = operative temperature, $^{\circ}\text{C}$

$6.45 = 1 \text{ clo} / (0.155 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1})$

The effective clothing insulation (I_{cle}) is the insulation (54,55) from the skin to the clothing surface, which excludes any added effect of the increased surface area of the clothed body (f_{cl}) and uses the human body surface (i.e. DuBois) as its standard surface.

$$I_{cle} = I_T - I_a = 6.45 (\bar{T}_{sk} - T_o) / H_s - I_a \quad (2)$$

where

I_{cle} = effective clothing insulation, clo units

I_a = resistance at the surface of the clothed body, clo units

The intrinsic clothing insulation (I_{cl}) is the insulation (46,48,55,56) from the skin to the clothing surface:

$$I_{cl} = I_T - I_a / f_{cl} = 6.45 (\bar{T}_{sk} - T_o) / H_s - I_a / f_{cl} \quad (3)$$

where

I_{Cl} = intrinsic clothing insulation, clo units

f_{Cl} = clothing area factor (typically for each clo unit increases by $20\% \pm 5\%$).

The following gives a composite of the relation between I_{Cl} , I_{Cle} and I_T :

$$I_{Cl} = I_{Cle} + I_a(1 - 1/f_{Cl}) = I_T - I_a/f_{Cl} \quad (4)$$

Equation 4 is important when comparing clothing properties from different studies. Insulation values for clothing ensembles cannot be wholly compared without specifying whether they refer to the total, the effective, or the intrinsic clothing insulation. I_{Cl} is usually measured with a heated copper manikin, while f_{Cl} can be measured with a photographic method (22,56); I_{Cle} may be measured directly on humans (49,54).

Non-evaporative (dry) or sensible heat loss: The sensible (non-evaporative) heat exchange (DRY) by the processes of radiation (R) and convection (C) for humans wearing garments made of various porous fibers can be described in two generalized formats:

$$DRY = hF_{Cl} (\bar{T}_{sk} - T_o) = \frac{1}{I_T} (\bar{T}_{sk} - T_o), \quad W/m^2 \quad (5)$$

where h is the combined heat transfer coefficient; \bar{T}_{sk} , the mean skin temperature under the garment; I_T includes I_{Cl} , the intrinsic insulation of the garment worn expressed as $0.155 \text{ m}^2 \cdot \text{K}/\text{W}$ and I_a the insulation of the surrounding air. From the double eq. 5 it is evident that $F_{Cl} = I_a/(I_a + I_{Cl})$ and $I_a = 1/h$, where h is the combined heat transfer coefficient ($\text{W} \cdot \text{m}^{-2} \text{K}^{-1}$) from the exterior body surface by radiation and convection. The term F_{Cl} is known as Burton's Thermal Efficiency Factor (16,27), originally determined as an efficiency term of clothing in resisting dry heat loss between the skin and the environment.

F_{Cl} , is also given by the ratio $h_{Cl}(h + h_{Cl})^{-1}$ equivalent to $I_a/(I_a + I_{Cl})$ as in eq. 5 where h_{Cl} and I_{Cl} are, respectively, the intrinsic conductance and intrinsic insulation of the clothing worn, ($h_{Cl}=1/I_{Cl}$), and T_o ($^{\circ}C$) is the operative temperature, which is (28,30) composed of the average of the mean radiant (\bar{T}_r) and ambient air (T_a) temperatures, weighted by applicable linear transfer coefficients (h_r and h_c) for radiative and convective exchange respectively, or

$$T_o = (h_r \bar{T}_r + h_c T_a) / h, \text{ where } h = h_r + h_c. \quad (6)$$

An alternative definition of T_o may be presented by

$T_o = T_a + (ERF)/h_r$, where ERF is Effective Radiant Field ($W \cdot m^{-2}$). ERF is especially important in describing the net solar energy (Fig. 1) absorbed by an exercising person's body surface (27,28,32,34).

The following model equation relates F_{Cl} to h and clothing insulation where

$$F_{Cl} = 1 / (1 + 0.155 \cdot h \cdot I_{Clo}), \quad N.D. \quad (7)$$

and I_{Clo} for clothing insulation is now expressed in empirical clo units.

Using these concepts we shall show how evaluation of the net resistance of the specific clothing may be done quantitatively in situ. This method is based on partitional calorimetric analysis (54,55). In this method the assumption is that for any unit area of skin surface, the sensible heat exchange with the directly adjacent clothing surface equals the sensible heat exchange from the clothing surface itself. In reality, as pointed out later a slight error exists when sensible and latent heat losses occur simultaneously at skin and clothing surfaces (45,61,68). However, for our purposes we can consider heat flux as a unidirectional property through a porous material. Thus, for a local area (A_j) of clothed skin surface, its sensible heat exchange (DRY_j) from eq. 5 is now:

$$DRY_j = A_j F_{Clj} h_j (T_{sk} - T_{oj}) = A_j h_j (T_{Clj} - T_{oj}), \quad W/m^2 \quad (5')$$

where h_j is the local combined heat transfer coefficient at surface-j. It is further assumed that the local combined coefficient h_j would apply also to the skin surface, if the clothing were removed. T_{Clj} is the temperature of the

exposed clothing surface, T_{skj} is the local skin surface temperature beneath the clothing, and T_{oj} is the operative temperature of the environment affecting the clothing surface. If there is no radiant field present (i.e. $\bar{T}_r = T_a$), then $T_{oj} = T_a$, of the ambient air surrounding the subject. The local F_{clj} is given by:

$$F_{clj} = (T_{clj} - T_{oj}) / (T_{skj} - T_{oj}). \quad (8)$$

T_{clj} , the temperature of the clothing surface itself, can be measured accurately with a non-contact self compensating radiometer; T_{skj} , the local skin surface temperature, can be measured with properly calibrated thermocouples. In all experiments the wall and air temperatures are always equal, and T_{oj} is therefore equal to the ambient temperature T_a , set equal to 20°C.

Local values of the convective heat transfer coefficient h_{cj} can be determined from air movement by the technique of naphthalene sublimation (52). The local value for the linear radiation transfer coefficient h_{rj} ($W \cdot m^{-2} \cdot K^{-1}$) can be determined from (30,32,34):

$h_{rj} = 4 \sigma \epsilon (A_{rj}/A_D) ((T_{clj} + T_{aj})/2 + 273.2)^3$, where σ is the Stefan Boltzman Constant, the ratio (A_{rj}/A_D) is the effective shape factor for the local surface area in reference to a 4π environment and ϵ is the emissivity (generally, close to 1).

The total sensible heat loss from the body skin surface in a uniform environment at temperature T_a is therefore:

$$DRY = h F_{cl} (T_{sk} - T_a), \quad W \cdot m^{-2} \quad (9)$$

$$h F_{cl} = (A_1 h_1 F_{cl1} + A_2 h_2 F_{cl2} + \dots + A_n h_n F_{cln}) / A_D \quad (9a)$$

$$= (\sum A_j h_j F_{clj}) / A_D, \quad W \cdot m^{-2} \cdot K^{-1} \quad (9b)$$

Further, in terms of I_{cl} and I_a or h

$$h F_{cl} = 1 / (I_{cl} + I_a), \quad W \cdot m^{-2} \cdot K^{-1} \quad (10)$$

or

$$I_{cl} = 1 / (h F_{cl}) - 1/h, \quad m^{-2} \cdot K^{-1} \cdot W^{-1} \quad (11)$$

in which $h = (1/A_D) \sum A_j h_j$ and hF_{Cl} are given by eq. (9a) above.

The insulation value so derived by eq. 11, i.e. ($I_{Clo} = I_{Cl}/0.155$) represents the clothing insulation for the particular porous fiber matrix under consideration. The derived value (hF_{Cl}) represents the effective sensible heat transfer coefficient for the exercise activity concerned.

Table 3 here

Table 3 illustrates one such experiment indicating how local measurements of skin and clothing temperatures in a female subject were used to evaluate the thermal efficiency factor F_{Cl} and the value for the effective clothing insulation. The eight areas of the body surface used for measurement are the forehead, chest, back, upper arm, forearm, back of hand, thigh and calf. The relative fraction of the total body surface area is indicated by A_j/A_D in Table 3. The temperature data apply for a clothed resting subject in an experimental test chamber at 20°C still air condition. These measurements were made approximately one hour to one and a half hours after entering the chamber. The clothing worn consisted of a track suit, (60% cotton, 40% polyester), bra, bikini, socks, and regular gym shoes. The face and hands were uncovered and their respective surface temperatures were thus included in both T_{sk} and T_{Cl} measurements. From experiments illustrated by Table 3, it is apparent that I_{Cl} can be evaluated either by summing local measurements of $(A_j/A_D)h_jF_{Cl}$ or by direct use of averages of T_{Cl} and \bar{T}_{sk} .

The above represents one approach to measuring clothing insulation in vivo from partitional calorimetry; another way is by use of direct calorimetry (49). Either method is not difficult except for the variance in net heat flux through the skin. More common is the measurement of insulation values by use of static heated manikins (13,46,48).

Table 4 here

Table 4 gives a composite of intrinsic clothing insulation values for common sport garments derived from manikin studies. One summation formula is given to use as a rough calculator of total insulation. However, caution should be taken when using the formula in attempting to match appropriate clothing insulation for a sport to weather conditions. Recent studies (46) show that insulation is best predicted from actual fabric thickness and extent of body surface area covered by a garment. Total clo (I_T) may also be predicted from ensemble weight (kg) less shoes by the formula $I_T = 0.366 \text{ weight} + 0.71$ $r^2 = 0.94$; $SEE = \pm 0.18$ (46).

Clothing does not insulate uniformly over the body surface and heat flow is either re-distributed or often escapes unevenly. For this reason it is impractical to deduce insulation properties wholly from a heated manikin with constant \bar{T}_{sk} .

Insensible Heat Loss and Moisture Parameters: The evaporative heat exchange from the skin surface can be described in two different formats employing the vapor pressure gradient between skin and ambient as the driving force for mass transport. One initial model for evaporative heat transfer was proposed by Woodcock (65) and is used extensively in describing vapor permeation characteristics of military clothing; its concept was obtained from heated cylinder model studies:

$$E_{sk} = (L_a \cdot i_m) / I_T (P_{s,sk} - P_a) \quad W/m^2 \quad (12)$$

L_a is the Lewis number in $^{\circ}C/Torr$ or the sea level value ($2.2^{\circ}C/Torr$ or $16.5 K/kPa$) for the ratio h_e/h_c , where h_c is the average convective heat transfer coefficient over an unclothed skin surface (44). The Lewis number is constant for still air although it varies slightly as a function of skin temperature ($2.24 \pm 3\%$ $^{\circ}C/Torr$, Gagge, personal communication). With turbulent air flow L_a becomes $2^{\circ}C/Torr$, the psychrometric constant. The "moisture permeability index", i_m , in eq. 12 above is a dimensionless factor of the measure of the mass

transfer of water vapor through the clothing. By definition (using L_a as 2.2 °C/Torr) the value of i_m , is approximately unity for an unclothed subject but varies according to the impedance provided by different garment layers. In this case, $i_m = L_{lay}/L_a$ which includes the Lewis constant (45) owing to clothing (L_{lay}) and air. Equation 12 holds when thermal radiation between air layers of a multiple ensemble is not a significant factor.

Another approach to quantify evaporative heat exchange is by the relation

$$E_{sk} = w e F'_{pcl} (P_{s,sk} - P_a), \quad W \cdot m^{-2} \quad (13)$$

where w (known as a skin wettedness factor) is the fraction of body surface wet with perspiration (26) and F'_{pcl} is known as an effective permeation constant for the transfer of water vapor, as a gas, through any porous garment. Its quantification has been the subject of intense investigation (25,30,39,50,53,57) and can now be directly evaluated quantitatively as shown in Fig. 5 in part due to the use of sensitive humidity meters (30,35,36,38,57) whereby skin humidity of the specific site or close by is directly measured without indirect calculation.

Fig. 5 here

Use of such sensors overcomes certain problems such as condensation of water vapor when local temperature is below that at the measuring site occurring in tubes which connect to other less direct measuring devices.

The original approach used to quantify the permeation efficiency factor in eq. 13 was by Nishi (53). Based on his studies, the convective heat transfer coefficient (h_c), which is a function of air movement, was estimated by analogy to naphthalene sublimation. This factor corresponds to Woodcock's original $i_m = L_{lay}/L_a$, but only for the clothing layer (45,57). Recent studies (45) have unified the two approaches by adjustments to the value of the total vapor resistance ($R_{e,T}$) of the combined clothing and air layers.

Alternatively, both permeation factors (i_m or F'_{pcl}) may be experimentally evaluated during exercise with a completely wet skin (where $w=100\%$), or when thermoregulation begins to fail and body temperature, heart rate, and other heat strain indicators are rising. In such cases, verification of the efficiency of garment type in allowing latent heat transfer can be done. This is done by a partitioned heat balance assessment. The heat balance (from Fig. 1) may be written as

$$S = (m \cdot c / A_D) \Delta \bar{T}_b \cdot \Delta t^{-1} = (M - W - E_{res} - C_{res}) - E_{sk} - DRY, \quad W/m^2 \quad (14)$$

where S is the rate of body heat storage, in which m is body mass, c the specific heat, and \bar{T}_b the mean body temperature. The bracketed term is the net metabolic heat (M_{sk}) loss from the skin surface and is dependent on work done (W), the evaporative heat loss (E_{res}) and the convective heat loss (C_{res}) from the lungs. All terms in the bracket can be evaluated. The sum ($E_{res} + E_{sk}$) or total E can be determined from assessment of a subject's continuous rate of weight loss during exercise. The term $(\Delta \bar{T}_b / \Delta t)$ is proportional to the rate of rise of internal body temperature during exercise which can be measured as the rectal (T_{re}) or esophageal temperature (T_{es}). Esophageal temperature is often the better indicator of core temperature since T_{es} is twice as responsive as T_{re} to changes in heat storage (33,52).

When the loss by $E_{sk} + DRY$ equals the metabolic heat loss from the skin surface (M_{sk}), the expected change in an observed internal body temperature such as $(\Delta T_{es} / \Delta t)$ is small during the state of relative thermal equilibrium (i.e. $S < 5\% M$). By using a steadily increasing thermal stress caused by rising humidity at a constant air temperature during constant levels of exercise (i.e., constant M) there occurs a condition, when relative equilibrium ceases, that causes a sudden rapid rise in T_{es} and other variables. During the relative equilibrium phase, S should be less than $\pm 5\%$ of M and can be evaluated if necessary by

$$S = mc(0.1 \Delta \bar{T}_{sk} + 0.9 \Delta T_{es}) / \Delta t, \quad W/m^2 \quad (15)$$

Fig. 6 here

Fig. 6 and Fig.7 depict how evaporative coefficients can be evaluated from discrete internal body temperature inflections during resting and exercise experiments. In resting studies, subjects (11) typically sit on a Potter balance which measures continuous body weight changes; wind is directed in front by a large fan. The air and wall temperatures are accurately controlled to always equal the subjects' mean skin temperature thus nearly blocking dry heat transfer. In one such evaluation during a 2 1/2 hour long experiment the humidity was raised in a series of 25 minute long steps from 10 to 40 Torr. A pan of mineral oil on the scale under the subject caught any sweat that dripped off and prevented its evaporation. Tests were conducted over a wide range of air velocities with the subjects clothed (0.63 clo or $0.098 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$) and unclothed. In Figure 6 typical physiological and sensory responses from one of the subjects at one air velocity are plotted against the vapor pressure gradient ($\Delta P = P_{s,sk} - P_a$). The heart rate (HR), esophageal temperature (T_{es}), mean skin temperature (\bar{T}_{sk}) and the rate of water loss from the skin (M_{sk}) remained relatively constant until a critical vapor pressure difference (ΔP_{crit}) was reached. At lower vapor pressure differences, heart rate and skin temperature increased while the rate of evaporative weight loss decreased substantially. Similar responses were observed for the subject's perceived discomfort and sense of sweating. These sensations increased steeply for $\Delta P < \Delta P_{crit}$.

As would be expected ΔP_{crit} increased with clothing and decreased with increasing air velocity. Interestingly, the difference in ΔP_{crit} values for subjects at the same air velocity with and without clothing is constant at about 2.5 Torr (Table 5).

Table 5 here

For exercising experiments, Fig. 7 shows how the failure point for evaporative heat regulation by clothed subjects can be determined during exposure to increasing humidity at two different constant ambient air temperatures. These types of experiments regularly can be used to obtain the maximum effective evaporative heat transfer coefficient (9).

Fig. 7 here

At the certain critical conditions, the factor w , skin wettedness, is interpreted as being unity. The resulting experimental value for F'_{pcl} can therefore be determined directly for clothing of natural or man-made fibers. By this method, at a critical condition when skin wettedness is 100%, it may be assumed that the maximum possible value of the product $(w_e F'_{pcl})$ has occurred for the total body; this maximum is directly evaluated from observed values for M , W , T_{sk} , T_a , and P_a and a previously determined value for hF_{cl} . Thus

$$(w_e F'_{pcl})_{\max} = (H_{sk} - S) / (P_{s,sk} - P_a), \quad W \cdot m^{-2} \cdot \text{Torr}^{-1} \quad (16)$$

CRITIQUE OF METHODS IN CLOTHING EVALUATION

The basic concepts introduced in the previous sections are generally valid for porous clothing when dry heat loss and evaporative heat transfer are considered as separate processes. Manikin results that involve effects of dry insulation and moisture flow from a completely wet skin also serve as useful indicators of clothing properties. Quite a different situation prevails in the dynamic state when vapor flow passes through multiple layers of varied fiber construction in an ensemble and secreted sweat is not fully evaporated (21,23,38,45,61).

The problems of condensation and necessity of keeping sweat out of clothing have been recognized by circumpolar people since antiquity as evident in Wulsin's account of the Eskimo and Chuckchee of northeastern Siberia (72). However, the problems were apparently not understood by early polar explorers.

Belding et. al. (6) cite historical notes of Cherry-Gerard in 1922 from Scott's polar expedition:

"...all of this sweat instead of passing through porous wool of our clothing and drying off us, froze and accumulated. It just passed away from our flesh and became ice. But when we got to our sleeping bags, we became warm enough to thaw the ice: part remained in our clothes and part passed into skins of our sleeping bags and soon were sheets of armor plate."

Belding et. al's. (6) study was one of the first to characterize heat balance during extreme cold. They found that for subjects exercising in an Arctic Uniform (7550 g, 3 clo) at a constant work rate of 6 mets between T_a 's of -32°C to -40°C , most of the sweat produced was taken up in the clothing (Table 6).

Table 6 here

Moderate sweating could be dispelled in the outer layers but excessive sweating recondensed in the under clothing. Their results first conclusively showed that:

1. transfer of sweat is not dependent on skin to ambient vapor pressure difference solely;
2. rather, the vapor flow is dependent on conductance of heat from layer to layer in a clothing system;
3. the specific resistance to vapor transfer is therefore a property of fiber conduction and air trapped in clothing.

This study also provided an initial finding that humans can be cool but comfortable during Arctic exposure if accumulation of sweat is modified by activity level. Woodcock (65,66,68) also came to a similar conclusion and first suggested that the layering principle of clothing works because as each layer of clothing is removed, with a high intensity of exercise, a quantity of heat is dispelled by the successful evaporation of sweat. Therefore, the limiting property is not sweat secretion per se but that which is evaporated. Usually the colder the climate the greater is the impedance to sweat evaporation imposed by

extra layers of clothing worn during moderate activity. Woodcock (65) believed that instead of keeping a person warm as possible, .."the purpose of clothing should be to keep one in thermal equilibrium".

A static manikin study (61) done at low wind speeds confirms Belding's et. al. (6) initial finding by showing that mass and dry heat flow were additive in effect rather than separate. Others (23,38,45) have pointed out that if actual vapor condensation occurs on the inner face of a multiple-layered clothing ensemble, latent heat will be released at that point and such release renders a higher local temperature. Similarly, moisture absorption which occurs in such multiple-layered ensembles is affected by the physical and chemical constituency of their fibers. Generally, fibers with smaller diameter capillaries respond by condensing a given air-moisture volume at a lower relative humidity; on the other hand, larger diameter fibers condense vapor at higher relative humidity. This process is a special absorptive one also called regain. Regain is a variable quantity among fibers categorized as natural or synthetic (68).

Regain properties can be visualized by the following example: if a wool suit weighing 1361 g were to absorb 227 g H_2O , the heat evolved upon drying would be about 127 W, roughly the amount of heat the body generates at rest in 1.5 h. Interestingly, Behmann (4) found in human experiments that the net heat loss in drying of a wet fabric also decreases with a concomitant lowering of capillary conductivity and such heat loss was affected by an increase in surface roughness. Although similar swatches exhibited equal thermal insulation in the dry state, polyamide (a high moisture transmitting synthetic), cotton, and wool fabrics showed wide variances in evaporation to moisture regain. A plot of evaporation to regain (as a % of dry weight) revealed that polyamide and cotton have four times and two times, respectively, higher evaporation rates ($g \cdot m^{-2} \cdot h^{-1}$) than wool up to regains of 80% for each fabric.

A PRIMER FOR ATHLETES ON FIBERS

Although not within the purview of this chapter, a brief understanding of the biophysical and chemical properties of fibers in athletic wear is a useful thing. This is analogous to knowing about good nutrition when engaging in some athletic event without knowing details of the biochemistry of exercise. The multipurpose garment for the athlete may be an intractable objective. For the cold: as in jogging, hockey, etc an ensemble is desirable that is impervious to liquid water, windproof yet permeable to variable water vapor produced during different activity levels. For warmer environments, an ensemble must allow evaporative heat transfer but it should be light and afford solar protection. Historically, wool, cotton and other natural fibers have been used to solve the above problems. Biophysical properties of natural fibers can be improved to some extent (cross-linking of cotton or descaling of wool) but for the most part, synthetic substitutes are being used more and more for multipurpose garments. The synthetics are not subject to alteration in price from season to season, these new fibers display similar characteristics and "feel" owing to advances in polymer chemistry and mechanical testing (24,43,47,64), and many of these synthetics are not affected by micro-organisms (43). Fiber efficacy is characterized by at least seven properties: fiber diameter, crimp and elastic moduli, thermal characteristic and bulk density, moisture and wicking tendencies (water transmittance from the skin to the exterior in garments), air permeability and element of contact (10,21,64). Many of these have been discussed in the previous sections. This section will compare certain properties of natural and synthetic fibers in athletic wear.

Thermal space and bulk density. Fine diameter fibers are preferred for athletic wear because of their flexible nature and large surface areas. For example, average Merino wool has a total surface around 800 ft² per pound (10); for an

average suit this is an area of some 2500 ft². Finer diameter fibers (cotton and silk) may reach surface areas of 3000 ft² per pound. As such, the surface area allows closer contact between the skin and the ambient air.

As pointed out previously, effectiveness of thermal insulation is a property of the air entrapped in the fabric. When thermal conductivity (k_w) of a wool fabric is plotted against its bulk density, a curvilinear rise is seen with k_w flat up until it reaches a bulk density of 0.5 g·cm⁻³; below this bulk density, the thermal conductivity approaches that of air, 0.026 W·m⁻¹·K⁻¹ (10,58).

Degree of contact. Since early times, it has been recognized that the insulating property of fabrics can be altered by extending the annular spacing between skin and the garment. Wetting of the fabric is not a factor in alteration of this property, the reason being that there still exists freedom of circulation of warm air within the space. The effect is noticeable at low wind speeds and in still air. With high wind speeds impinging on the protective layer, all materials tend toward an equal thermal resistance (Fig. 2) and the critical property is volume of air enclosed rather than type of fabric (10,13,21).

Extent of contact that a garment displays over the skin surface is a more important property than its fiber composition. Since bulk density is the more important criterion in insulative resistance, attempts by manufactures have been made to alter air permeability. Air permeability can be altered by allowing diffusion of fresh air through the clothing (zippers) or other natural clothing vents (bellows property) particularly for low permeable garments. Knitted fabrics have a high degree of permeability to air while twill weave fabrics exhibit low permeability. Increased contact of a garment with the skin also increases chilling or clamminess effect. Continuous filament fibers impart this effect primarily because of contact. On the other hand, fibers with natural or those made to have high synthetic elasticity show little fiber contact with the

skin. Actual thermal characteristics (vapor flow, thermal conductivity) are affected by the volume of entrapped air (10,21,64).

Fiber treatment and construction. Wool has logically been used in garment construction because wool is an excellent insulator owing to its resiliency by which the fiber springs back to maintain an original volume of trapped air for an extended period of time (10,18,51,64). The honeycombed tubular structure and scales present in wool fibers allows them to retain their resilience, which is an advantage when wet since the thermal insulating properties remain stable. Wool fibers also can transmit moisture (wick) from the inner to exterior boundary layer. Cotton, however, is not very resilient compared to wool, wicks rapidly but absorbs moisture as well (10,59,64,68). Mecheels' et. al. (47) studies show that cross-linking of cotton fibers, a process which reduces its hygroscopic properties, (Fig. 8) allowed substantial wicking with less "post-exercise" evaporation (65,66).

Fig. 8 here

Silk fibers also have high absorbency but they are very expensive compared to similar absorbent synthetic fibers. Of the synthetic fibers, acrylic and polyester are the most widely used. Acrylic is a resilient fiber and traps air much like wool. It is not absorbent but does wick moisture to an extent. Polyester does possess limited absorbency and resiliency but generally, by itself, has poor wicking properties. New organic additives to the fiber have improved the wicking action by processing the hollow fiber to have an inner hydrophobic property but an outer hydrophilic surface. This allows athletic garments made from such treated polyester to dispel moisture by a "spreading" process to the exterior (64).

In essence, newer treated synthetic fibers used in athletic wear allow the fiber's properties to enhance the transport of insensible perspiration away from the wearer's skin surface. Skin wettedness at a point site should therefore be

reduced; however, this has not been proven (23,35). Generally, the way these treated synthetic fibers dispel moisture is nothing more than a combination of either cascade capillary transfer of moisture from one fiber adjacent to another, by hydrophobic transfer of water molecules since the fibers have variable or little moisture absorption, or by a spreading action. We will see later that with a full garment, the carrying capacity of water vapor transfer is limited and governed by intensity of exercise (23,35,38).

By far the most touted fiber for athletic wear is polypropylene. Polypropylene is a synthetic fiber with an organic base. It has low thermal conductivity, low moisture regain and weight (0.9 g/cm^3) and purported high wicking properties. This would seem to be ideal for exercise and cold wear except that undergarments made with this fiber trap oils from sweat, exhibit low melting points, and the organic compound wears out. Other synthetic fibers use polytetrafluoroethylene (PTFE) either laminated onto wovens or knits or applied along with polyurethane as a porous coating to common textiles (cotton, nylon). The theory of operation is that such garments allow water vapor generated from sweating to pass through micropores (diameters 5×10^{-7} to $3 \times 10^{-6} \text{ m}$). Since latent heat loss by water vapor generates molecules of water averaging $4 \times 10^{-10} \text{ m}$ in diameter (15), but drizzling rain has a diameter roughly $5 \times 10^{-4} \text{ m}$, by simple membrane physics these garments purport to allow "breathability" but also protection from rain.

Along with fiber characteristics, fabric construction enters into the ability of a garment to conduct heat and moisture. The fabric construction may appear as woven, knit or non-woven material in athletic wear. Woven fabrics have interlacing yarns that intersect at ninety degree angles. If the interlacing is tight, not too much dead air can be trapped so the thermal insulation is minimal. Tightly woven fabrics with synthetic hydrophobic fibers are effective wind

breakers. On the other hand, knits can be distinguished by their interlocking loops and thereby are bulkier than wovens. The looping characteristics allow the stagnant air to be trapped and thus also serve to insulate better than wovens. Thermal underwear, sweaters, ski pants, etc. which allow movement are typical knits. Fiber pile clothing, favored by backpackers, is a knit with polyester pile placed close to the body layer and a knit backing juxtaposed on the outer surface. The latest fabric construction incorporates non-woven fabrics in which layers of fiber material are bonded or matted together chemically (melt-blown) or by pressure (43,64). Familiar non-woven fabrics are felt products. More recent ones include thick mats incorporating polyesters or acrylic fibers with outer woven shells. These non-woven fabrics retain a degree of resilience when wet and trap air effectively so they have good thermal insulation. One non-woven batting made up of polypropylene fibers appears by the trade name Thinsulate (37). This fabric is made up of olefins spun into microfiber construction which effectively trap air molecules on the surface of the fibers and therefore raise the amount of air per a given volume. It is claimed to have almost twice the insulative value as a similar thickness of wool or down-filled material (37).

Wicking and semi-permeable garments. In the past, high moisture regain was a desirable property in dissipation of vapor (59). High regain fibers protected the wearer from sudden alterations in air temperature and humidities. For example, movement from a comfortable dry environment to the outdoors in which the air temperature is much lower, but high in relative humidity would not be felt as much by wearing a garment high in regain properties such as wool. Degree of buffering to a temperature change of a particular textile is dependent to an extent on the regain to relative humidity relationship (10,21). The higher the regain for a given relative humidity change the larger is the water absorption (45,51). However, with the advent of synthetics with wicking or high moisture

permeation properties the less is the value of high regain fibers. Complications to water vapor dissipation exist in garments with these properties as detailed elegantly by Farnworth and his colleagues (23) using a sweating flat plate. Fig. 9 and Fig. 10 depict two instances in which wicking and water vapor permeation were tested on a sweating flat plate.

Fig. 9 here

For Fig. 9 a layer of Thinsulate was placed beneath Goretex or impermeable fabric at a box temperature of -17°C . The extent of moisture permeation during a large sweat pulse (heat loss) was not appreciable compared to a mass balance calculation and the authors point out that water vapor condensed in the Thinsulate prior to its dispersion to the semi-permeable laminate.

Fig. 10 here

Fig. 10 shows experiments which simulate low and high sweating rates ($150 \text{ W}\cdot\text{m}^{-2}$ and $220 \text{ W}\cdot\text{m}^{-2}$) underneath polypropylene and cotton swatches. Except for a higher decay after the sweat pulse evident with the polypropylene, no appreciable influence of wicking on evaporative heat loss is evident in these experiments. Similar results of equivalence in moisture transfer with chemically treated cotton have been noted before (24,44). Therefore, it is doubtful that, during heavy exercise, polypropylene would wick sweat away from the skin any more efficiently than cotton underwear.

Fig. 11 here

Figure 11 shows a typical experiment from a recent study in which moisture permeation was ascertained by dew point sensors underneath clothing (35) during light exercise ($31\% \dot{V}\text{O}_2 \text{ max}$, 350 W). A Goretex ensemble with high clothing insulation did display almost a 45% higher permeation than an impermeable garment and only 26% less than a completely porous track suit

during fan-directed wind speeds up to $3 \text{ m}\cdot\text{s}^{-1}$. However, these results were from observations in which rate of weight loss was observed for up to two hours at T_a of 25°C and low dew point temperatures. They should not be interpreted for transient conditions or during higher work rates in which sweating is exacerbated. At best, our results showed that the semipermeable garment allowed moisture permeation to an extent not greater than $82 \text{ W}\cdot\text{m}^{-2}$ of regulatory sweating or, for a steady light activity ($175 \text{ W}\cdot\text{m}^{-2}$), about 46% of M .

The studies above should not be misconstrued to show that garments incorporating PTFE laminates are not useful. Indeed, coupled with linings made up of Thinsulate or other types of insulation material they do maintain high insulative properties. However, there are limitations to the absolute surface area of microporous openings available compared to the high sweat volumes secreted during heavy intensity exercise. Subsequent condensation of vapor underneath the outer layer when ambient temperatures get lower than about 15°C also restrict the garment's efficacy at the present time as the ultimate multipurpose athletic garment (5,38,45).

SPECIAL AIDS (ADVANTAGES) USED IN ATHLETIC CLOTHING

Aerodynamics. Special problems exist for athletes during sports competition. A dilemma occurs primarily in the speed sports in which design of clothing must impact on thermal factors. Suitable clothing made as smooth and tight as possible to minimize drag (Fig. 12) can have a decided edge in a close competition as documented in the studies by Kyle (42).

Fig. 12 here

In warm air temperatures, the athlete must depend on two main factors for thermal balance: technological designs for optimum ventilation and moisture permeation such as loose jerseys or singlets (which seem at odds with the effects present in Fig. 12), and the person's competence at heat dissipation related to

fitness and heat acclimation. Kyle's studies show that a loose polyester jersey for competition cyclists can slow the racer as much as 2 min in a 25 mile race. Interestingly, perfectly smooth jerseys were not perfectly drag free principally because of the aerodynamic effect in which rough surfaces display turbulence in the boundary layer and the air flow is directed more uniformly over the surface contours (similar to a golf ball).

In the cold, the same smooth design requirement may not hold because a necessary property for optimum thermal insulation is indeed related to drag. Resistance to air movement through a mass of fibers depends on the fiber's solid surface. The greater the drag the more air can be entrapped for good insulation (10,71).

Another problem specific to cyclists is related to the solar load incurred during competition racing outdoors. Aluminized suits that would display minimum wind drag at racing speeds would be a great contribution. However, such low emissivity fabrics generally have poor moisture permeation properties (18).

Clothing weight. Encumbrance due to thick clothing often serves to produce a decrement in performance. Much of the decrement is associated with added weight. For example, Teitlebaum and Goldman (62) observed that persons doing treadmill exercise ($1.6 \text{ m}\cdot\text{s}^{-1}$) in an arctic uniform weighing 6000 g displayed a metabolic rate 80 W higher than when the same weight was carried in a belt.

Analogous to the aerodynamic drag evident in design of clothing during competition cycling is the effect of added weight on times during distance running. Stevens (60) manipulated metabolic cost equations to ascertain the cost of carrying extra weight and thereby predicted the extra time it would take to complete a race of a given distance.

Fig. 13 here

Figure 13 shows one such plot relating the extra time necessary to complete a marathon with extra clothes. In the figure, I have calculated the rough total clothing insulation (I_T , clo units) based on the regression equation of McCullough (46). Typically, for the runner's weight shown in Fig. 13, Stevens estimated that a change from a 100% nylon shorts and singlet (weight 145.4 g) to a 100% cotton shorts and singlet (233.7 g) would add 88.2 g to a runner's weight and about 22.6 s to a usual race time of 3 h 40 min. These are negligible differences in time and also in clothing insulation values. However, the addition of a sweat suit with nylon shell (clo of 1.48) would add 1.34 kg to the runner's body weight and 5 min 43 s to a person's usual race time. In competition runs, such an effect of weight and clothing necessarily becomes critical in respect to Fig. 3 requirements. Equally so is the garment's fiber composition. Not added in the calculations above was any effect owing to excessive wetting of the 100% cotton shorts and singlet, which might be an added factor in determining race time.

SUMMARY

In this chapter, I have presented a potpourri of examples of proper clothing to wear during various exercise demands in different environments. This will not be wholly exact for all persons. For example, during the 1984 Olympics in Los Angeles, clothing wear related to the particular environment was totally different. We have already detailed the aerodynamic necessities of cyclists and runners. At the other extreme, equestrians had to contend with a warm, moderately humid environment plus a solar load which added to effective heat stress while wearing clothing having nearly 0.8 to 0.9 clo values plus head gear which limited evaporative heat loss. Obviously, garments with high water vapor permeation and bellows properties were necessitated. Runners in the marathon faced equal thermal challenges. But, coupled with these, they incurred variable levels of hypovolemia and cardiovascular strain. A. Salazar, for example, was advised to omit shower sprays and he ran with a prototype high permeability singlet. The excessive wetting plus time to maneuver to the spray was deemed of no value since Mr. Salazar chafes easily from wet clothes (L. Armstrong, Ph.D., personnel communication).

One interesting challenge to this advice is to consider the clothed runner as a wet globe thermometer under forced convection (Fig 1). A high contact fabric, especially like cotton, does render evaporative cooling provided that the skin to ambient vapor pressure gradient is not diminished by high relative humidity. Salts in sweat could possibly reduce the skin's vapor pressure (12); however, Woodcock and Breckenridge (67) point out that "secreted sweat (especially with heat acclimation) is so dilute that no appreciable lowering of vapor pressure would occur unless sweat were concentrated many times by evaporation". Thus the degree of "human" wet bulb depression simulated by a completely wet runner may or may not be an advantage given that all other variables are also constant

(i.e. humidity, weight of clothing as in Fig. 13, etc) or the level of hypovolemia is not excessive and the person is fully heat acclimated. Problems such as these may be theoretical but they serve to show that the thermal biophysics and physiology of exercise follow similar fundamental pathways which can be highly pertinent.

As we sought to point out in this chapter, these pathways have merged in the last 30 years with developments such as warmth without bulk for backpackers (which is a welcomed contrast to heavy Arctic wear), types of material which allow athletes to remain somewhat comfortable while sweating, and other advances which luckily displaced use of less appealing sports apparel such as the old woolen baseball uniform.

Certainly, there are many problems which have to be solved like the controversy about wickable material or condensation problems in semipermeable garments with heavy exercise. We never were able to cover adequately in this chapter the behavioral or thermal modelling aspects. One feasible property which may not be too futuristic is the development of fibers which either react to ambient temperature (or preferably changes in body temperature) and provide adjustments in insulation or to the diameter of micropores of a multipurpose garment depending on exercise intensity.

Table 1. Variation in Insulation (I).

Resistance variable	Ranges in I		Cause of changes
	clo	$\text{m}^2\cdot\text{K}/\text{W}$	
Peripheral tissue	0.15-0.8	0.023-0.124	Vasomotion
Clothing	1-4	0.155-0.62	Behavioral thermoregulation (removal or addition of clothing)
Air	0.2-0.8	0.03-0.124	Air movement

Compiled from ref (16).

Table 2. Different exercise levels and corresponding values of heat production.

Activity	Metabolic rate ($\text{W}\cdot\text{m}^{-2}$)	Met
Sleeping	42	0.7
Basal	46.5	0.8
Sitting	58.2	1.0
Standing	69.8	1.2
Walking (level)		
1.5 mph	105	1.8
3.0 mph	151	2.6
4.0 mph	209	3.6
Running (level)		
10 mph	582	10.0
Heavy exercise	1000	17.2

Compiled from (1,18,30); 1 met = $58.2 \text{ W}\cdot\text{m}^{-2}$; mph $\times 0.447 = \text{m}\cdot\text{s}^{-1}$.

Table 3. Direct evaluation of effective clothing insulation. $T_a=20^{\circ}\text{C}$, $T_{dp}=9^{\circ}\text{C}$.

OUTER CLOTHING TEMPERATURES ($^{\circ}\text{C}$)								
SITE	HEAD	CHEST	UPPER ARM	LOWER ARM	HAND	BACK	THIGH	CALF
min 60	29.25	26.81	25.12	27.94	28.32	28.06	26.93	27.68
min 70	29.3	26.93	25.04	28.4	28.3	26.9	26.9	27.8
min 80	30.2	26.2	24.9	28.2	29.1	28.3	27.3	27.6
$\bar{x} \bar{T}_{cl}$	30.14	26.55	24.97	28.31	28.69	28.32	27.14	27.69
A_j/A_D	.07	0.175	.07	.07	.05	.175	.19	.20
T_{clj}	2.11	4.65	1.75	1.98	1.43	4.96	5.16	5.54

\bar{T}_{sk} (thermocouples underneath clothing) = 31.5°C ; \bar{T}_{cl} = 27.58°C ; v = 0.10 m/s ; \bar{h}_c = $2.6 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$; \bar{h}_r = $4.7 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$; $h = \bar{h}_c + \bar{h}_r$; $I_{cle} = 1/(0.155\cdot h)\cdot(31.5-27.58)/(27.58-20.0) = 0.45 \text{ clo}$ or $0.07 \text{ m}^2\cdot\text{K}\cdot\text{W}^{-1}$.

Table 4. Clothing insulation of common athletic individual units and garments.

Item		Intrinsic clo	
		light	heavy
Socks:	ankle	0.04	0.08
	knee	0.08	0.13
	tights, running (polypropylene)	0.06	0.11
Underwear:	bra & panties	0.05	-
	half slip	0.13	-
	full slip	-	0.19
	T-shirt	0.09	-
	running singlet	0.06	-
	fishnet	0.10	-
Shirt:	short sleeve tennis	0.18	0.25
	long sleeve football	0.22	0.29
Sweater:	short sleeve	0.18	0.33
	long sleeve	0.20	0.37
	turtle neck	0.24	0.43
Jacket:	short riding or ski	0.22	0.49
	long	0.33	0.73
Trousers:	football knickers	0.18	0.23
	regular long	0.26	0.35
	ski	0.40	0.53
Shoes:	athletic	0.04	-
	boots	0.08	0.11
Helmets:	riding	0.77	-
	football	1.20	-
Track suit ensemble		0.5	0.7
Arctic ensemble		4.3	4.6

This table compiled from refs (40,46,49,56) and author's data; rough total intrinsic clo estimation may be obtained by $I_{clo} = 0.82 \times \text{sum of units (46)}$.

Table 5. Critical vapor pressure differences.

Air Velocity, v , m/s	Critical Vapor Pressure Gradient Nude, ΔP_{crit} , Torr	Critical Vapor Pressure Gradient Clothed, ΔP_{crit} , Torr	Effective Vapor Pressure Gradient through Clothing, ΔP_{clo} , Torr
0.1	$14.6 \pm 1.8^*$	$17.4 \pm 4.6^*$	2.8
0.4	11.2 ± 2.3	13.7 ± 1.1	2.5
0.9	9.5 ± 0.9	12.1 ± 1.3	2.6
2.4	6.0 ± 0.9		

*Deviations from mean bound the 95% confidence interval. From (12).

Table 6. Effect of exercise in an arctic uniform (3clo).

T_a °C	M $W \cdot m^{-2}$	\dot{m}_s g/120 min (g/min)	moisture in clothing g/120 min (g/min)	% of \dot{m}_s	effective sweating g/120 min (g/min)	%	\bar{T}_{sk} °C	T_{re} (°C) initial/final	Comfort State
-32	354	722 (6.0)	599 (4.9)	83	320 (2.7)	44	31.1	36.9/38.1	Hot
-28.9	368	659 (5.5)	607 (5.1)	92	284 (2.4)	43	27.8	37.1/38.1	Warm
-40.0	369	179 (1.5)	190 (1.6)	105	70 (0.6)	39	27.2	36.9/37.9	Comf

From Belding et. al. (6).

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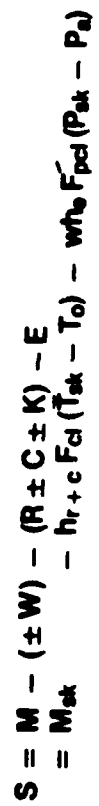
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FIGURE LEGENDS

- Fig. 1. Thermal model of a clothed subject exchanging energy with the environment, the heat balance equation, and convective heat transfer for a subject in a uniform wind and while running. Adapted from R.P. Clark (20) and Carlson and Hsieh (17).
- Fig. 2. Relationship between thermal resistance ($m^2 \cdot K \cdot W^{-1}$) or clo values and increases in air movement or forced convection. From Breckenridge (13).
- Fig. 3. Relationship between ambient temperature and thermal insulation (clo units). From this chart an estimate can be made of the extent of heat loss or heat gain and steady state levels of exercise. From Adams and Iampietro (1).
- Fig. 4. The relationship between regulatory sweating and clothing (clo units) during a walk in the desert. For little clothing which is porous the physiological limit is set by ability to produce sweat. With increase in clo and protection from (R+C), the microclimate next to the skin becomes saturated and a general failure of the cooling process (E-drip) ensues. From Gagge (27).
- Fig. 5. Measure of skin vapor pressure and evaporation rate through semi-permeable (Gore-Tex) and fully permeable (Standard Suit) clothing. From Holmer and Elnas (39).

- Fig. 6. Mass transfer properties and physiological and sensory observations with decreases in P_{sk} to P_a gradient in resting subjects. From Berglund and Gonzalez (12).
- Fig. 7. Esophageal temperature changes with decreases in the gradient of $P_{s,sk}$ to P_a . Arrows denote where inflections occur at critical points for failure of thermoregulation during exercise, clothed in shorts (0 clo) and a porous running garment (0.32 clo). From Nishi et. al. (55).
- Fig. 8. Relationship of % relative humidity (%RH) and time under various types of clothing during exercise. From Mecheels et. al. (47).
- Fig. 9. Heat loss through separate layers of Gore-Tex and impermeable fabrics. From Farnworth and Osczevski (23).
- Fig. 10. Heat loss determined at two simulated sweating rates through cotton or polypropylene. From Farnworth and Osczevski (23).
- Fig. 11. Observed effective permeation as a function of air movement in a typical subject exercising with three different garments. From Gonzalez and Cena (35).
- Fig. 12. Aerodynamic properties of various kinds of clothing on a runner. From Kyle (42).
- Fig. 13. Estimates of the increases in running time to complete a marathon with added weight (and clothing insulation). From Stevens (60).



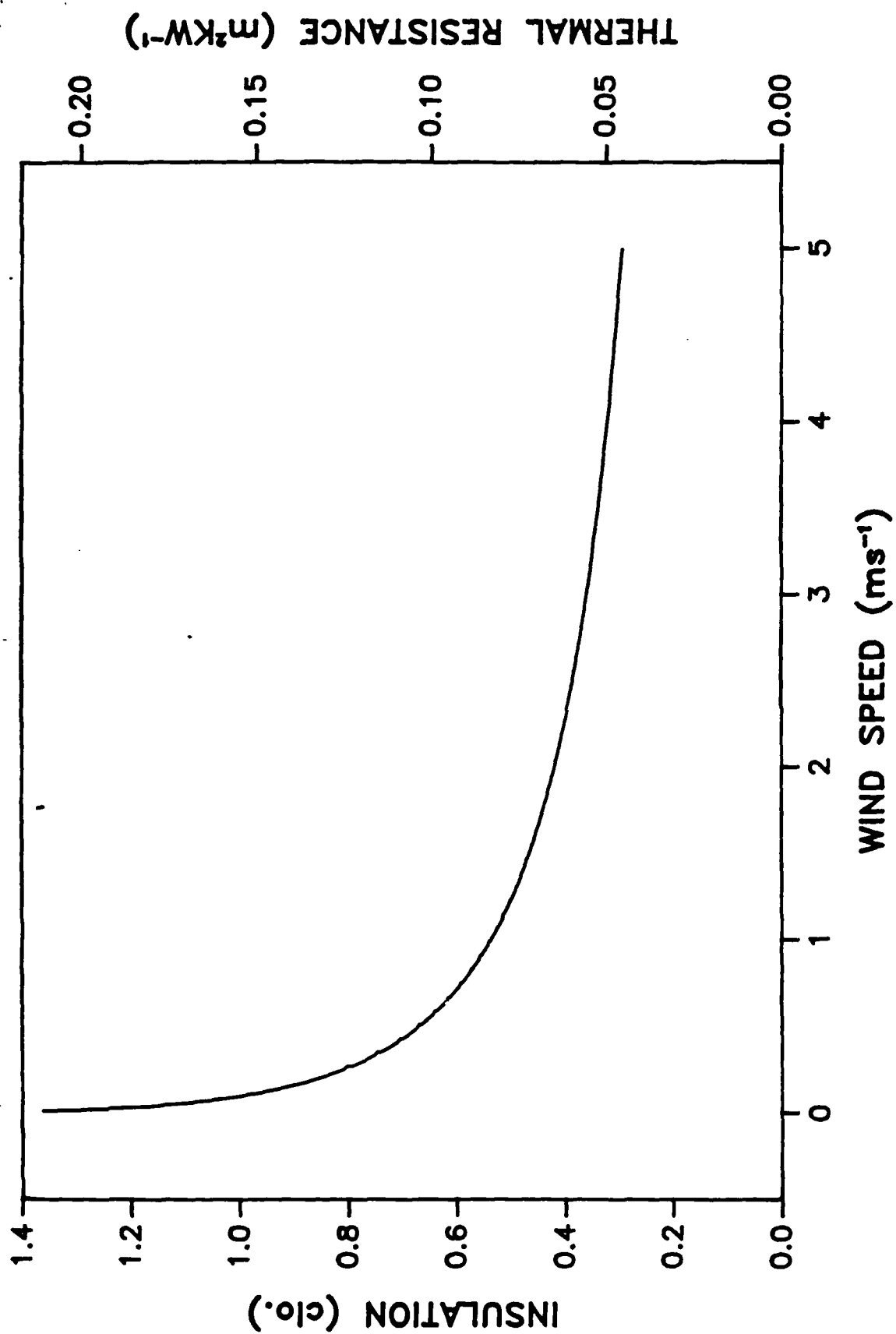


Fig. 2

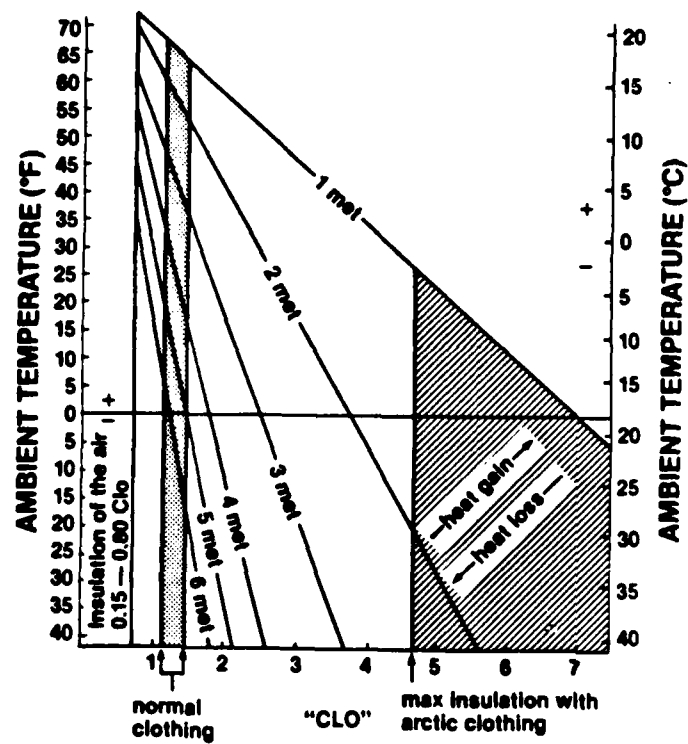


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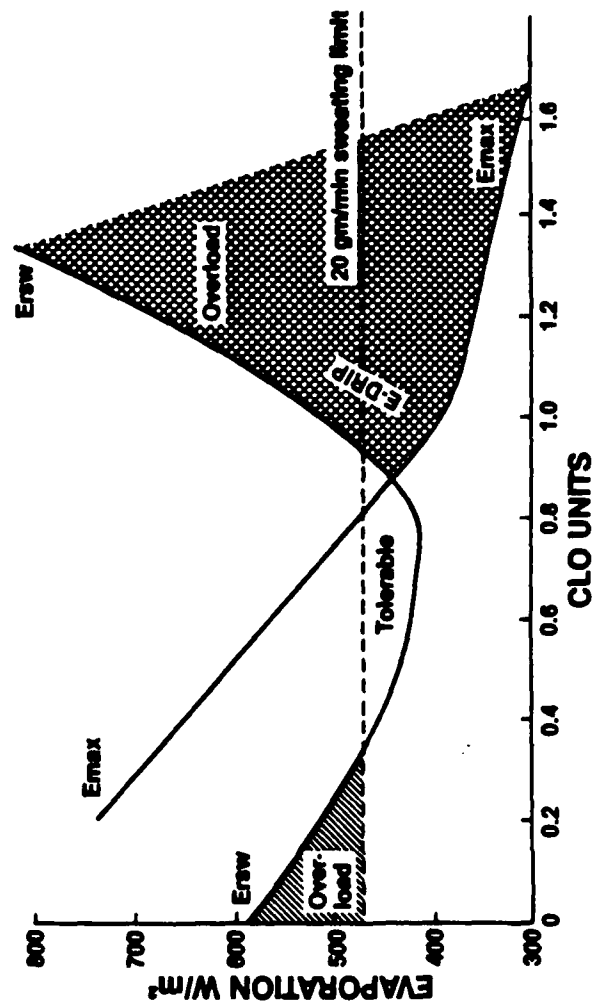


Fig 4

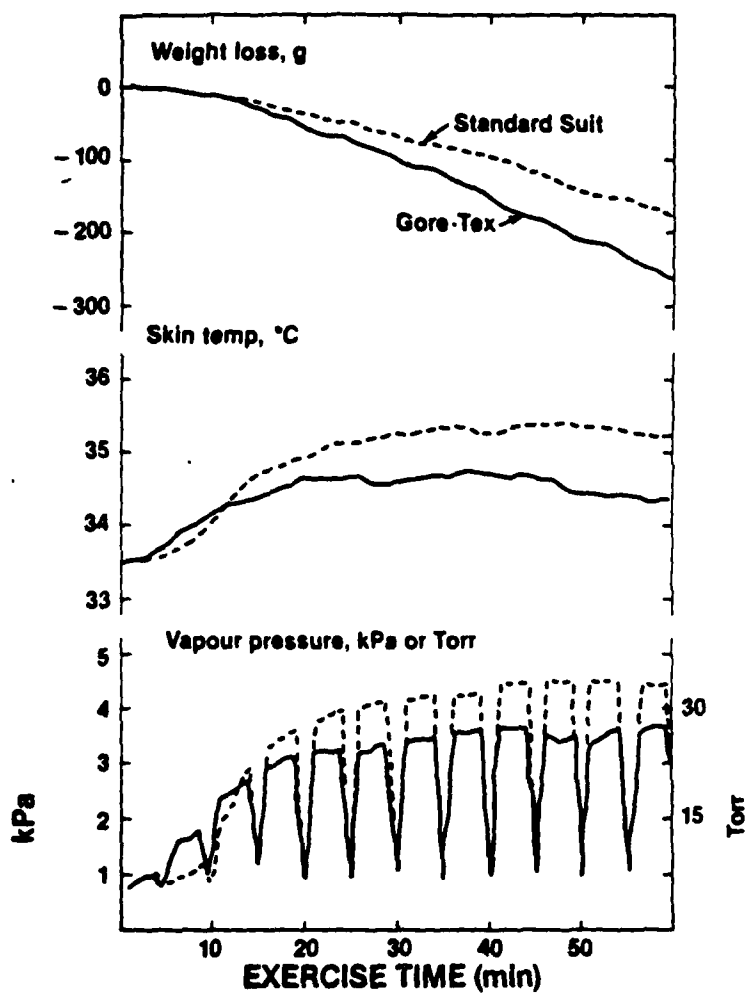


Fig 5

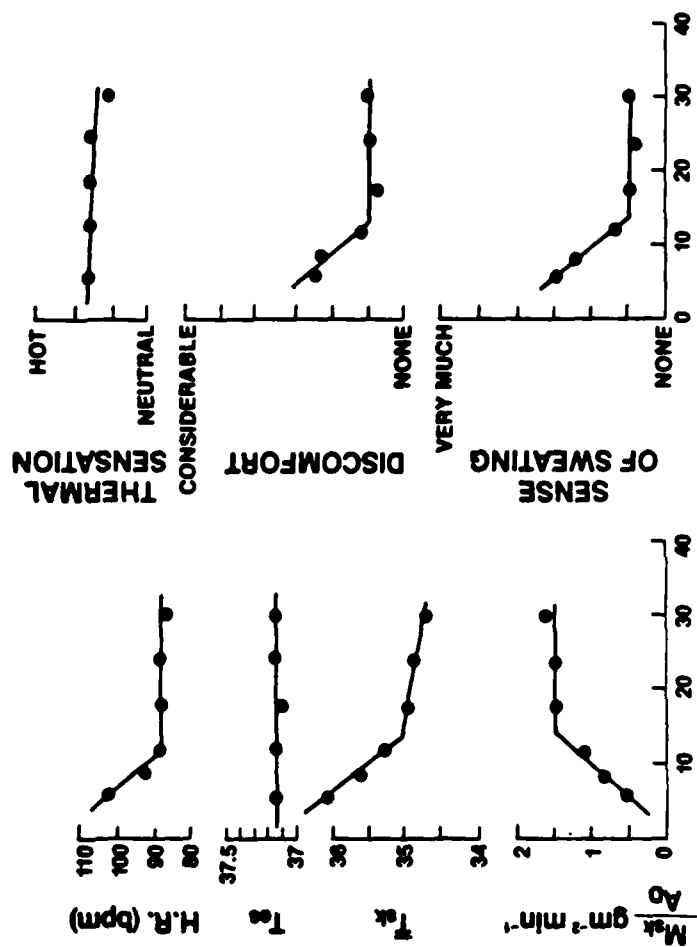


Fig 6

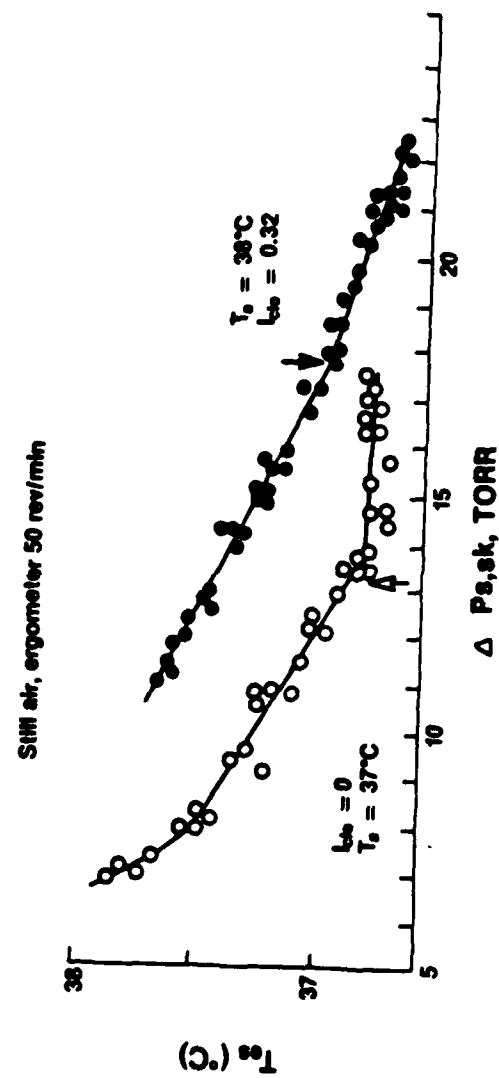


Fig 7

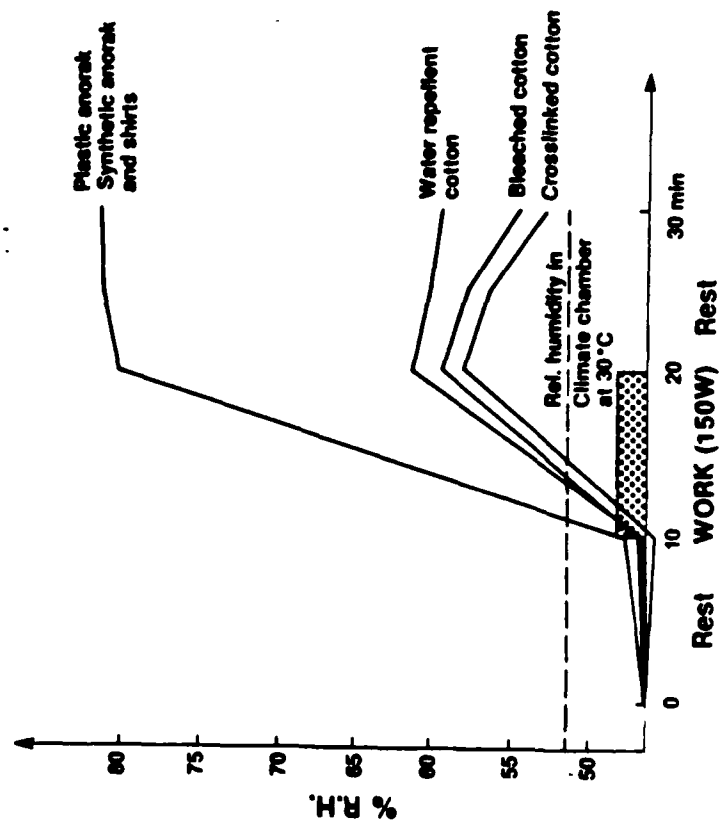


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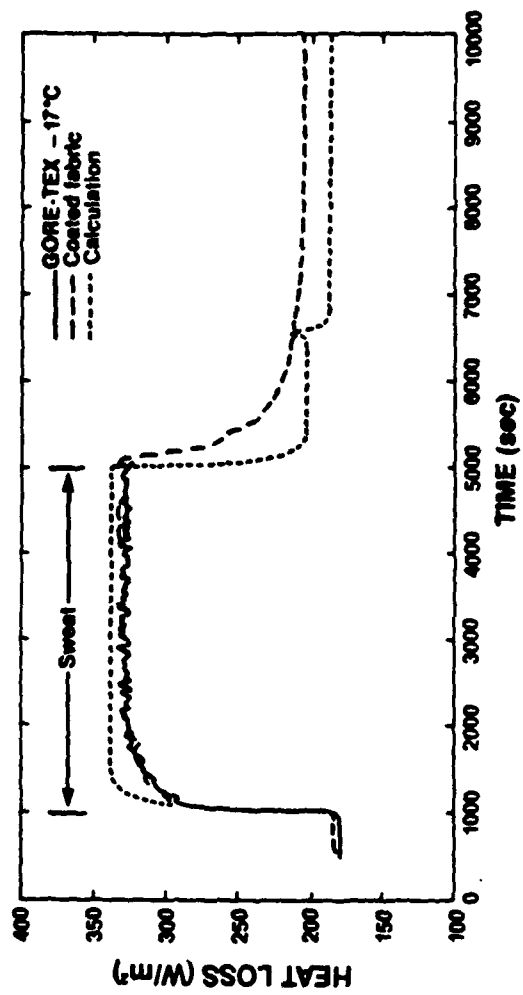


Fig 1

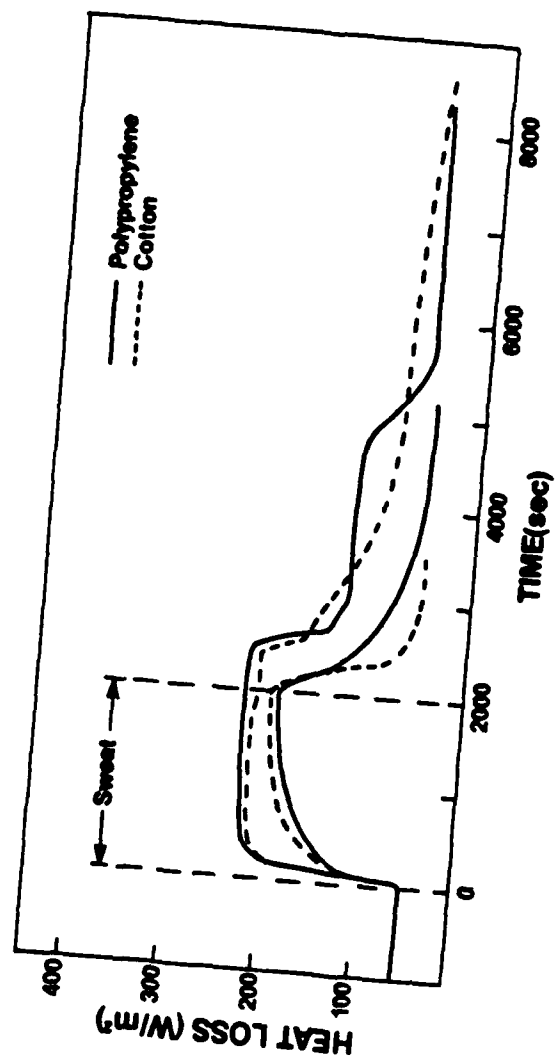


Fig 10

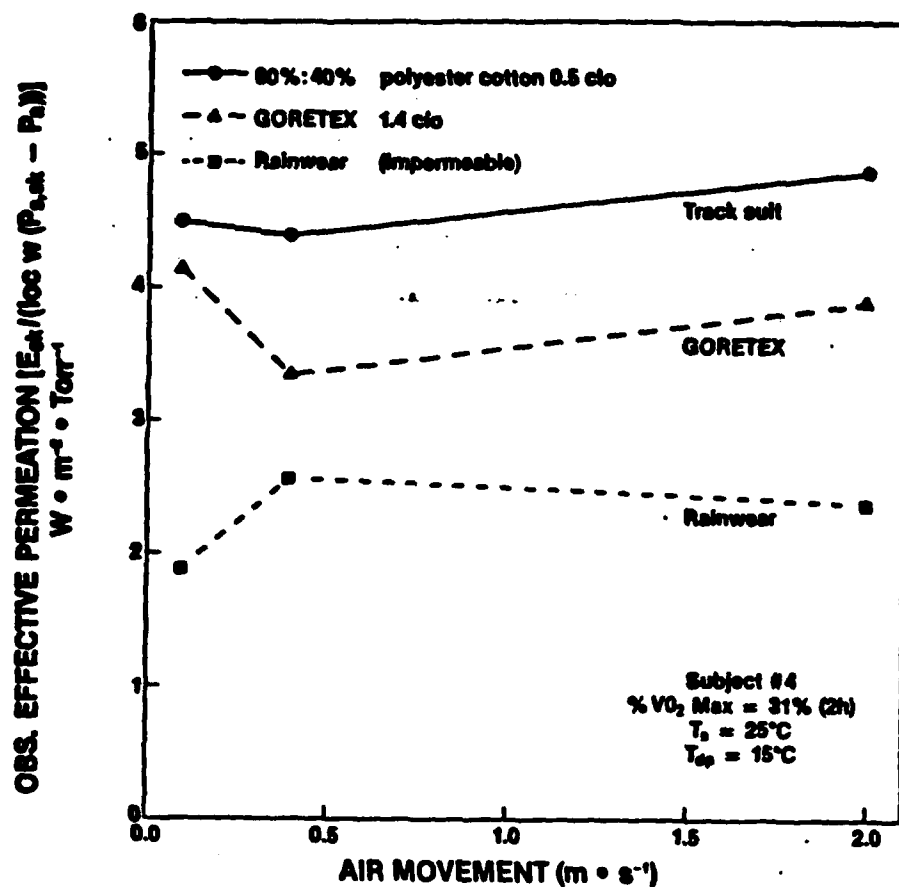
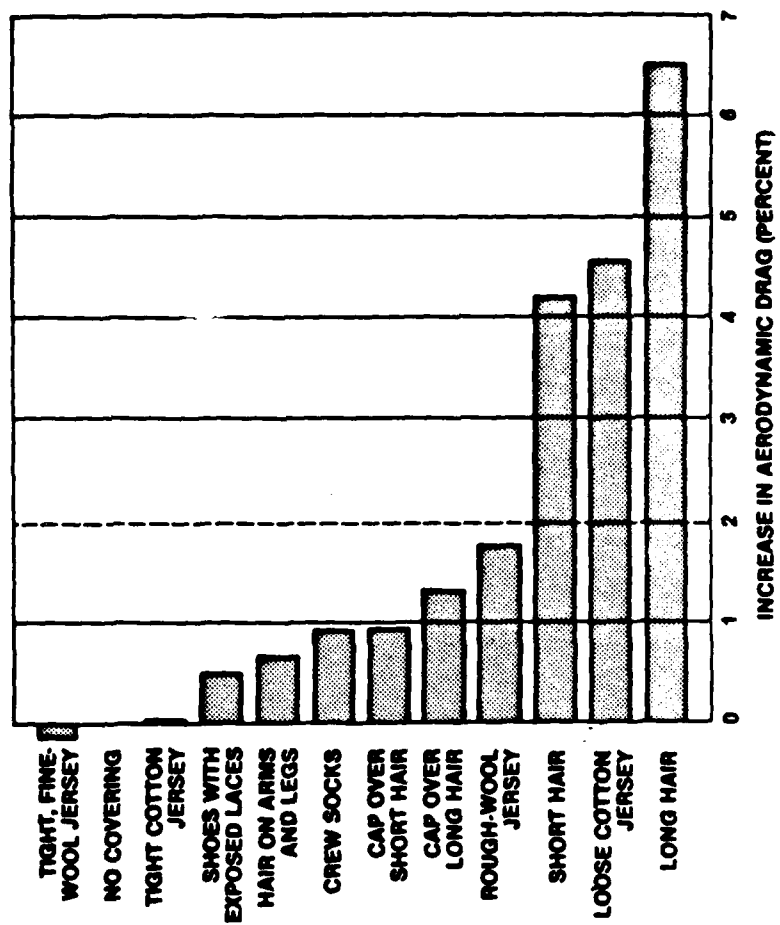


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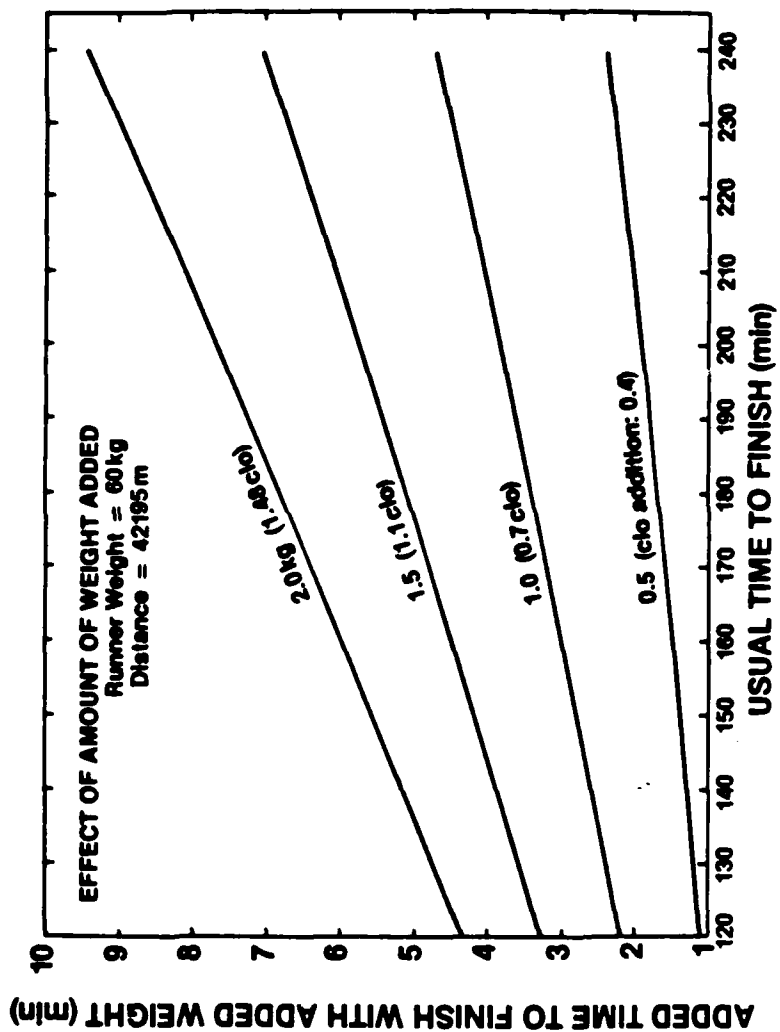


Fig 13

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