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industrial health and safety

Evaluation of the work load in hot environments

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1. INTRODUCTION

For several years now the BBC has allocated substantial finance to ergonomics research projects aimed at improving working conditions in stressful hot environments. These research projects were carried out partly in the laboratory and partly under real conditions. The aim of this report is to consider the main ideas and findings of those researches against the general background of hot environments in industry and the problems these entail.

This report is intended for the practitioners of ergonomists and therefore does not set out to be either a critical review of new basic developments in the thermal regulation of the human body, or an exhaustive inventory of technical means of providing protection against extreme conditions of environmental heat and humidity.

It aims only to provide the reader with a rational procedure for making an objective evaluation of the overall severity of the conditions in a work situation and, on the basis of this evaluation, for applying ergonomics to improve or correct the situation.

2. THE CONCEPTS OF STRESS AND STRAIN

In the animal kingdom human beings come in the homiotherm class, i.e. the internal temperature of the human body only fluctuates physiologically within a narrow temperature band, between 35.5 and 38.5°C. This means that the heat generated by the human body plus any additional heat from external sources and the amount of heat which man can lose to the thermal environment are in a state of equilibrium almost all the time. This equilibrium is represented by the following equation:

Equation No 1:

$$H_p + H_r = H_d$$

where H_p = heat produced by the human body;

H_r = any additional heat received from the immediate environment;

H_d = heat dissipated by the body in the environment.

In this equation $H_r = 0$ for certain thermal environment values, and increases in direct proportion as the environment becomes 'hotter'. Consequently it appears that H_d, which is a function of the thermal environmental conditions by virtue of the equilibrium expressed by equation No1, measures heat stress. This stress ('contrainte' in French and 'Belastung' in German) depends solely on body heat production and the physical parameters which determine heat exchange between the body and the environment.

In equation No 1 the term H_d can be varied over a wide range by means of various physiological mechanisms. The different physiological responses imposed by a given heat stress all come under the heading of "strain" ("astreinte" in French and "Beanspruchung" in German). Physiological strains take various forms, all dependent on the severity of the heat stress and on an individual factor representing certain physiological aptitudes. Equation No 2 defines physiological strain as follows:

Equation No 2:

$$\text{Physiological strain} = a \cdot H_d$$

where a = individual reacitivity;

H_d = heat stress.

For a closer definition of the concepts of stress and strain we must first analyse the methods of measuring heat stress and their classification in the context of industrial work. We shall then establish the methods for measuring physiological strains and the upper tolerance limits for these strains which are compatible with 8 hours' work in an industrial situation. Lastly we shall try to establish a methodology for applying ergonomics to the study and improvement of working conditions in a hot environment.

3. ASSESSMENT HEAT STRESS

As seen above heat stress may be defined as the total physical input on man of the thermal conditions to which he is subjected. The term 'thermal conditions' includes both the thermal environment to which man is exposed and the production of secondary heat when energy is expended in muscular work.
Equation No 1 accounts for this dual origin of heat stress, i.e. metabolism and environment. Metabolic heat stress is also called endogenous heat stress, as opposed to exogenous heat stress caused by the environment.

3.1. Analysis of metabolic heat stress

Life, i.e. the functioning of the cells constituting all the tissues and organs of the body, consists of continuous physical movement, i.e. work in the physical sense. Work is performed using the energy produced by the chemical reactions of metabolism. Directly or indirectly the major proportion of this energy is turned into heat. When man is resting, in the fasting state, and is exposed to a 'neutral' environment, i.e. one which does not constitute an external source of heat, he expends approximately 50 W/m^2 or 44 $kcal/h/m^2$ (rate of energy produced per unit of body area). This output, known as 'basal metabolism' is converted entirely into heat. The energy involved comes from oxidation of the glucids, lipids and protids obtained from food. The volume of oxygen consumed in these oxidation processes is thus a good indicator of the amount of energy expended.

When man performs physical work he expends extra energy. This extra energy is expended on muscular contraction, which generates the mechanical work performed outside the body. It is reflected in increased oxygen consumption. The gross efficiency of muscular work is below unity, partly because of the chemical reactions which generate the energy used in cell function, and partly because of the mechanical conditions under which contractile forces are applied to the body structure.

If one considers merely the increase in oxygen consumption compared with basal consumption, i.e. if one merely takes account of the increase in metabolic energy flux, the (net) efficiency of muscular work yield is approximately 30%.

In other words, for every 100 kcal of energy consumed by man 30 are converted into heat outside the body and 70 are converted into heat in the active muscles themselves. On the other hand, if the calculation is based on the total amount of energy consumed by a man (including basal metabolism which is completely converted into heat), the efficiency of muscular work is reduced to 20-22% (gross efficiency). Oxygen consumption is an indicator of the total amount of energy used by the human body. This total amount of energy is called metabolism for short. It is an energy flux. Not all this energy is converted into heat within the body, as some of it is expended in mechanical work outside the body and some into caloric energy within the organism. If we know the energy yield of a muscular activity we can calculate the proportion of energy used in each case.

Equation No 3

$$H_p = M_b + (M - M_b)\, r'$$

where M_b = basal metabolism;

r' = net mechanical efficiency of muscular work;

H_p = production of heat by the human body;

M = total energy metabolism.

More generally we can write:

Equation No 4

$$H_p = M - W$$

where W = mechanical work performed per time unit (power).

H_p and M are as defined above.

The metabolism M is generally estimated by measuring oxygen consumption. Rohmert (1974) has made a detailed analysis of the problem of measuring energy metabolism in an industrial environment.

Type of activity		Metabolism, kcal/h
Light work	Seated - no movement	100
	Seated - small movements of arms and torso	100-140
	Seated - small movement of arms and legs	140-160
	Standing - light work at machine or bench	140-160
Moderate work	Seated - considerable movement of arms and legs	160-200
	Standing - light work plus walking	160-200
	Standing - moderate work plus walking	200-250
	Walking - moderate lifting or pushing	250-400
Heavy work	Lifting, pushing or pulling heavy loads intermittently	400-500
	Exhausting work	500-600

Table No 1 : Energy metabolisms for various types of activity.

The mechanical power developed during work can be estimated by a detailed time and motion study (Rohmert et al., 1974). If it is impossible to determine directly the mechanical work performed it is recommended that it should be assimilated to 25% of the energy expended is excess of the 'seated - no movement' figure (100 kcal/h). The following equation can be used to calculate heat production in the organism when the energy metabolism is known:

Equation No 5

$$H_p = M_b + (M - M_b) . (1 - r')$$

using the symbols defined above.

A dynamic type of work requiring, for example, energy expenditure of 300 kcal/h will generate heat in the body equal to (300 - 100) (1 - 0.25) + 100 = 250 kcal/h.

The figure of 30% for gross mechanical efficiency is only valid for dynamic work. This figure drops considerably as the static component of the work increases. For work which is completely static (e.g. supporting a load) the external work performed is nil, i.e. all the energy expended during static work is converted into heat inside the body. Estimation of the relative proportions of static and dynamic work is analysed in Rohmert's review (1974).

Where it is not possible to measure oxygen consumption approximate evaluations of the energy metabolism must be made using tables proposed by Spitzer and Hettinger (1966) or Fanger (1970). An example is provided by Table No 1, which gives energy expenditure values for certain standard types of activity.

The values given in this table refer to energy metabolism.

When calculating the flow of heat produced in the body a correction must be made to take account of the energy expenditure for different activity levels. Fanger (1970) gives a table of energy expenditure for various tasks. These values can be used according to equation No 5.

3.2 Analysis of ambient heat stress

In a given work environment the human body exchanges heat with that environment. Heat exchange may result in a net gain or net loss of heat for the body. We shall first define the main physical parameters which set these heat exchange values and then consider the various physical processes of heat exchange involving the body.

3.2.1 Physical parameters determining heat exchange between man and the environment.

Heat exchange is a function of two types of parameter, viz. physical parameters relating to the temperature and humidity of the environment and physical parameters relating to the skin.

3.2.1.1 Physical parameters for the thermal environment.

To describe a thermal environment fully 4 physical parameters are necessary, viz. air temperature, radiant temperature, air velocity and humidity.

3.2.1.1.1. Definition and measurement of dry bulb temperature

Dry bulb temperature is the temperature measured with a temperature sensor. The sensitive section of the instrument is dry and shielded from the surrounding surfaces. These conditions are satisfactory when the sensor is placed within the axis of a tubular screen, to which it is connected only by very thin threads of very low thermal conductivity. Air is blown axially inside the screen at a speed of 3 m/s to give good convection exchange between the sensor and the atmosphere.

Different types of sensors are available, viz. liquid expansion thermometers (using mercury, alcohol, etc.), solid expansion thermometers (bi-metal), resistance thermometers, thermocouples and thermistors. The advantages and disadvantages of these different types of temperature sensors are discussed in an article by Metz (1967). In practice an accurate measurement can be using the dry bulb of an Assman type psychrometer.

3.2.1.1.2 Definition and measurement of effective mean radiant temperature

The effective mean radiant temperature is the virtual uniform temperature of the walls of a spherical enclosure with which the body exchanges an amount of radiative heat theoretically equal to the amount actually exchanged with the environment. The real environment is usually heterogeneous as regards the temperatures of its nearer and further surrounding surfaces. This measurement can thus only be taken with an instrument which sums together the radiant heat flows in all directions.

To make this measurement a temperature sensor must be placed in a device which is either spherical or which corresponds to the shape of the human body. The main feature must be a surface absorption coefficient equal to unity. The resulting temperature is a function of the radiation temperature of all the surrounding surfaces, the dry bulb temperature and air speed. The average radiation temperature can be calculated by making a correction for the dry air bulb temperature and the air speed.

The instrument most commonly used is the black globe thermometer. The globe is made of a metal which is a good conductor, such as copper. The metal must be very thin (0.1-0.2mm), the bulb is 15 cm in diameter and its external surface is painted matt black. Missenard (1959) recommends a cylinder 7 cm in diameter and 20 cm high as corresponding more closely to the shape of the human body. In both cases the mean radiant temperature is obtained from the following equation:

Equation No 6

$$Te = \sqrt[4]{(Tg + 273)^4 + \frac{kc}{s} (Tg - Ta) \sqrt{Va}} - 273$$

where Te = effective mean radiant temperature (°C);

Tg = black globe or black cylinder temperature (°C);

kc = convection coefficient of the globe or cylinder;

s = universal radiation constant: $5.75 \cdot 10^{-8} (W/m^2 \cdot °K^4)$

Ta = dry bulb temperature (°C);

Va = air speed (m/s).

The convection coefficient of the 15 cm diameter globe is 16 W/m^2.°C.

This method can only be used for radiations on wavelengths totally absorbed by the human skin. If a proportion of the radiation is in the visible part of the spectrum it is partly reflected by the skin. This is not the case for the surface of the black globe.

3.2.1.1.3 Definition and measurement of air velocity

The air velocity to be considered is that of air flowing across the skin. Consequently it is a function of the actual air velocity in the immediate environment of the subject and also of any motion made by the body or limbs, since such movements can reduce or increase the effective air speed if the flow is along a straight axis.

The influence of the movements made by the subject is difficult to estimate since they are not linear and often only concern one part of the body. Studies by Nishi (1973) and Candas (1974) show that pedalling a bicycle ergometer at 60 r/min corresponds to an apparent increase in air speed of some 0.4-0.5 m/s. If the subject is walking, Nishi states that the linear walking speed should be added to the measured air speed. Consequently it seems reasonable to increase the measured air speed by 0.5 m/s if the subject is stationary while working with important motion of the upper limbs, and to add the figure for the linear movement of the body to the measured air speed if the subject moves about considerably. Fanger (1970) gives the air speed increases which should be applied for a number of tasks.

Measurement of the effective air speed in the enclosure around the subject raises two kinds of problems, some of them due to the nature of the physical phenomena involved, i.e. turbulent or laminar flow patterns, and others to the principles applied in manufacturing the instruments.

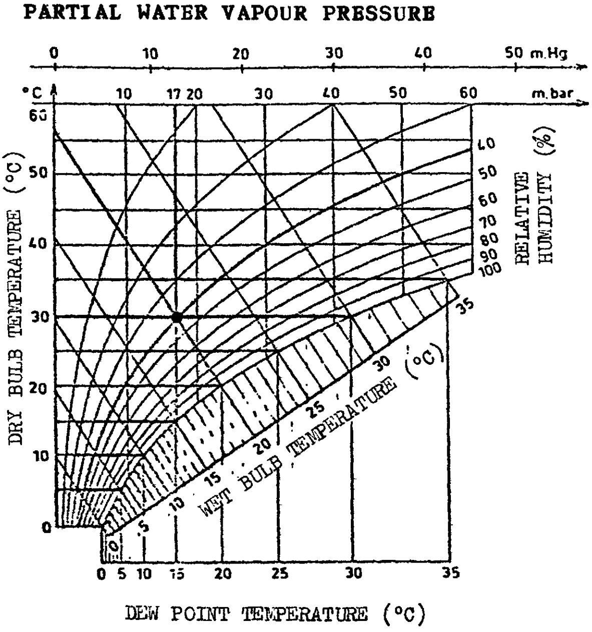

Figure 1 Psychrometric chart. The thermal environment represented in this chart has the following characteristics: dry bulb temperature = 30°C, wet bulb temperature = 20°C, dew point temperature = 15°C, relative humidity = 40%, partial water vapour pressure = 17 mbar or 12 Torr.

Since in industrial physiology the practical application of measuring air velocity lies in its influence on heat exchange, the most appropriate method is to value it as a function of the heat exchange which can occur between a solid and the ambient atmosphere. For this reason the hot wire anemometer appears to be the best instrument for measuring air speed in an industrial environment, particularly when the air flow is turbulent and moving at less than 1 m/s. For laminar air flows at higher speeds the conventional propeller, vane or cup anemometers can be used. The advantages and the disadvantages of these different measuring instruments are discussed in an article by Metz (1967).

3.2.1.1.4 Definition and measurement of atmospheric humidity

The main properties of humid air are represented in the psychrometric chart in Figure 1. The important quantity in thermal physiology is the partial pressure of water vapour expressed in Torr or mbar. No instrument exists for measuring this value directly. It is therefore always measured indirectly.

Figure 1 shows that only the dew-point temperature relates directly to the partial water vapour pressure. The dew point hygrometer therefore appears to be the preferred instrument for measuring atmospheric humidity.

Two other methods for obtaining the partial water vapour pressure are available, but they both require two parameters to be determined simultaneously, either dry bulb temperature related to wet bulb temperature, or dry bulb temperature related to relative humidity.

Wet bulb temperature is measured together with dry bulb temperature using an instrument called a psychrometer. The bulb of the wet thermometer is covered by a wick soaked with distilled water. An air speed exceeding 3 m/s is obtained either manually, using a sling psychrometer, or by using an Assman psychrometer, which has a small fan. The Assman psychrometer may be regarded as the preferred instrument for industrial measurements since no ancillary instruments are required and it is very robust.

Relative humidity is measured using a mechanical hygrometer, the oldest form of which is certainly the hair hygrometer. This type of instrument must be maintained carefully and calibrated frequently if air humidity is to be measured accurately.

3.2.1.2 Physical parameters for the skin

Heat exchange between man and the environment is affected by three parameters concerning the skin, viz. skin temperature, skin wettedness and the area over which heat exchange takes place. Skin temperature and wettedness are specific to each region of skin and can vary widely between the different areas of the body. In the interests of practicality we shall only consider weighted averages of these two values. Weightings are made for isothermic areas of body surfaces.

3.2.1.2.1 Average skin temperature

Skin temperature does not remain constant. It is a function of air temperature and the amount of energy expended. The average skin temperature lies between

33.5 and 34°C when the subject feels comfortable. As long as skin temperature does not exceed 35.5°C the work/environment combination is tolerable since a new and stable body temperature mechanism can come into play. Above this limit body temperatures rise continuously since the situation does not allow the thermal balance of the body to be maintained. The relationship between average skin temperature and dry bulb temperature for a nude subject, according to Candas (1974), is as follows:

Equation No 7

$$\bar{T}s = 27.0 + 0.21 \ \ Ta$$

where $\bar{T}s$ = average skin temperature (°C);
Ta = dry bulb temperature (°C).

This empirical equation has been established for air temperatures between 10 and 30°C and energy expenditures between 290 and 580 W. The expenditure of energy exerts a greater influence as the air temperature rises. At an air temperature of 10°C it is 0.1°C higher at 580 W than at 290 W, whereas at an air temperature of 30°C the difference is 1°C.

When the average skin temperature reaches 35.5°C it remains at this level as long as the thermal balance can be maintained. In practice, i.e. at work, man is clothed and these relations cease to be valid. For this reason we must consider a skin temperature which approaches maximum comfort since man generally exhibits a thermoregulatory behaviour by means of his clothing. The average skin temperature thus achieved by choice of clothing is approximately 34°C.

3.2.1.2.2 Average skin wettedness

There are two expressions in general use, viz. the equivalent fraction of skin wettedness and the relative humidity of the skin. If we take the saturation pressure of cutaneous water vapour P_{s}, sH_2O , and the actual pressure of cutaneous water vapour P_{s,H_2O}, the relationship between the two defines the relative skin wettedness.

Equation No 8

$$\mu = \frac{P_{s,H_2O}}{P_{s,sH_2O}}$$

A similar expression involving the intensity of heat exchange by evaporation between man and the ambient air gives a definition of the equivalent fraction of skin wettedness. We shall define this when we have described evaporative heat exchange.

3.2.1.2.3 Skin surface involved in heat exchange

The skin surface area of the average person is approximately 1.8 m^2, but heat exchange do not take place equally over the whole surface. On the other hand convective heat exchange (see 3.2.2.2) does involve practically the whole body surface.

Therefore no correcting factor is required for a subject seated or standing in a normal posture. This is also true in the case of evaporation exchanges when the whole skin surface is wetted, since evaporation exchange can be assimilated to water vapour convection.

On the other hand some radiative exchange (3.2.2.3) occurs by means of mutual radiation between two skin surfaces (e.g. legs, arms and trunk ...). Therefore not all the body surface contributes to radiation exchange with the environment. In general, for normal postures, both seated and standing, it is considered that radiation exchange with the working environment takes place over 80% of the body surface.

3.2.2 Heat exchange between man and the environment

Like any inert bodies, the human body exchanges heat with the environment in three ways, viz. conduction, convection and radiation. The ability to secrete sweat and thus wet the surface of the body provides a fourth way of heat exchange, viz. evaporation.

3.2.2.1 Conduction

Conduction is the transmission of heat between the body surface and solid objects in contact with it. For each unit of surface area this heat flow is a function of the thermal conductivity coefficient, of the thickness of the conductor and also of temperatures T_1 and T_2 of both faces of the conductor.

Equation No 9

$$P = \lambda \cdot \frac{(T_1 - T_2)}{e}$$

where P = conductive heat transfer (W/m^2);

λ = thermal conductivity coefficient ($W/m^2.°C.cm$);

e = thickness of conductor (cm).

In industrial practice the conductive heat flow can usually be neglected, since body surface in contact with another solid are generally a small proportion of the total body surface (feet, buttocks or hands). In addition, when the temperature of these solid objects is very different from skin temperature a layer of protective clothing giving good insulation is interposed between the two surfaces. This means that the amount of heat flow is kept very small. One can therefore assimilate it quantitatively with the radiation and convection heat exchange which would take place if the surfaces in question were not in contact with solid objects.

3.2.2 Convection

Convection is the transfer of heat from the skin to the surrounding air or vice-versa. In quiet air and by unit of surface area this heat flow is proportional to a convection coefficient and to the difference between the air temperature and the average skin temperature.

Equation No 10

$$C = h_c (Ta - \overline{T}s)$$

where C = convective heat transfer (W/m^2);

h_c= convection coefficient ($W/m^2.°C$);

Ta = dry bulb temperature (°C);

$\overline{Ts}$ = average skin temperature (°C).

The convection coefficient depends on the geometrical form of the body and also on the speed at which the air flows across the skin.

According to Missenard (1974), and in agreement with most of the other authors, equation No 11 or 12 can be used to determine the convection coefficient for a nude subject, standing or seated, and subjected to a horizontal air flow.

Equation No 11

If $Va \leqslant 1 m/s$

$$hc = 3.5 + 5.2\ Va$$

Equation No 12

If $Va > 1 m/s$

$$hc = 8.7\ Va^{0.6}$$

where hc = convection coefficient ($W/m^2.°C$);

Va = air velocity across the skin (m/s).

3.2.2.3 Radiation

Radiation is heat transmission through the immediate environment by electromagnetic waves, particularly in the infrared range. The body can emit or absorb heat in this form through the air, regardless of the air temperature. For a given unit of surface area this heat flow is proportional to the universal radiation constant, the absorptance of the skin and the difference of the fourth power of absolute skin temperature and absolute effective mean radiant temperature of the enclosure.

Equation No 13

$$R = \alpha . s . \left[\left(\frac{Te + 273}{100} \right)^4 - \left(\frac{\overline{T}s + 273}{100} \right)^4 \right]$$

where R = radiative heat transfer (W/m^2);

α = skin absorptance (0.96);

s = 10^8 multiplied by the universal radiation constant ($5.75\ W/m^2.°K^4$);

Te = effective mean radiant temperature of the walls (°C);

Ts = average skin temperature (°C).

The curve relating the radiative heat flow to the radiant temperature of the walls is parabolic, but it can be broken down into a series of straight lines running at gradually increasing angles to the horizontal. In this simplified form the following equation applies:

Equation No 14

$$R = hr\ (Te - \overline{T}s)$$

where R, Te and Ts are as defined above;

hr = linear radiation coefficient ($W/m^2.°C$).

The coefficient hr must be varied according to the radiation temperature and average skin temperature as in equation No 15 below.

Equation No 15

$$hr = 0.227 \left(\frac{Te + \overline{Ts}}{200} + 2.73 \right)^3$$

where Te and $\overline{Ts}$ are as defined above.

3.2.2.4 Sweat evaporation

Evaporation transmits latent heat and almost always constitutes a heat loss for the body. The evaporation of 1 g of water from the organism absorbs 0.6 kcal. In man evaporation takes place in the respiratory tract and from the skin. The water and heat losses in the respiratory tract are approximately 8 watts at rest. These can increase substantially during vigorous physical exercice. According to Fanger (1970):

Equation No 16

$$Ep = 0.0023\ M\ (58 - Pa_{H_2O})$$

where Ep = pulmonary evaporation (W);

M = energy metabolism (W);

Pa_{H_2O} = partial pressure of water vapour in the air (mbar).

Evaporation from the skin removes the water secreted by the sweat glands or water which diffuses through the outer skin layers. In the latter case the process is termed insensible perspiration, which constitutes an unavoidable heat loss of approximately 8 watts. Sweat can only be evaporated if previously secreted by the sweat glands. It is proportional to an evaporation coefficient and to the difference between the partial pressures of ambient water vapour and cutaneous water vapour.

Equation No 17

$$E = he\,(Ps_{H_2O} - Pa_{H_2O})$$

where E = evaporative heat transfer (W/m^2);

he = evaporation coefficient (W/m^2.mbar);

Ps_{H_2O} = partial skin water vapour pressure (mbar);

Pa_{H_2O} = partial ambient water vapour pressure (mbar).

The coefficient he is directly related to the convection coefficient hc as defined above. This physical relation, known as the Lewis's rule (1922), is as follows:

Equation No 18

$$he = 1.67\ hc$$

where he = evaporation coefficient (W/m^2.mbar);

hc = convection coefficient (W/m^2.°C).

When the skin temperature is known, the corresponding saturating pressure of cutaneous water vapour can be determined. To estimate the actual pressure of cutaneous water vapour it is necessary, in view of equation No 8, to know the relative humidity of the skin. This value is generally not known. Thus it is impossible to calculate the effective evaporative heat flow. On the other hand it is possible to calculate a maximal evaporative heat flow, in the hypothesis of a totally wetted skin surface (= 1.0) and of a maximal tolerable skin temperature of 35.5°C, i.e. a saturating pressure of cutaneous water vapour of 58 mbar.

Equation No 19

$$Emax = 1.67\ hc\ (58 - Pa_{H_2O})$$

where $Emax$ = maximal possible evaporation (W/m^2);

hc = convection coefficient ($W/m^2.°C$);

Pa_{H_2O} = ambient water vapour pressure (mbar).

For this maximal evaporation to take place, the total skin surface must be wetted. The percentage of body wettedness can then be estimated in terms of the <u>equivalent fraction of skin wettedness</u> on the basis of the amount of evaporation required to maintain constant temperature.

Equation No 20

$$Er = M - W \pm C \pm R$$

where Er = evaporation required (W/m^2);

M = energy metabolism (W/m^2);

W = external work performed (W/m^2);

C = convective heat transfer (W/m^2);

R = radiative heat transfer (W/m^2).

The body tries to effect this evaporation (Er), since it is required to maintaining its central temperature constant. When the body succeds in carrying out evaporation Er the thermal balance reaches an equilibrium.

When $Er \geqslant Emax$ it is obvious that the whole skin area will be wetted, since the body will increase maximally its sweat secretion to increase the evaporative heat loss. The evaporation rate actually observed will then approach maximal possible evaporation.

When $Er < Emax$ it is equally obvious that the amount of evaporation actually observed may be equal to the amount required. However, to achieve this evaporation it will not be necessary for all the skin surface to be wetted, but only the fraction w corresponding to the ratio Er/Emax:

Equation No 21

$$w = Er/Emax$$

where w = equivalent fraction of skin wettedness (%);
Er = evaporation required (W/m^2);
Emax = maximal possible evaporation (W/m^2).

Factor w represents an equivalent fraction of skin wettedness. The whole process operates as if the fraction w of the skin surface were entirely wetted and the evaporative heat flow were localized there, whereas the non-wetted fraction (1-w) which were supposed to remain dry would not transmit any evaporative heat.

3.2.3 Influence of clothing on heat exchange

Clothing constitutes a barrier between the skin surface and the environment. This barrier impedes convection and radiation heat exchange as well as evaporation heat exchange. When a man is clothed, he creates a microclimate for himself around his skin surface. This microclimate has an air temperature, Ta_e, the thermal insulation afforded by the clothing and the amount of body heat generated. It has also a partial water vapour pressure, fa_i, which is a function of the external water vapour pressure, fa_e, the vapour permeability of the clothing and the water vapour generated by the body. The air speed in the microclimate is usually the result of the natural ventilation afforded by the clothing. The characteristic radiant temperature of the microclimate is that of the internal surface of the clothing Te_i (which is a function of the air temperature Ta_e, the external radiant temperature Te_e, the thermal insulation afforded by the clothing and the body heat generated).

The influence of the clothing on heat exchange is consequently very complex. The problem can be simplified using a number of approximations.

3.2.3.1 Variation of sensible heat exchange

In view of equations Nos 10 and 14 the convection and radiation heat exchange taking place in a given environment between man and his environment can be expressed as follows:

Equation No 22

$$R + C = hc\ (Ta - \overline{Ts}) + hr\ (Te - \overline{Ts})$$

Furthermore a virtual environment can be defined, with equal temperatures for air and walls, in which the sum of convective and radiative heat exchange is equal to that imposed by the real environment. If we call the air or wall temperature of this virtual environment the 'operative temperature' we have the following equation:

Equation No 23

$$R + C = hc\ (To - \overline{T}s) + hr\ (To - \overline{T}s)$$

where To = operative temperature (°C).

From equations Nos 22 and 23, operative temperature is defined:

Equation No 24

$$To = Ta + \frac{hr\ (Te - Ta)}{hc + hr}$$

Applying the concept of operative temperature, the sensible heat exchange may be expressed as follows:

Equation No 25

$$C + R = (hc + hr)\ (To - \overline{T}s)$$

When the subject is clothed this sensible heat exchange will be reduced in varying proportions depending on the thermal insulation afforded by the clothing. Equation No 25 can be used to define the ambient air insulation, as follows:

Equation No 26

$$\bullet \quad Ia = \frac{1}{hc + hr} = \frac{(Tc - \overline{T}s)}{(C + R)}$$

where Ia = air insulation (°C/W.m^2).

Where appropriate, insulation provided by the clothing (I_{cl}) should be added to the air insulation factor to give the following:

Equation No 28

$$\frac{1}{hc + hr} + Icl = \frac{(To - \overline{T}s)}{(C + R)_{cl}}$$

where $(C+R)_{cl}$ = sensible heat exchange for a clothed subject (W/m^2).

Equation No 28 may also be written as follows:

Equation No 29

$$(C+R)_{cl} = \left(\frac{hc + hr}{1 + (hc + hr)\ Icl}\right) . (To - \overline{T}s)$$

Clothing	I_{cl} clo
Nude	0
Shorts	0.1
Typical tropical clothing	0.3 - 0.4
Light summer clothing	0.5
Workman's overalls	0.6
Top clothing	0.9
Conventional city wear	1.0

Table No 2: Thermal insulation expressed in clo units afforded by different types of clothing.

Equations Nos 25 and 29 give the following equation:

Equation No 30

$$(C + R)_{cl} = (C + R) \frac{1}{(hc + Hr)\ I_{cl}}$$

Consequently the reduction coefficient for sensible exchange f_{cl} is as follows:

Equation No 31

$$f_{cl} = \frac{1}{1 + (hc + hr)\ I_{cl}}$$

The insulation afforded by clothing is expressed in °C/W.m^2. The clo is a practical unit representing the thermal insulation of 0.155 °C/W.m^2 afforded by a set of clothes (Gagge et al 1954). From a practical point of view it corresponds to the thermal insulation afforded by standard city wear (shirt, waistcoat, jacket, trousers and shoes).

Table No 2 gives the value in clo units for a number of types of clothing. Using Table 2 we can therefore determine the coefficient f_{cl}.

Equation No 32

$$f_{cl} = \frac{1}{1 + 0.155\ (hc + hr)\ clo}$$

where clo = number of clo units of thermal insulation.

Obviously this method does not take account of certain specific properties of certain fabrics or clothes particularly with regard to their ability to reflect heat. These figures assume that the behaviour of the clothing in relation to convection and radiation is the same, which is not always the case. Nevertheless this simplified method is very useful since it does enable the influence of clothing on convective and radiative heat exchange to be estimated fairly closely.

3.2.3.2 Variation of latent heat exchange

By analogy with sensible heat exchange we can define a reduction coefficient for clothing, to be applied to evaporative heat exchange.

Equation No 19 enabled us to determine a maximal possible evaporation for a nude subject. The maximal evaporative flow is reduced when the subject is clothed.

Equation No 33

$$E_{max,\ cl} = f_{p,cl} \cdot E_{max}$$

where $E_{max,cl}$ = maximal possible evaporation - subject clothed (W/m^2);

E_{max} = maximal possible evaporation - nude subject (W/m^2);

$f_{p,cl}$ = evaporation reduction coefficient.

It has been demonstrated that the permeability to water vapour of cotton garments is directly proportional to the thermal insulation afforded by the fabric (Nishi et al. 1970). By analogy with the equations for convective and radiative exchange the following relations can be demonstrated:

Equation No 34

$$f_{p,cl} = \frac{1}{1 + 0.086 \cdot he \cdot clo}$$

or again by virtue of Equation No 18:

Equation No 35

$$f_{p,cl} = \frac{1}{1 + 0.143 \cdot hc \cdot clo}$$

where hc = convection coefficient ($W/m^2.°C$);

clo = number of clo units for the clothing.

The last equation only applies to cotton clothes. It produces a good estimate of the maximal evaporative heat exchange for a subject wearing this type of clothing.

4. ASSESSMENT OF PHYSIOLOGICAL STRAINS

A number of changes take place in the metabolic mechanism when man is subjected to heat stress. To maintain thermal equilibrium a number of physiological mechanisms must be brought into play. Unless the stress is excessive, these physiological mechanisms will maintain body temperatures within limits compatible with health and normal functioning of the central nervous system.

As a whole, heat transfer satisfy a dual physical identity:

Equation No 36

$$Hp = T.I.C. = T.E.C.$$

where Hp = heat production (W/m^2);

$T.I.C.$ = internal heat transfer (W/m^2);

$T.E.C.$ = external heat transfer (W/m^2).

The conditions for this dual identity must be met in order to give thermal equilibrium.

The total quantity of heat produced is equal to the energy metabolism from which must be substracted that portion of energy which is converted into mechanical energy transmitted outside the body (see equation No 4).

Internal heat transfer is mainly through the blood, which carries the heat from the point at which it is generated (the viscera and muscles) to the point of elimination, i.e. the skin.

The processes of heat transfer were analysed in the chapter on heat stress. The most important heat exchange process which the body controls is sweat evaporation.

Three main physiological strains must therefore be analyzed, viz. thermostatic strain, sweating strain and circulatory strain. Circulatory strain occurs because there must be adequate blow flows for transferring heat within the body. Sweating strain is caused by the requirements of the external heat transfer system, in which the contribution of sweat evaporation is in direct proportion to the level of heat stress. Lastly thermostatic strain results from the necessity of body temperature changes for actuating the sweating and circulatory mechanisms, which constitute the two previous forms of strain.

4.1 Sweat strain

The most effective physiological mechanism for adjusting external heat transfer in a warm environment is sweat evaporation. The skin surface contains a large number of sweat glands. Their main function is to secrete an aqueous liquid containing mineral salts and several other constituents of the body fluids. Sweat evaporation carries away approximately 0.6 kcal per gramme of water evaporated.

The physical phenomenon of evaporation is analyzed above in Para. 3.2.2.4. The effect of sweat secretion is to wet entirely a certain proportion of the skin's surface, thus producing an adequate evaporative heat loss. The term w in equation No 21 represents the equivalent fraction of skin wettedness.

Because of the distances between the orifices of the sweat glands on the skin surface and the asynchronism of the activity of the different sweat glands, equivalent fraction of skin wettedness of approximately 0.5, may be the sum óf a large number of fully wetted surfaces separated by surfaces which have remained dry.

In fact it is observed that some skin areas become totally wetted while other areas are only partly. To give a simplified example, a w of 50% may be made up of 20% totally wetted skin, 60% skin wetted to 50% of its maximal capacity and 20% completely dry skin. At this point, if the evaporative heat flow is to increase it is apparent that the increased sweat output which occurs can wet the dry areas, increase the wettedness of the partially wetted areas and produce in the completely wetted areas more sweat than can be evaporated, with the result that the excess sweat drips from the skin surface and therefore does not contribute to its evaporative cooling. These phenomena are actually observed. We must therefore define the evaporative efficiency of thermal sweating as follows:

Equation No 37

$$i = \frac{E}{S}$$

where i = evaporative efficiency of thermal sweating;

E = rate of evaporative water loss (g/h);

S = rate of sweat loss (g/h).

Consequently it is apparent that under certain conditions sweat loss must exceed evaporative loss simply to adjust the equivalent fraction of skin wettedness to the value required to produce qdequate evaporation.

In equation No 37, E corresponds to the external heat transfer by evaporation but is not the amount directly controlled by the organism. In fact the organism regulates the sweat rate which, depending on the ambient temperature and humidity conditions and the average skin temperature, will produce a given evaporative heat loss. The maximal sweat rate may reach 1200 g/h for a period of several hours. Under certain particularly dry conditions the figure for evaporative heat loss, expressed as the mass of water evaporated, can be equally high.

The maximal sweat loss and the ability to maintain it over several hours depends on the degree of acclimatization and the amount of water and minerals available in the organism. Acclimatization increases sweating in two ways, by accelerating its onset on initial exposure and by increasing the maximal loss during exposure. Prolonged and intense sweating causes water and mineral depletion in the body. Dehydration can be very severe and water must be replaced during exposure in order to maintain the correct amount. Salt depletion can be very severe in non-acclimatized subjects, but is practically non-existent in an acclimatized subject, since losses are adequately replaced by ingestion. The problems regarding the type and extent of these depletions, and also their prevention and treatment, are considered in Chapter 9, which deals with protection against heat stress.

4.2 Circulatory strain

The only mechanism for adjusting the internal heat transfer plays on the blood flow between the sites where heat is produced and those where it is lost outside the body. To simplify matters we can regard metabolic heat as being entirely produced within the body and being lost entirely through the skin surface. Given the average thickness of the epidermis, the minimal tissue heat conductance is very low, viz. 5.3 $W/m^2.°C$. Internal heat transfer takes place partly by means of this tissue conductance, but mainly through the cutaneous blood flow.

When the subject is at rest and in a thermally neutral environment this cutaneous blood flow is equivalent to a conductance of 7.3 $W/m^2.°C$. Allowing for the specific heat of blood this conductance can be compared to that of a blood flow equal to 6.3 $l/m^2.h$ leaving the deep-body region at the temperature of that region and returning at skin temperature. At rest total conductance is therefore equal to 12.6 $W/m^2.°C$. It can remove 50 W/m^2 of metabolic heat when the temperature difference between the deep-body region and the skin is 4°C.

Vasomotricity enables the organism to regulate cutaneous blood flow within very wide limits. Under extreme conditions vasodilatation can produce a blood flow to the skin of 300 $l/m^2.h$. A flow of this magnitude equals a tissue conductance of 350 $W/m^2.°C$. This level of conductance would allow total evacuation of a basal metabolism of 50 W/m^2 at a difference of 0.15°C between deep-body and skin temperature. At the other extreme intense vasoconstriction can reduce cutaneous blood flow to almost nil. Even if there is no blood flow a minimal conductance of 5.3 $W/m^2.°C$ persists, which corresponds to the tissue conductance. The fluctuation margin is therefore much narrower for cold conditions than for hot.

Since the main function of the blood flow is to carry the respiratory gases it is easy to imagine situations where the two functions conflict. The oxygen transfer function and the heat transfer function must be carried out at the same time. If we consider for example the work performed by the lower limbs, it is easy to imagine that the same blood flow can perform both functions. It is true that the blood supplied by the femoral arteries can first of all supply the active muscle masses and then, through an offshoot of veins to the network of superficial veins, act locally as an efficient carrier of heat towards the skin. Consequently this blood flow carries out the oxygen transfer function and a heat transfer function simultaneously, and the skin covering the lower limbs plays an active part in heat exchange with the surrounding air.

However, when ambient conditions are very severe it is essential for a progressively larger fraction of the skin area to play an active part in the external transfer of heat. Consequently the blood flow must carry heat to skin areas which are not adjacent to active muscle masses. Naturally this fraction of the blood will only perform a heat transfer function, and will necessitate a further increase in cardiac output, but with no change as regards oxygen consumption.

Vogt (1966, 1968), Vogt et al. (1971) have demonstrated that it is possible to partition these two components of cardiac output. Taking the heart rate as an indicator of cardiac output, the number of additional heart beats obtained by deducting the heart rate measured on the subject sitting at rest from his total heart rate, can be subdivided into "metabolic extra heart beats", which act mainly as oxygen carriers while performing a local heat transfer function for the skin areas adjacent to the active muscles, and "thermal extra heart beats", which perform an exclusively heat transfer function in the skin areas which are not adjacent to the active muscles.

The practical interest of this partition is obvious. The heart rate, which can easily be recorded in an industrial situation, can thus provide an estimate of the work stress and also of the heat stress. A method of evaluating these two stresses in an industrial situation has been developed with financial help from the ECSC. The method (Vogt et al. 1970, 1972) has since been validated and used for practical purposes in the iron and steel industry and other industrial branches.

4.3 Thermostatic strain

By thermostatic strain we mean the variations in body temperature which result from heat stress with or without muscular work stress. Two aspects should be analyzed, their cause and their functional significance.

Variations in body temperature are caused exclusively by temporary thermal imbalances. In fact temporary imbalances are mainly caused by the necessity of attaining the off-set levels required by the physiological thermoregulatory system. These are attained at the end of a certain time lapse which depends on the time constants of the different parts of the body and the transfer functions of the regulating mechanisms, which temselves have latency and a time constant (and perhaps also a threshold).

Thermostatic strain must thus be interpreted in terms of off-set levels (load error). When body temperatures are at their basal levels, the external and internal heat transfers are close to their basal levels. No sweating takes place and the normal cutaneous blood flow is 6 $l/m^2.h$. When the heat transfers become insufficient a change in body temperature is observed. In turn their off-set levels determine adequate readjustments of the internal and external heat transfers which are more or less proportional to them. We may therefore write the following equation (Nadel et al. 1974; Libert et al. 1974):

Equation No 38

$$S = a.(Tre - 36.9) + b\,(\overline{T}s - 34.0)$$

where S = sweat rate (g/h);

Tre = rectal temperature (°C);

$\overline{T}s$ = average skin temperature (°C);

(Tre - 36.9)=rectal temperature off-set;

($\overline{T}s$ - 34.0) = average skin temperature off-set.

In order to predict sweat loss accurately on the basis of body temperatures, it is often necessary to ascertain their derivative action (rate of change in function of time). Furthermore sweat loss is determined by the temperatures of all the skin and deep-body sites, not solely by rectal and average skin temperature.

Integration of all the regulatory off-sets takes place in the hypothalamus, where nervous impulses are emitted at a rate which is a function of the regulatory off-sets detected. The impulses from the hypothalamus determine local sweat rates or vasomotor reactions which in turn can be modulated as a function of the local temperature (Nadel et al. 1974) of the sweat glands or blood vessels.

For as long as readjustments are possible, provided the regulatory mechanisms governing external and internal heat transfer are not overloaded, body temperatures keep at a new, stable level which can be maintained for a very long period. The absence of a new stable pattern indicates that readjustment is impossible and means that exposure to the particular climate must be interrupted. In that case *regulatory thermostatic strain* is replaced by *cumulative thermostatic strain*.

5. PSYCHOSENSORIMOTOR STRAINS

Psychosensorimotor strains are a direct consequence of physiological strains in so far as physiological strains impair the functioning of the sense organs, nervous centres and the muscles. Grivel (1972) has carried out a very comprehensive bibliographical analysis of these strains and has also contributed some personal results which are described in detail in an ECSC synoptic review. In simple terms Grivel distinguishes on the one hand psychosensorimotor strains directly caused by heat, by which he means those caused by the reactions which influence thermoregulation, and on the other hand psychosensorimotor strains indirectly caused by heat, by which he means those caused by reactions which are not by nature thermoregulatory, but which are a non-specific direct consequence of heat stress.

Of the psychosensorimotor reactions directly caused by heat the most important is thermoregulatory behaviour. There are several facets to this, such as activity, clothing, posture, diet, ventilation, movement etc. It is a known fact that these all have a direct effect either on heat stress or physiological strains. This feed-back is very important and its effects are rather artificially dissociated from those of the physiological thermoregulatory loop.

It is mainly because of such thermoregulatory behaviours that caution is necessary when extrapolating laboratory results to industrial situations. In thermophysiological experiments in the laboratory very strictly controlled conditions are laid down which exclude any scope for behavioural reaction. Likewise it is thermoregulatory behaviour which makes it difficult to define certain physiological regulatory mechanisms precisely.

Among the pyschosensorimotor reactions indirectly caused by heat, perceptual and performance activities must be distinguished. Perceptual activities, such as perception of time, vision and hearing, are influenced by heat stress. These effects can be interpreted mainly in terms of nervous system activation (aromal) due to heat stress.

The performance activities which involve muscular force (industrial work) are always adversely affected by heat stress. This deterioration, which is apparent at effective temperatures as low as 28°C (see chapter 6) results from the competition between the oxygen transfer and heat transfer functions of the blood flow. For a given circulatory strain, the capacity to carry oxygen is reduced as the need to carry heat rises.

Variations in performance activities not requiring muscular force (watching, memorizing, intellectual activities, decision-making etc.) under the effect of heat stress are much more complex. The speed indicators (reaction times, rythm of activity) evolve in two phases. On initial exposure, performance rate often improves. This improvement persists for 20 - 40 minutes depending on the intensity of the heat stress and subsequently gives way to a deterioration. The turning-point generally comes at a deep body temperature of 38°C. This critical temperature is affected by other environmental factors such as noise, dazzling, lack of sleep, work, etc.

Indicators of accuracy (errors and omissions) are always immediately deteriorated by heat stress. A similar deterioration is observed for all adverse physical factors in the environment.

The variations which have been observed in speed indicators and accuracy indicators become more sensitive to heat stress as the task becomes more complex. Modern trends are making supervisory tasks more and more complex. It can be concluded from this that it is becoming increasingly essential to provide ambient temperature and humidity levels which are conducive to the performance of these tasks.

6. OVERALL ASSESSMENT OF ENVIRONMENTS - PERMITTED MAXIMUM TEMPERATURES

An analysis of heat stress and of physiological strains shows clearly the complexity of the problem of working in a hot environment. Since the beginning of the century numerous authors have tried to establish a compound index which would express a climatic condition as a single figure and so enable it to be compared to other conditions. If such an index could be devised and validated it would also provide a simple means of formulating maximum admissible limits or a system of legally binding standards.

A great number of indexes have been proposed. Since we cannot review them all we shall confine ourselves to discussing those for which limit values have been proposed. First of all we must define the concept of a single figure 'index', or more generally that of the overall estimation of a heat environment.

One type of overall estimate can made on the basis of single figure indexes derived directly from a combination of physical measurements which does not take explicit account of the physiological or psychological effects. This artificial combination is supposed to take account of the overall severity of conditions. This is so in the case of the wet bulb globe temperature, which is the only indicator in this category which we shall consider.

An alternative kind of overall estimate can be made on the basis of indexes which have been obtained from a combination of physical measurements on the basis of observed physiological or psychological effects. These sealings take account of the severity of a combination of hot conditions judged on the basis of the physiological or psychological criterion used in drawing up the index. This is so in the case of the corrected effective temperature (the criterion used being the instantaneous impressions of subjects moving back and forth from one conditioned room to another); as well as in the case of the required sweat rate and of the predicted four hour sweat rate (the criterion used being observed sweat rates).

A third type of overall estimate can be made on the basis of the physiological indicators themselves, these being recorded during exposure. This applies to the continuous or intermittent recording of the heart rate and/or the internal temperature (oral, axillary or rectal) and for the intermittent recording of sweat loss (by a series of weighings).

Separate consideration should be given to the simulation on a digital or analog computer of the probable evolution pattern of the main physiological parameters. These are simulation models which enable the maximum permitted exposure period to be determined with a minimum of error.

Of course the upper tolerant limits are based on the physiological strains to which subjects are exposed. The limiting parameters are physiological. The determination of maximum stress limits consequently implies knowledge of the link between strain and stress. All the physiological strains are interconnected. Priority must be given to limiting internal thermostatic strain. It is imperative not to exceed certain deep body temperature levels for fear of serious accident due to hyperthermia. The limits expressed in single figure stress indexes which we review below are based on experiments during which thermostatic strains were recorded continuously.

In order to be practical in the analysis given below we shall distinguish between single figure indexes requiring physical measurements and those involving physiological indicators.

6.1 Single figure indexes based on the measurement of several physical environmental values

The overall severity of a set of climatic conditions can be evaluated on the basis of certain hypotheses by using an appropriate combination of environmental parameters. One problem which arises immediately is that of whether the metabolic, temperature or humidity conditions are homogeneous or heterogeneous. Where working conditions remain constant over long periods of time it is convenient to use single figure indexes. When, on the other hand, working conditions are not constant as regards either time or place, the use of these indexes becomes problematic, since an average estimate of the work and heat exposure conditions has to be made beforehand.

6.1.1 Homogeneous heat and humidity conditions

When the heat, humidity and metabolic conditions are stable, or can be considered as a stable average condition over a period of time, one of the four single figure indexes mentioned in the introduction to this chapter can be used.

6.1.1.1 Wet bulb globe temperature

This equivalence index was described in 1957 by Yaglou and Minard under the title of Wet Bulb Globe Temperature, better known under the abbreviation WBGT. It is calculated on the basis of three environmental parameters, viz. dry bulb temperature, (Ta), black globe temperature (Tg) and natural wet bulb temperature (Thn). This latter value is obtained by using a thermometer with the bulb kept wet by means of a wick of wetted gauze *which is not artificially ventilated.* Thus this parameter takes account of the partial pressure of water vapour in the air and also of the natural air velocity.

Equation No 39

Indoors or outdoors under cover:

$$WBGT = 0.7\, T_{h,n} + 0.3\, Tg$$

Equation No 40

Outdoors, exposed to the sun:

$$WBGT = 0.7\, T_{h,n} + 0.2\, Tg + 0.1\, Ta$$

where $T_{h,n}$, Tg and Ta are as defined above in the text.

For a semi-nude subject, and taking account of the air velocity (Va), it is recommended that the following values should not be exceeded for a continuous working period of 8 hours with a ten-minute rest period per hour of work (Musacchio, 1974)

Work	Va < 1.5 m/s WBGT max.	Va > 1.5 m/s WBGT max.
Light M < 200 W	30 °C	32.5 °C
Moderate 200 W < M < 300 W	28 °C	30.5 °C
Heavy M < 300 W	26 °C	29 °C

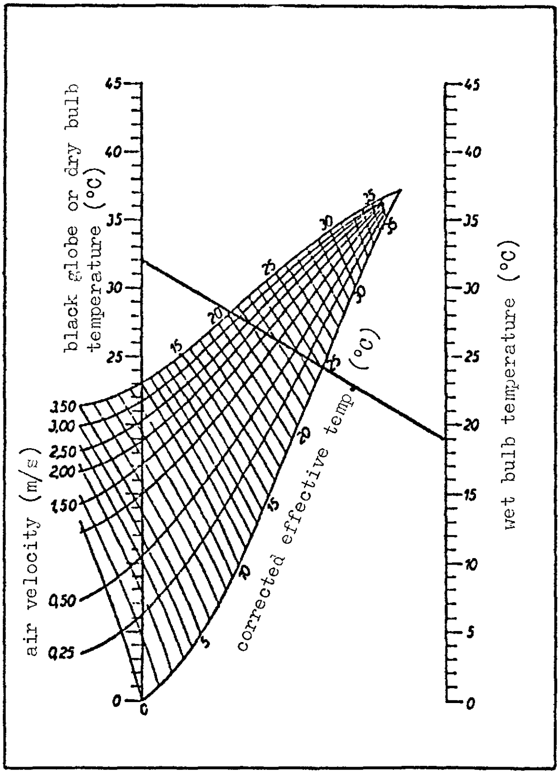

Figure 2 Corrected effective temperature scale. In the example illustrated in this figure black globe temperature = 32 °C, wet bulb temperature = 19 C, air velocity = 1 m/s. These conditions produce an effective temperature of 22 C.

6.1.1.2 Corrected effective temperature

The effective temperature scale is the oldest of the equivalence scales described. It was established in 1927 by Yaglou. According to this system two environments which differ in their various physical properties are regarded as equivalent if a person passing directly from one to the other does not perceive any thermal change. The original scale has been modified several times to take account of radiation, clothing and metabolism.

Figure 2 represents the corrected effective temperature (C.E.T.) scale which applies to men when semi-nude. This scale takes account of thermal radiation since it is recommended to use the black globe temperature rather than dry bulb temperature if there is a large discrepancy between these two values.

The maximum C.E.T. values permissible for an 8 hour working period per day are given below as a function of the metabolic level (WHO report 1969)

Metabolisms	C.E.T. non-acclimatized subject	C.E.T. acclimatized subject
2.6 kcal/kg.h	30 °C	32 °C
4.3	28 °C	30 °C
6.6	26.5 °C	28.5 °C

6.1.1.3 Required sweat rate

We have already defined the evaporation rate required to maintain the heat balance. Equation Number 20 gave us this definition:

Equation No 20

$$Er = M - W \pm C \pm R$$

where Er = evaporation required (W/m^2);
M = energy metabolism (W/m^2);
W = external work performed (W/m^2);
C = convective heat transfer (W/m^2);
R = radiative heat transfer (W/m^2).

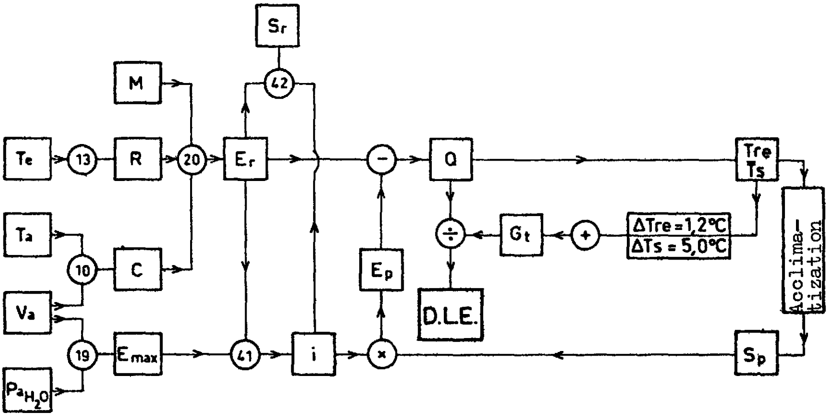

Figure 3 Principle for calculating required sweat rate and the amximum period of exposure to a hot environment. The symbols are explained in the annex. (D.L.E. = maximum period of exposure).

In order to achieve this rate of evaporation two conditions must be met simultaneously. The organism must reach a sufficiently high degree of skin wettedness for the required rate of evaporation to take place and it must be physiologically capable of the corresponding sweat rate.

The first condition implies that the required evaporation rate should not exceed the maximal evaporation rate permitted by the environment. If this condition is satisfied it should be seen whether the required sweat rate does not exceed the amount which is physiologically possible. Determination of required sweat rate implies a knowledge of the evaporative efficiency of thermal sweating as defined in equation No 37. A study made by Givoni (1963) gives a method of determining the evaporative sweat efficiency taking account of the relation between the required evaporation rate and the maximal permitted evaporation rate, i.e. in accordance with equation No 21 taking account of the equivalent fraction of skin wettedness (W). According to Givoni, the relation between the evaporative yield of thermal sweating (i) and the equivalent fraction of skin wettedness (w) is as follows:

Bquation No 41

$$i = 1,5e^{-2w}$$

where e is the base of natural logarithms.

Once the evaporative efficiency of thermal sweating has been determined it is possible, when knowing the required evaporation rate, to calculate the rate of sweating necessary to achieve this evaporation.

Equation No 42

$$Sr = \frac{Er}{i}$$

where Sr = required sweat rate (W/m^2);

Er = required evaporation rate (W/m^2);

i = evaporative efficiency of thermal sweating.

Figure 3 gives the basic diagram for calculating the Required Sweat Rate. Values exceeding 0.7 l/h for a non-acclimatized subject and 1 l/h for an acclimatized subject must be regarded as intolerable in the long term. A series of nomograms drawn by Vogt and Metz (1967) provide a quick method of determining the Required Sweat Rate for an individual in light work clothes.

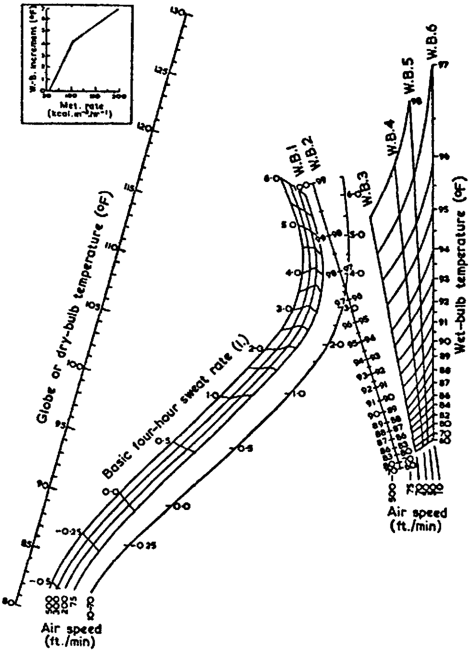

FIG. 11.—The Predicted Four-hour Sweat Rate index (P4SR).
(From: *Physiological Responses to Hot Environments*, ed. R. K. Macpherson, *Special Report Series No.* 298, H.M S.O., 1960.)

Figure 4

N.B. 100 ft/min = 0·5 m/s.

6.1.4 Predicted four hour sweat rate

This scale was proposed in 1947 by McArdle et al. and is abbreviated to P_4SR.

This diagram was constructed empirically on the basis of the results of a very long series of observations of sweat loss in men wearing just shorts or a boiler suit. Tests were carried out at different energy expenditure rates. All the subjects were acclimatized. Figure 4 shows the method of using this index, which is used to predict the amount of sweat which will be secreted during a four-hour exposure period. Metabolism is taken into account indirectly, in so far as it has been assimilated to an equivalent increase in wet bulb temperature (see left upper section of figure 4). The value obtained from the basic nomogram (B4SR) has to be further corrected to take account of the activity and clothing of the subject, for getting P4SR values, as follows:

Conditions	Corrections
Subject in shorts seated at rest	$P_4SR = B_4SR$
Subject in shorts working	$P_4SR = B_4SR + 0.014 (M - 54)$
Subject in outer clothes seated at rest	$P_4SR = B_4SR + 0.25$
Subject in outer clothing working	$P_4SR = B_4SR + 0.25 + 0.02 (M-54)$

where M is in kcal/h•m^2.

P4SR values exceeding 4.5 litre must be avoided since at this level there is a sharp increase in the number of men who find these conditions intolerable, even though they are acclimatized.

The four single figure indexes which we have just examined have the advantage of being easy to use. Unfortunately it is never possible to make an exact correction for the clothing worn by the subject. Furthermore, if the value recorded exceeds the maximum permitted limits it is not possible to determine a maximum period beyond which there is a risk of organic damage. Lastly, since exposure and/or work are not constant, the use of these indexes is very problematic. It would require a model to simulate the different physical and physiological phenomena involved to predict results with sufficient accuracy in the case of a fluctuating activity level and intermittent exposure to heat stress.

6.1.2 Heterogeneous heat and humidity conditions

Heat and humidity conditions are most often heterogeneous in the industrial situation. Energy metabolism and ambient conditions vary as a function of time. In addition to this variation of physical conditions with time the subjects move about, and in so doing are often exposed to widely differing heat and humidity conditions.

Experimental conditions in the laboratory are in stark contrast to industrial reality. Laboratory conditions are usually uniform as regards time, since there are great practical difficulties in producing and particularly in controlling heterogeneous heat and humidity conditions. For this reason studies under such conditions are rare. The use of the single figure indexes defined above raises certain problems, e.g. as to whether the index should be determined on the basis of a time-weighted average for the main heat and humidity parameters. At present we cannot give a categorical answer. This problem can only be solved by simulation on a digital or analog computer.

The present state of knowledge regarding external heat transfer, internal heat transfer and its physiological regulation has opened the way to a simplified model of the thermoregulatory process in man. The model proposed in an annex is derived from a model published by Gagge et al. (1971).

Most of the equations discussed above were used in setting up this model. It takes account of the clothing worn by the subject and also his physical characteristics such as weight and size, and physiological features such as acclimatization.

This model can simulate the time evolution of the main physiological parameters for exposure to heat. The total exposure time is subdivided into elementary time spans of constant exposure and work rate, whose number and length are illimited. For every elementary time span, following input data are required:

Energy efficiency of the work (0. WE 1.);

Energy metabolism (W/m^2);

Thermal insulation value of clothing (in CLO units);

Dry bulb temperature (°C);

Black globe temperature - globe 15 cm in diameter (°C);

Air speed (m/s);

Atmospheric relative humidity;

Time span (min.).

The model simulates the evolution in time trends of the following physiological output variables:

average skin temperature (°C);

deep body temperature (°C);

total heat storage (W/m^2);

rate of rise in average body temperature (°C h);

heat equivalent of non evaporated sweat loss (W/m^2);

pulmonary evaporation rate (W/m^2);

insensible perspiration rate (W/m^2);

sweat evaporation rate (W/m^2);

maximal possible evaporation (W/m^2);

time (min).

This model can be used to evaluate the physiological reactions of a person subjected to any sequence of heat, humidity and muscular work conditions.

The forms and numerical values of the equations for this model have been established on the basis of experiments which have generally been carried out in stable ambient conditions. They must therefore be validated in practice for transient conditions. Initial experiments in the laboratory show that the predictions made by this model are satisfactory for a nude subject. However, many more experiments are necessary to test its general validity, particularly for a clothed subject.

In homogeneous conditions, as long as the physiological parameters remain stable, the conditions may be rated as tolerable over a long period. Where the conditions vary, an upper limit must be fixed to the internal temperature which must not be exceeded without taking special care. This limit value will be discussed in a later paragraph on the maximum limits for thermostatic strains.

A model of this type also has the advantage that it can simulate the evolution in time of its physiological output variables during recovery, when the heat, humidity and metabolic conditions for this recovery are known. In extreme cases this model should make it possible to determine the minimal recovery time necessary for the main physiological variables to return to their initial levels or levels compatible with a further exposure period of useful length. However, use of the model in this way is not to be recommended since it has been set up on the basis of experimental results relating to homogeneous heat and humidity conditions. Deliberate extrapolation to extremely variable conditions is still problematic and could lead to erroneous predictions. It should therefore be interpreted with care.

6.2 Use of physiological parameters

A man subjected to a sequence of widely varying exogenous and endogenous heat stresses exhibits cumulative strain patterns. The evolution of any physiological strain in function of time shall therefore account for the time pattern of the stresses. The time integral of the strains shall further be related to the time integral of the stresses. The three physiological strains described in the preceding chapter can be used to make this kind of global evaluation of a set of conditions.

6.2.1 Thermostatic strain

It is theoretically possible to measure body temperature in the industrial situation. A rectal probe, such as a thermistor, resistance thermometer or thermocouple, can be used to record the rectal temperature. This value can be transmitted by microwaves. The oral temperature, which is most easily measured, is difficult to interpret. The buccal mucous membranes are generally cooled to a large extent by respiration. This cooling affects the oral temperature so that it is not representative of the internal body temperature.

Skin temperature can also be recorded in several places using thermo-couples placed against the skin. Remote recording is possible. Skin temperature can also be measured with a thermistor with a very low time constant. A few seconds are sufficient to give a proper value of skin temperature.

Upper limits for body temperatures have been proposed. A local skin temperature of 45°C is near the pain threshhold. It will be difficult to exceed this value simply because of the defence mechanisms against pain. An upper limit for rectal temperature is more difficult to propose. When the rectal temperature is stable 38.5°C can be tolerated (Wyndham 1974). On the other hand, in unstable conditions 38°C should not be exceeded. Due to the thermal inertia of the pelvic cavity containing the rectum, rectal temperature at any given moment lags behind any temperature change in deep-body temperature. The upper limit of 38°C moreover has been recommended by a group of experts working for WHO (1969).

6.2.2 Sweat strain

This would appear to be a simple measurement because it can be assimilated to a variation in body weight. In the industrial situation it is in a fact a more complex matter and requires a detailed weight balance which takes into account the weight of ingested foods and beverages, of excreta other than sweat, and also the weight of any clothing which may be put on or taken off between weighings of the subject.

When it is possible to measure it, it is obvious that sweat loss gives a good estimate of the heat stress experienced. A sweat loss of I l per hour can be maintained for several consecutive hours. This, however, is a maximum. An hourly loss in excess of this value would make it necessary to interrupt exposure. Furthermore, the total amount of sweat secreted during one shift must be limited. Providing water intake is adequate, a total volume of 5 litres per shift should not be exceeded, according to the WHO group of experts (1969).

6.2.3 Circulatory strain

In practice this is the most convenient measurement of physiological strain. There is a wide choice of telemetry equipment which gives very satisfactory results when recording heart rate throughout a shift. As we have seen above, the heart rate reflects circulatory strain. By virtue of the dual function of the blood flow this strain enables heat stress and metabolic stress to be estimated simultaneously (see paragraph 4.2).

Measuring methods have been developed and validated. These are described in detail in an article by Vogt et al. (1970). The instantaneous heart rate values also lead to several specific conclusions. The heat transfer function of the blood flow involves, in physiological terms, that there is a close relationship between heart rate and rectal temperature. A study involving more than 50 subjects has demonstrated that a rise of 1°C in rectal temperature produces an average increase in heart rate of 30 b/min. There are wide differences between individuals, which can only be accounted for by testing each indivicual in a climatic chamber. On the basis of the relationship established between increased rectal temperature and increased heart rate the thermostatic strain limits proposed in paragraph 6.2.1 can be expressed as circulatory strain limits. For a given physical activity the progressive rise in heart rate between starting and interrupting work should not exceed 30 b/min. Thus, for a seated subject performing a moderately light job such as manipulating controls, which requires in a comfortable environment a heart rate of 90 b/min, a heart rate of 120 b/min should not be exceeded for the same activity in a hot environment. In addition, of course, the factors regarding diet, alcohol intake and tobacco smoking should be the same. Account must also be taken of any changes in the circadian rhythm of the heart rate. If any one of these values changes the 30 b/min rule ceases to apply.

Beyond this limit, which is a normally tolerated increase in heart rate, an upper tolerance limit for the heart rate should be fixed. The rate recommended by the WHO experts (1969) as a maximum is 160 b/min. As regards a maximal average heart rate which should not be exceeded over the whole duration of a shift the figure of 120 b/min may be suggested. In fact no figure has been proposed on the basis of long-term morbidity or mortality criteria which could be used to demonstrate circulatory wear resulting from circulatory strain over several years.

7. THERMAL NEUTRALITY AND COMFORT

In Chapter 6 we examined the problem of environmental extremes which should be avoided for a working period of eight hours, and also the problem of setting a maximum period for exposure to a given thermal environment. When heat and humidity conditions are within these limits it is known that this presents no immediate danger to the subject. His physical wellbeing is assured, at least in the short term. Nevertheless physiological strains, although not dangerous, can still be very severe and a source of severe discomfort to the subject.

In order to avoid severe physiological strains thermal environments must be designed which approach thermal neutrality as closely as possible. If in addition it is desired to induce in the subject a pleasant sensation of thermal comfort optimal heat and humidity conditions must be achieved within very fine limits.

Thermal neutrality exists when there is no sweating and no shivering. In fact no disagreeable sensations are observed when there is light sweating, i.e. not exceeding 100 g/h. On this basis, taking account of energy metabolism and the insulation provided by clothing, it is possible to calculate a range of temperature and humidity which will insure a sweat rate of less than 100 g/h, while no shivering will be observed. The mapping of such a neutral zone has been defined by Vogt et al. (1970).

Thermal comfort, implies rather more than physiological neutrality, since it also implies an impression of pleasantness produced by the ambient heat and humidity conditions. Fanger (1970) has developed a comfort scale on the basis of experiments carried out on students from North America.

The author tested the validity of this scale for Danish students, both male and female and also for elderly people. Its validity seems to be well established. In his work cited above, Fanger gives a number of diagrams which can be used to determine graphically the main comfort parameters regarding the environment.

When these ambient conditions are achieved not all the subjects are satisfied. According to Fanger it is impossible to exceed 95% satisfaction. This means that out of 100 persons exposed 5 will always consider that it is too hot or too cold.

The practical use of these comfort scales raises a problem. If it is a question of determining a comfortable thermal environment for a single individual the problem is easily solved. Only details of his metabolism and clothing need to be known in order to determine the optimal physical parameters of the environment.

When it is question of determining a comfortable thermal environment for a group of individuals who must share the same premises the problem is more comples. They generally wear a wide variety of clothing. Metabolic levels are a function of the activities of each person. Consequently each individual would like an environment tailored to his metabolism and clothing.

The answer may be found in behavioural regulation of each individual's clothing. To do this the heat and humidity conditions must be such that persons with the most active metabolism are not too hot when most clothes are removed and that those persons with the least active metabolism are not too cold in normal dress.

With this end in view, two limits should be determined between which the optimal condition lies. The upper limit is the comfort temperature for individuals with the most active metabolism, minimal permitted clothing and who are placed in the minimal observable air movement. The lower limit is the comfort temperature for those individuals with the least active metabolism, maximal permitted clothing and situated in the maximal observable air movement. There are two possibilities. When , thus calculated, the lower limit is not lower than the higher limit this means that it is impossible to satisfy all individuals in the same premises, since some of them will never feel **comfortable.** When the lower limit is lower than the higher limit intermediate ambient conditions will enable each person to reach thermal comfort by behavioural adjustments. Conditions arrived at in this way can only be too cold for the subject with the most active metabolism. But as the upper limit has been calculated on the hypothesis of minimum clothing these subjects are able to put on adequate clothing, and vice versa for subjects with the least active metabolism and maximum clothing.

8. ERGONOMIC METHODOLOGY IN THE STUDY AND DESIGN OF HOT WORKPLACES

When placed in a given thermal environment man reacts to it by a number of physiological adjustments and psycho-sensorimotor changes. The optimalization of an industrial thermal environment implies reduction to a minimum of these physiological adjustments and psychosensorimotor changes, which at the same time involves the optimalization of the end-effects in terms of health, safety and productivity.

It is possible to seek to optimalize heat and humidity conditions at three distinct levels. At the very least thermal environments can under no circumstances be tolerated if they constitute a danger to the health of any of the individuals exposed. As an intermediate step it is recommended that an environment should be provided which will draw near to thermal neutrality as closely as possible, in which everybody keeps a constant body temperature at the cost of moderate physiological adjustments. At the best, it is obviously desirable to provide a comfortable thermal environment for all individuals.

The ergonomist must provide as a minimum a working environment which will be considered tolerable by all the workers for a working period of eight hours. The limit values are given in Chapter 6.

As far as possible ergonomic correction should strive towards a thermal environment which draws near to thermal neutrality as closely as possible. At best, heat and humidity comfort should be provided. At each of these stages the two factors of clothing and metabolism should be borne in mind. This problem has already been considered in the chapter on heat and humidity neutrality and comfort.

8.1 Ergonomics methodology

Once he has set himself a target in this way, the ergonomist must divide his task into three stages, viz. diagnosis, treatment and verification.

Diagnosis should reveal the main source of thermal discomfort or hindrance. This investigation requires a series of measurements which include all the physical parameters for the work environment, such as radiation temperature, dry and wet bulb temperatures and air velocity. The measuring instruments and the appropriate technical precautions are discussed in Chapter 3.

These measurements should be repeated at frequent intervals so as to identify the times of greatest stress during the shift. Likewise these measurements must be made at all the points where the subjects perform work.

Concurrent estimation of the working metabolism and clothing will provide the basis for calculating summary indexes or for simulating the trends of the main physiological parameters on a digital computer. The last part of the diagnosis stage is the identification of the main source of discomfort. This may be common to all workers in the area under study, or specific to a particular job.

Once the main source or sources of thermal discomfort or hindrance are known we can proceed to the treatment stage.

There are several technological means of protecting men who are subjected to hot environments. Two groups of protective methods must first be distinguished, those which influence the physical parameters for thermal environments or the parameters for individuals (metabolism or clothing) and which consequently reduce heat stress, and those which do not modify heat stress but reduce physiological strain in the individuals exposed to it.

Correction of heat stress

There are several ways of counteracting heat stress. They cannot be discussed in detail in this chapter. We can only list, in the form of a summary, the main categories of protective methods analysed in a recent article by Vogt (1973). Effective reduction of heat stress has four objectives.

a) Protection against external heat sources, particularly the sun, shall be sought both for the opaque building components and for the glazed surfaces.
For the opaque building components, the aims are:

- -increased reflection coefficient of the walls (aluminium paint, copper coating, plastic paint, whitewash, etc.);
- -increased coefficient of external heat exchange with the walls, obtained by wetting the surfaces;
- -increased thermal insulation (by using different materials, double roofs, etc.).

For the glazed surfaces the aims are:

- -reduction of incident heat flow (positioning of windows, horizontal louvres, exterior blinds, etc.);
- -increased reflection coefficient of the glazing (double glazing separated by a layer of copper or gold, etc.);
- -absorption of incident heat flux in the glazing (blue or green paint).

b) Protection against interior heat sources is provided in the following ways:

Protection against convective heat sources such as furnaces:

- evacuation of the hot air column by natural convection;
- installation of an extractor hood over the furnace.

Protection against radiative heat sources is obtained by installing various screens, e.g.:

- single or dual layer opaque screen;
- transparent screen;
- cooled screens enclosing the heat source.

c) Ventilation of the premises on the basis of heat and cold balance calculations:

- using air obtained at roof level (this raises the problem of installing air-intake and blowing systems);
- using treated air (air conditioning).

d) In exceptional cases it is also possible:

- to reduce metabolism (automation);
- to limit the exposure period;
- to adjust the inside air velocity to an optimal value by using air sampled in situ, or pre-cooled air (cold air stream);
- to create a microclimate at the point of work:
  either by air conditioning booths;
  or by means of protective clothing which may or may not be ventilated and may or may not be self-regulating.

Heat protective clothing apply four different physical principle, either separately or in combination (Metz, 1964), viz:

a) to reduce the quantity of radiant heat absorbed by the clothing - this can be achieved by metallizing the external surface (aluminu-coated clothing);

b) to reduce the amount of heat conducted through the texture of the clothing - this can be done either by providing an insulated enclosure (static insulation), or by forcibly expelling a current of air from the enclosure through a large number of interstices, directed so as to counter the conductive inflow of heat by repelling it as it seeks, by convective transfer, to penetrate (dynamic insulation).

c) to reduce the air temperature under the clothing either by means of a self-contained source of cold worn under the clothing or using an external source of cold which can inject a current of cold air under the garment or cold liquid distributed by a network of tubes across the internal surface of the clothing;

d) to allow the sweat secreted by the skin to evaporate if, in spite of the protection afforded by the clothing, the body is still subjected to a certain heat load.

Apart from thermal efficiency, heat-resistant clothing should meet several other requirements. It must not deteriorate as a result of heat or hinder the movements of the operative; it should provide adequate protection for the face, hands and legs, allow acoustical communication and, where appropriate, provide protection against certain atmospheric pollutants. It must also be easy to put on and maintain.

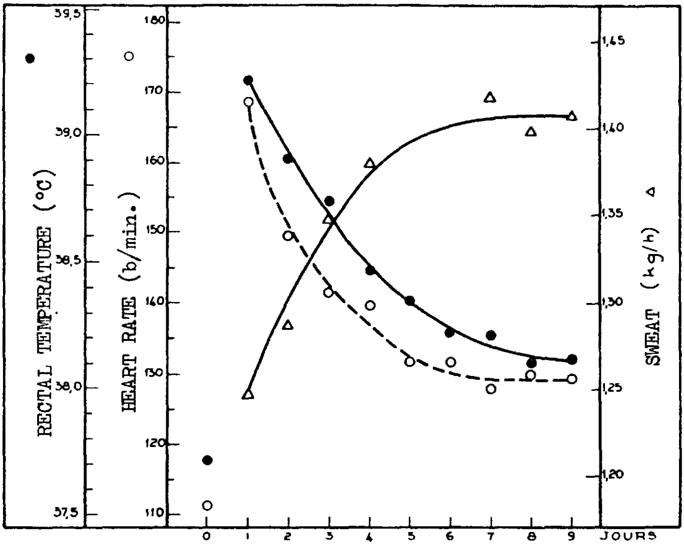

Figure 5 Changes in rectal temperature, heart rate and sweat loss over a nine day acclimatization period (taken from Lind and Bass, 1963).

A detailed study of heat-protective clothing is in progress at present. It is subsidized by the ECSC and concerns both the coal and steel industries. One objective is to classify existing clothing which is available commercially according to categories of hazard, and another is to propose new heat-protective clothing which will also be designed to give protection against splashes of hot metal in the steel industry or against explosions in the coal industry. One of the results of this study should be a major drive towards standardization.

8.3 Correction of physiological strain

8.3.1 Acclimatization

As compared with a non-acclimatized subject, an acclimatized subject suffers less physiological strain when subjected to the same heat stress. During a nine day acclimatization period, the three major physiological strains follow the patterns illustrated in figure 5.

Such an acclimatization can be achieved artificially either by means of repeated controlled exposure in a climatic chamber or naturally, whereby the subject performs his usual work initially for short periods and subsequently for longer periods. Some 10 days are sufficient to achieve adequate acclimatization.

8.3.2 Selection

For exposure to particularly severe conditions, such as mine rescue, fire-fighting etc., personnel must be selected. Pathological cases are eliminated first, leaving two further selection stages. The first stage may be described as that of negative selection and consists of rejecting persons of stocky body built in favour of tall persons. Zannini (1964) has demonstrated the importance of the surface/weight ratio in heat tolerance. This selection procedure must be followed by a positive selection procedure which necessitates a physiological examination of the subjects. Leyh et al. (1965) sought to lay down simple criteria for this selection procedure. According to them, heart rate and circulation data taken during a conventional step test carried out in a normal environment (25°C), provide valid selection criteria.

8.3.3 Food and drinks

Where the environment is tolerable over a long period, i.e. the average subject is not exposed to any severe discomfort during eight hours of work, the question of protection assumes the form of the prevention of certain chronic aliments

As regards drinking, the principle is that water intake should equal water loss throught sweat, urine and exhaled air. These losses can exceed one litre per hour. Metz (1964 - a) listed the principles of hygiene regarding drinks in an article on drinks in the industrial situation, and we give his main conclusions below.

a) Drinks should be taken as a function of the need for water, which is physiologically what happens if the drinks are non-alcoholic;

b) the most effective drink for satisfying the need for water is pure water;

c) drinks should be served cold (about 12°C);

d) caffeine intake should not exceed 400 mg per day, which corresponds approximately to three cups of strong coffee.

e) alcoholic drinks should not be allowed or at least limited to quantities which ensure that the amount of alcohol never exceeds 0.25 g/kg of body weight;

f) intake should be spaced out so that no more than a quarter of a litre is drunk at one time.

As regards food, fatty foods should be restricted. Additional salt is only justified for non-acclimatized workers who have recently been put on to a hot jub, in which cases additional salt must be administered exclusively in the form of salted liquid, e.g. meat broth or tomato juice slated at the rate of 20 g/l.

The third stage of the ergonomist's task is to verify the effectiveness of the methods used. A further series of physical and physiological measurements must be taken to determine the results of the scheme.

9. MAIN LINES OF RESEARCH TO BE ENCOURAGED

The six preceding chapters summarize and coordinate the main data constituting our present state of knowledge regarding thermoregulation. These chapters also serve to mention some gaps which ought to be filled, particularly when this knowledge is to be used in practical applications. Extrapolations from laboratory results to industrial situations is often problematic for reasons which have been given several times in our report.

Nevertheless these extrapolations must be tried, since laboratory data are the only rational basis for analysis and decision-making which can be used in an industrial situation. The most comprehensive and logical way of extrapolating these data is to simulate on the computer the probable physiological reactions of a person subjected to a given sequence of working and climatic conditions. The model proposed in this report is derived from Gagge's model. It is very simplified and therefore certainly.incomplete. It is desirable that such models should be developed so as to offer industrial practitioners a better working aid, which will enable them to make a fairly reliable appreciation of whether a given industrial situation is tolerable or not and having simulated the situation, to choose the best technical methods of improving it.

To develop such a model a large number of further research projects in the most varied of fields will be required. It is appropriate now to list and comment on the main avenues of research which should be explored over the next few years.

On the subject of 'heat stress', research should be directed to three distinct fields, viz. sensible heat exchange, the measurement of metabolic heat production in industrial situations, and clothing.

Convection and radiation heat exchange is defined in chapter 2. Quantification of these exchanges uses a number of coefficients, most of which have been determined empirically and only for the whole body. It is of particular importance to know precisely the local coefficients for convection and radiation exchange for the various parts of the body. Their knowledge would enable us to simulate more accurately the phenomena involved when certain parts of the body are clothed or unclothed and when their immediate thermal environment is heterogeneous. In addition these coefficients should be studied for the different physical postures adopted during industrial work. This kind of study, which would necessarily be fundamental research, would have immediate practical implications.

We need accurate knowledge concerning metabolic heat production, in order to decide whether a given work situation is tolerable. The most usual method is to measure oxygen consumption. Theoretically this is an excellent method but in other respects it has certain disadvantages. In many cases it is a considerable hindrance to the performance of the work. It does not enable metabolic heat production to be calculated reliably since it is essential to know the energy efficiency. This makes it desirable either to review and up-date the energy expenditure tables of Spitzer and Hettinger by incorporating the energy efficiency, or to try to develop a simple and sufficiently accurate method of measuring metabolic heat production: heart rate conjunction with body temperature, time and motion study of the type of work, etc.

The analysis of alterations in heat exchange due to clothing is without doubt the problem which should have most claim on our attention in the next few years. Clothing modifies all heat flows, convection, radiation and sweat evaporation. A physical study of fabrics should be undertaken, with the aim of proposing simple physical techniques for quantifying the main properties of a fabric. This work should then be taken a stage further and the fabric made up into an outfit of clothing of standard cut, which should be studied from a physiological point of view. This physiological study should use the physical properties previously determined to quantify their influence on the main heat flows. Lastly, it would be desirable, keeping to same fabric, to study the influence of the cut and size of a garment on the physiological effects of clothing. This kind of study seems to be an essential prerequisite for simulation on a computer with any degree of accuracy the evolution of the main physiological strain indicators over time.

It is equally necessary to do more work on several aspects of physiological strain. The most important of these aspects is without doubt the problem of regulating sweat loss. This has always been regarded as proportional to the concomitant body temperature set-offs. Several experiments demonstrate that this regulation process does not explain adequately all the results. The derivatives of body temperatures as a function of time certainly play a part and perhaps the differences between the temperatures of the various body sites. Lastly some skin areas or deep body regions may have a preferential effect in regulating sweating. Furthermore the degree of body hydration seems to play an important part in determining sweat secretion, although other factors not yet identified may also contribute to sweat fatigue. All these questions or hypotheses should be explored in order to perfect a quantitative model of the thermoregulatory process in the human body.

The second important problem to be considered is that concerning the evaporation efficiency of sweating. The function of the sweat produced is to wet the skin so that evaporation can restore thermal equilibrium. Certain skin areas are wetted while others remain dry. If the whole skin surface is wetted this means that a certain fraction of the sweat drips to the ground, and the evaporative efficiency of thermal sweating then falls below unity. The mass of sweat accumulated on the skin in order to achieve an adequate degree of wettedness is cooled by evaporation as well as the skin itself. It is a fraction of this amount of chilled water which drips from the skin, thus removing from the body a part of the evaporative cooling power. The evaporative efficiency of sweating must be more closely analyzed in order to obtain accurate heat balances. It is particularly important for a clothed subject, since the clothing itself is cooled to some degree by sweat evaporation.

The physiological reactions described when man is exposed to heat are those observed in the laboratory, i.e. when most of the other parameters are strictly controlled. In the industrial situation, man is also subject to a set of external factors which he cannot avoid.

The interaction of the physiological strains due to heat and the most important of these auxiliary factors should be analyzed. We regard three of them as being particularly important. The first is the circadian rhythm. It would be particularly interesting and useful to use two groups of shift workers to study and quantify the sensitiveness to time of day of the peripheral and central thermoregulatory mechanisms. The second auxiliary factor is alcohol intake, and the effect of alcohol on the thermoregulatory mechanisms also calls for our attention. Lastly, the usual drugs (sedatives, mild tranquillisers, etc.) certainly interact with the thermoregulatory process. These different factors must be taken into account if valid conclusions are to be drawn regarding a work situation in an industrial environment.

Acclimatization, or physiological adaptation to heat, has already been the subject of much study. However, it is still difficult to include it into a simulation model, except for extreme levels of acclimatization. It would be important to make a quantitative analysis of the development with time of the state of acclimatization and to be able to incorporate it in a simulation programme on a digital computer. Particular attention should be paid to the de-acclimatization which follows weekly interruptions or the holidays and recovery periods allocated to the workers.

This list, which has purposely been left incomplete, emphasizes the importance of fundamental research regarding the practical application of the relevant data.

Two aspects of *psychomotor strains* merit our attention. The first aspect concerns *behavioural thermoregulation in man*. Various possible behaviour patterns may have a considerable effect on the physiological strains and consequently on heat tolerance, viz. postural behaviour which effects heat exchange; clothing habits, which provide or remove a barrier between the skin and the ambient air; diet habits which can alter the degree of body hydration and the amount of salts in the organism. Other behaviour patterns, such as wetting one's forehead, drying one's skin, soaking one's hands and forearms in cold water, etc, should also be looked at because they interfere directly with the physiological thermoregulatory mechanisms. Some of these behaviour patterns no doubt produce a pleasant sensation but in addition bhey can have an adverse effect on the heat balance. Since they are generally observed during industrial work in the heat, it is desirable to study them in order to integrate them as possible influencing factors, into a general mathematical model. This type of study should be carried out in two parts, one analyzing their mode of action and the other analyzing their physiological effects.

In addition to studies on behavioural thermoregulation, it would be desirable to examine the changes in performance of psychosensorimotor tasks induced by hot environments. Many studies have lareadv been carried out, which are often contradictory. On the basis of the overall review made by Grivel we can think of a number of experiments during which central and peripheral temperatures would be applied artificially while an analysis was made of the variations experienced during fursnit or choice task, perhaps in conjunction with an additional watching task. There is no need to comment on the practical bearing of such studies. Modern industrial tasks are becoming increasingly similar to comparable artificial laboratory tasks. The errors which the operatives can make often have serious consequences and influency largely safety in a firm.

Lastly we consider that four types of more general problems should be given some attention by research workers. The first is that concerning the physiological severity in a work situation. When a person is exposed to heat and is made to perform a physical task, the most reliable tolerance criterion is deep body temperature. If a limit value is exceeded, exposure must be interrupted since there is considerable risk of heat distress or heat syncope. It is known for certain that a man's sensitivity to the severity of a situation is proportional to his deep body temperature. It would therefore be useful to investigate what physiological criterion or combination of criteria are associated with the subjective assessment of severity. Experiments carried out by Wyndham (1974) tend to show that the heart rate is the physiological effect which operatives tend to limit by behavioural adjustments. Studies of this type should be carried out in the steel industry, since they could be used to compare jobs using the criterion of perceived severity and the degree of physiological strain undergone, these two criteria not necessarily being interchangeable.

The second category of general problems is that of thermal environments which are variable as regards place and time. At present there do exist some single figure indexes which form a sufficiently valid basis on which to propose standards. In general these indexes can only be used with confidence when the physical parameters for the thermal environments are stable as regards time and place. These conditions are rarely met in industry. Usually air temperatures, globe temperatures, humidity and moving speed fluctuate in time and differ from one place to another. The problem is how to use physical measurements under these circumstances to make a quick estimate of the overall severity of the conditions. We do not know whether an average weighted as a function of time would reflect them accurately. It might be necessary to raise the values of the single figure indexes thus obtained, in case of wide fluctuations as regards time and place. Research should be carried out on physiological reactions to heterogeneous thermal conditions. This research work would also enable us to perfect the mathematical model which would constitute the ideal working aid.

The third category of general problems is that of breaks. When the working conditions are very hot, the operatives must be allowed periodic breaks in order to recover. At present there are no set rules regarding breaks. Research ought to be done on three specific points. The first point is the degree of 'fatigue' at which the break should commence. Should the break come when the organism has reached its physiological limits, of before then, and if so at what stage? The second point concerns the recovery environment. What is the optimal combination of temperature and humidity which will give the quickest rate of recovery? No doubt the optimal environment for recovery depends on the type of heat stress undergone. Lastly the third point concerns the length of the recuperation period. Should one wait for total recovery or should work be resumed after partial recovery?

A basic research project should produce answers to all these questions. The project should be supplemented by studies carried out in actual work situations, with the aim of taking account of a number of individual parameters which are difficult to monitor in the laboratory, such as individual preferences, breaks taken with work-mates, preferred occupations during breaks, etc..

The fourth category of general problems concerns the ultimate effects of hot environments. These ultimate effects are observable in the health, productivity and safety of the employees.

These ultimate effect are a function of the working conditions as a whole, including those of a sociological and economic nature. Thus the evaluation of these results as such and of the interaction of thermal conditions with the overall conditions entails several methodological difficulties. For this reason this type of evaluation could only be undertaken as part of a more general study which dealt with all the working conditions at once. The conceptual framework for an inquiry of this kind could be based on 'note' No 900-75-74 of the Institut National de Recherche pour la Securité, which is entitled 'Essai de classement des risques professionnelleset des actions de prevention' (An attempt to classify occupational risks and prevention techniques). The paper deals with the four interacting components of the work system, viz. the operator, his task, the equipment he uses and the environment in which he works.

Each of these can be influenced by all the others and can also exert an influence on all the others. Each of the possible combinations is a potential accident risk factor (safety), sickness risk factor (health) and performance factor (productivity).

When restored to its general context, evaluation of the ultimate effect of thermal environments would reveal their direct incidence and also their relative incidence and would provide a rational basis for decision between various prevention, correction or prediction techniques.

Lacking presently of the conclusions from an exhaustive epidermiological analysis of this kind, the approach of the problems of work in the heat can only be of pragmatic. Indeed this is often justified by the excessive or intolerable severity of certain work situations. But as such cases become more rare, an achievement which is partly due to ongoing practical applications, it becomes more difficult to decide which is the best action to take on, for example, climate noise, hours of work or holidays.

Considering the problem of hot environments against its widest possible background does not by any means reduce the usefulness or the necessity of the more functional studies and research projects already carried out or which are still desirable, since 'these' remain indispensable to a more rational analysis of the problem of hot working environments and to a more rational development of the solutions they require.

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Symbols and units

C = convection heat
E = evaporation heat
E max = maximal possible evaporation
EP = pulmonary evaporation
Er = evaporation required to maintain internal heat balance
fcl = Coefficient of reduction in sensible heat exchange through clothing;
fp, cl = Coefficient of reduction in latent heat exchange through clothing;
hc = convection heat exchange coefficient
he = evaporative heat exchange coefficient
hr = linear coefficient of radiation heat exchange
Hd = heat stress
Hp = body heat production
Hr = heat exchange between body and environment
i = evaporative yield of thermal sweating
Ia = thermal insulation afforded by the air
Iv = thermal insulation afforded by clothing
It = total thermal insulation
kc = black glove or black cylinder convection coefficient
M = metabolic heat
Mb = basal metabolism
P = conduction heat
Pa_{H_2O} = partial pressure of ambient water vapour
Ps_{H_2O} = partial pressure of cutaneous water vapour
Ps, s^{H_2O} = saturation pressure of cutaneous water vapour
R = radiation heat
r' = net energy yield from muscular work
s = universal radiation constant
S = sweat loss
Sr = sweat loss required
Ta = dry bulb temperature
Te = average radiation temperature
Th = wet bulb temperature

Th,n = natural ambient wet bulb temperature
Tg = black globe temperature
Tre = rectal temperature
$\overline{T}$s = average skin temperature
TIC = internal heat flow
TEC = external heat flow
v = clothing
Va = air velocity
w = equivalent fraction of skin wettedness
W = external work performed
α = absorption capacity of skin
λ = thermal conductivity coefficent
μ = relative skin wettedness

CONVERSION OF UNITS

1. FORCE: Dimension: $M.L.T^{-2}$

   1 newton (N) = 1 $kp.m.s^{-2}$ = $1.02.10^{-1}$ kg = 102g

   1 kilogramme (kg) = 9.98 newtons (IN = $1.02.10^{-1}$ kg)

2. ENERGY: Dimension: $M.L^{2}.T^{-2}$

   1 joule (J) = 1 newton.1 metre = 1 $kp.m^{2}.s^{-2}$ = 102g.m

   1 calorie (cal) = 4.18 joules (1J = $2.39.10^{-1}$ cal)

   1 kilocalorie (kcal) = $4.18.10^{3}$ joules (1J = $2.39.10^{-4}$ kcal)

   1 kilogramme/metre (kgm) = 9.81 joules (1J = $1.02.10^{-1}$ kgm)

   1 kilowatt/hour (kWh) = $3.6.10^{6}$ joules (1J = $2.78.10^{-7}$ kWh)

   1 British thermal unit (Btu) = $1.06.10^{3}$ joules (1J = $9.47.10^{-4}$ Btu)

3. POWER: Dimension: $M.L^{2}.T^{-3}$

   1 watt (W) = 1 joule/second = 1 $kp.m^{2}.s^{-3}$ = $102g.m.s^{-1}$

   1 kilocalorie/hour ($kcal.h^{-1}$) = 1.16 watts (1W = 0.86 $kcal.h^{-1}$)

   1 kilogramme/metre/minute ($kgm.min^{-1}$) = 0.163 watts

4. PRESSURE: Dimension: $M.L^{-1}.T^{-2}$

   1 pascal (Pa) = 1 newton/square metre = 1 $kp.m^{-1}.s^{-2}$ = $102g/m^{2}$

   1 millibar (mbar) = 100 pascals (1Pa = 10^{-2}mbar)

   1 torricelli (torr) = 133 pascals (1Pa = $7.5.10^{-3}$ torr)

   1 millimetre of water (mm H_2O) = 9.81 pascals (1Pa = 0.102 mmH_2O)

1 atmosphere (atm) = $1.013.10^5$ pascals (1Pa = $0.987.10^{-5}$ atm)

5. TEMPERATURE

T° CELSIUS = 0.55 (T°F - 32)

T° FAHRENHEIT = 32 + 1.8 T°C

T° KELVIN = T°C + 273

```
00100         1*
00100         2*
00100         3*
00100         4*        ANNOTATED PROGRAMME FOR SIMULATING
00100         5*        THERMOREGULATORY SYSTEM IN MAN
00100         6*        TWO STAGE MODEL
00100         7*        CLOTHING SIMULATION
```

Symbols in the simulation model

CLO = number of clo units of thermal insulation;

COLD = central command in response to negative feedback from the regulatory system;

CRSIG = deep body temperature feedback from the regulatory system;

DILAT = vasodilation command;

ERES = pulmonary evaporation;

EDIF = insensible sweat;

HFCR = heat stored in the deep body region;

HFSK = heat stored at skin level;

REGSW = sweat command;

SKBF = cutaneous blood flow;

SKSIG = peripheral temperature feedback from the regulatory system;

SMAX = maximal sweat loss;

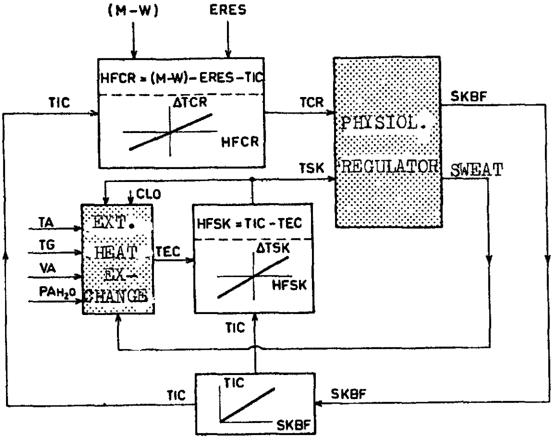
STRIC = vasoconstriction command;

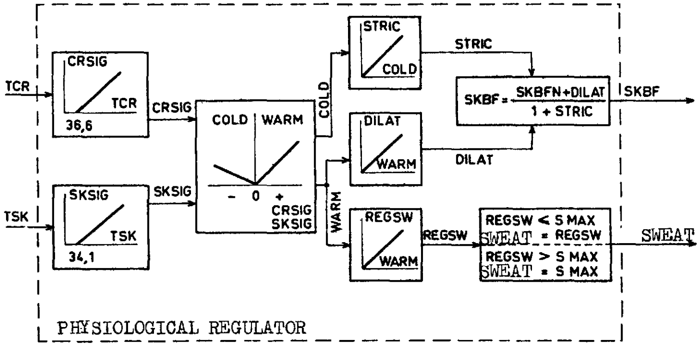
TCR = deep body temperature;

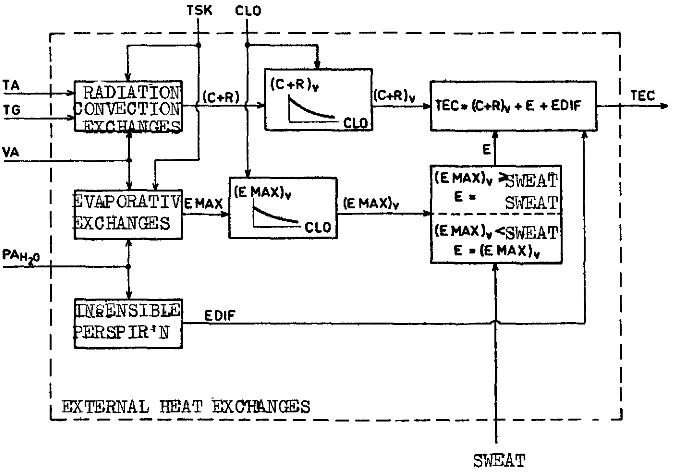
TSK = skin temperature;

WARM = central command in response to positive feedback

The simulation model is described in chapter 6.1.2.


(M–W)
ERES
HFCR = (M-W) - ERES - TIC
ΔTCR
HFCR
TIC
TCR
PHYSIOL. REGULATOR
SKBF
SWEAT
TSK
CLO
TA
TG
VA
PAH₂O
EXT. HEAT EX-CHANGE
TEC
HFSK = TIC - TEC
ΔTSK
HFSK
TIC
TIC
SKBF
TIC
SKBF


TCR
TSK
CRSIG
TCR
36,6
SKSIG
TSK
34,1
CRSIG
SKSIG
COLD
WARM
- 0 +
CRSIG
SKSIG
COLD
WARM
STRIC
COLD
DILAT
WARM
REGSW
WARM
STRIC
DILAT
REGSW
SKBF = (SKBFN + DILAT) / (1 + STRIC)
SKBF
REGSW < S MAX
SWEAT = REGSW
REGSW > S MAX
SWEAT = S MAX
SWEAT
PHYSIOLOGICAL REGULATOR


TSK
CLO
TA
TG
VA
PAH₂O
RADIATION CONVECTION EXCHANGES
(C+R)
(C+R)ᵥ
CLO
(C+R)ᵥ
TEC = (C+R)ᵥ + E + EDIF
TEC
E
EVAPORATIVE EXCHANGES
E MAX
(E MAX)ᵥ
CLO
(E MAX)ᵥ
(E MAX)ᵥ > SWEAT
E = SWEAT
(E MAX)ᵥ < SWEAT
E = (E MAX)ᵥ
INSENSIBLE PERSPIR'N
EDIF
EXTERNAL HEAT EXCHANGES
SWEAT

```
 00100     8*      C
 00100     9*      C      NOMBRE  TOTAL DE  SIMULATION A  EFFECTUER  NSIMUL
 00100    10*      C      NTX= PAS EN  MIN. SOUHAITE A L'IMPRESSION DES
 00100    11*      C                         RESULTATS
 00100    12*      C
 00101    13*             DOUBLE PRECISION  REGSW
 00103    14*             READ (5,2100)  NSIMUL,NTX
 00107    15*        2100 FORMAT (26I3)
 00110    16*             TX=NTX/60.
 00110    17*      C
 00110    18*      C
 00110    19*      C      CARACTERISTIQUES  PHYSIQUES DU SUJET EXPOSE
 00110    20*      C      POIDS EN  KG    TAILLE  EN  CM  ET  ACCLIMATEMENT
 00110    21*      C      ACCLIM = 0.  SI  NON  ACCLIM. =1.  SI   ACCLIM.
 00110    22*      C
 00111    23*             READ (5,104) POIDS,TAILLE,ACCLIM
 00116    24*         104 FORMAT (3F5.2)
 00116    25*      C
 00116    26*      C      SURF =SURFACE  EN  SQ.M
 00116    27*      C
 00117    28*             SURF=(POIDS**0.425)*(TAILLE**0.725)*71.84*1.E-04
 00117    29*      C
 00117    30*      C
 00120    31*             DO  2200  JSIM=1,NSIMUL
 00120    32*      C
 00120    33*      C
 00120    34*      C      NOMBRE  DE  SEQUENCES  DE  CHAQUE  SIMULATION NSEQ
 00120    35*      C
 00123    36*             READ (5,2100)NSEQ
 00123    37*      C
 00123    38*      C      CONDITIONS  INITIALES
 00123    39*      C      TSK =TEMPERATURE  CUTANEE  INITIALE  EN C
 00123    40*      C
 00126    41*             TSK=34.1
 00126    42*      C
 00126    43*      C      TCR = TEMPERATURE  CENTRALE  INITIALE  EN  C
 00126    44*      C
 00127    45*             TCR=36.6
 00127    46*      C
 00127    47*      C      KMIN = CONDUCTANCE  MINIMALE  EN   W/(SQ.M*C)
 00127    48*      C
 00130    49*             KMIN=5.28
 00130    50*      C
 00130    51*      C      SKBFN = DEBIT SANGUIN CUTANE NORMAL EN   L/(SQ.M*HR)
 00130    52*      C
 00131    53*             SKBFN=6.3
 00132    54*             SKBF=SKBFN
 00132    55*      C
 00132    56*      C      ERSW  ET  WRSW = EVAPORATION  SUDORALE
 00132    57*      C                INITIALE   EN   W/(SQ.M*HR)
 00132    58*      C
 00133    59*             ERSW=0.0
 00134    60*             WRSW=0.0
 00134    61*      C
 00134    62*      C      EDIF = PERSPIRATION  INSENSIBLE  INITIALE
 00134    63*      C                  EN   W/(SQ.M*HR)
 00134    64*      C
```

```
00135      65*               EDIF=5.0
00135      66*      C
00135      67*      C        EDRIP = SUDATION NON EVAPOREE INITIALE
00135      68*      C                EN   W/(SQ.M*HR)
00135      69*      C
00136      70*               EDRIP=0.0
00137      71*               DO  2300  ISEQ=1,NSEQ
00137      72*      C
00137      73*      C
00137      74*      C        CONDITIONS  THERMO HYGROMETRIQUES  VESTIMENTAIRES
00137      75*      C              ET  METABOLIQUES
00137      76*      C        DE CHAQUE  SEQUENCE  DE  SIMULATION
00137      77*      C        WE = RENDEMENT ENERGETIQUE DU TRAVAIL
00137      78*      C        RM = METABOLISME  ENERGETIQUE  EN  W/(SQ.M*HR)
00137      79*      C        CLO = NOMBRE DE  CLO
00137      80*      C        TA = TEMPERATURE  SECHE  DE  L'AIR  EN  C
00137      81*      C        TG = TEMPERATURE  D'UN  GLOBE  NOIR  DE  15 CM
00137      82*      C             DE  DIAMETRE  EN C
00137      83*      C        VA = VITESSE  DE  L'AIR  EN M/S
00137      84*      C        RH = HUMIDITE  RELATIVE
00137      85*      C        EXPOS = DUREE  DE  LA  SEQUENCE  EN  MIN.
00137      86*      C
00137      87*      C
00137      88*      C
00142      89*               READ (5,103) WE,RM,CLO,TA,TG,VA,RH,EXPOS
00154      90*           103 FORMAT (8F5.2)
00155      91*               PRINT 4000,NSIMUL,NTX,POIDS,TAILLE,ACCLIM
00164      92*          4000  FORMAT (1H1,///,5X,'NSIMUL = ',I4,3X,'NTX = '
00164      93*              $  ,I4,3X,'POIDS = ',F7.
00164      94*              *2,3X,'TAILLE = ',F7.2,3X,'ACCLIM = ',F7.2,3X,/////.
00165      95*               PRINT 990
00167      96*           990 FORMAT (1H0,///,3X,'      WE       RM         CLO      TA'
00167      97*              $'         TG          VA'
00167      98*              $'     RH      EXPOS')
00170      99*               PRINT 991,WE,RM,CLO,TA,TG,VA,RH,EXPOS
00202     100*           991 FORMAT (2X,8F8.2)
00203     101*               PRINT 4001
00205     102*          4001 FORMAT (////)
00206     103*               EXPOS=EXPOS/60.
00207     104*           307 PRINT 1001
00211     105*          1001 FORMAT (1H0,3X,'     TSK         TCR        STORE       '
00211     106*              $'STORC       EDRIP         '
00211     107*              *' ERES       EDIF        ERSW         EMAX         TIME ')
00212     108*               PRINT 4001
00212     109*      C
00212     110*      C        TE =            TEMPERATURE  DE  RAYONNEMENT  C
00212     111*      C
00214     112*               TE=(SQRT(SQRT(((TG+273.)**4.)+2.5E07*(TA-TG)*
00214     113*              $(VA**0.5))))-273.
00214     114*      C
00214     115*      C        CHR = COEFFICIENT  LINEAIRE  DE  RAYONNEMENT
00214     116*      C                      EN   W/(SQ.M*C)
00214     117*      C
00215     118*               CHR=0.227*((((TE+TSK)/200.)+2.73)**3.)*0.72*
00215     119*              $(1.+0.15*CLO)
00216     120*               IF (VA-1.) 2000,2010,2010
00221     121*          2000 CHC=3.5+5.2*VA
```

```
 00222     122*                GO TO 2020
 00223     123*         2010   CHC=8.7+VA**0.6
 00224     124*         2020   CHC=CHC+0.002*(RM-60.)
 00225     125*                CTC=CHC+CHR
 00225     126*       C
 00225     127*       C        TR = TEMPERATURE  OPERATIVE  EN  C
 00225     128*       C
 00226     129*                TR=TA+((CHR*(TE-TA))/CTC)
 00227     130*                WK=WE*RM
 00230     131*                FCL=1./(1.+0.155*CTC*CLO)
 00231     132*                FPCL=1./(1.+0.143*CHC*CLO)
 00231     133*       C
 00231     134*       C        ERES = EVAPORATION PULMONNAIRE  EN  W/(SQ.M*HR)
 00231     135*       C
 00232     136*                ERES=0.0023*RM*(44.-RH*PTTBL(TA))
 00233     137*                EV=ERES+EDIF
 00234     138*                TIMX=0.0
 00235     139*                TIME=0.0
 00236     140*                PPHG=RH*PTTBL(TA)
 00237     141*                DTIM=0.01666666667
 00240     142*          600   CONTINUE
 00240     143*       C
 00240     144*       C        ECHANGES  DE  CHALEUR  DANS  LE  SYSTEME  PASSIF
 00240     145*       C        FLUX  DE  CHALEUR  ENTRE  LE  NOYAU  ET  LA  PEAU
 00240     146*       C                  EN    W/SQ.M
 00240     147*       C        FLUX  DE  CHALEUR  ENTRE  LA  PEAU  ET  L'AMBIANCE
 00240     148*       C                  EN    W/SQ.M
 00240     149*       C
 00241     150*                HFSK=(TCR-TSK)*(KMIN+1.163*SKBF)-CTC*(TSK-TR)*
 00241     151*               $FCL-(EV-ERES)
 00242     152*                HFCR=RM-(TCR-TSK)*(KMIN+1.163*SKBF)-ERES-WK
 00242     153*       C
 00242     154*       C        TCSK  ET  TCCR  SONT  LES  CAPACITES  THERMIQUES
 00242     155*       C        DE  LA  PEAU  ET   DU  NOYAU  EN   W*HR/C
 00242     156*       C        COEF = RAPPORT  NOYAU/ECORCE
 00242     157*       C
 00243     158*                COEF=0.0442+0.3509/(SKBF-0.01386)
 00244     159*                TCSK=COEF*POIDS*0.97
 00245     160*                TCCR=(1.-COEF)*POIDS*0.97
 00245     161*       C
 00245     162*       C        VARIATIONS  DE  TEMPERATURE  DU  NOYAU
 00245     163*       C                  ET   DE  L'ECORCE
 00245     164*       C
 00246     165*                DTSK=(HFSK*SURF)/TCSK
 00247     166*                DTCR=(HFCR*SURF)/TCCR
 00247     167*       C        L'UNITE  DE  TEMPS  EST  L'HEURE
 00247     168*       C
 00247     169*       C
 00247     170*       C        POUR NE  PAS  DEPASSER  UNE  VARIATION  UNITAIRE
 00247     171*       C                   DE   TEMPERATURE
 00247     172*       C         DE   0.1  C
 00247     173*       C
 00250     174*                U=ABS(DTSK)
 00251     175*         5874   CONTINUE
 00252     176*                IF (U*DTIM-0.1)  873,873,874
 00255     177*          874   DTIM=DTIM*0.5
 00256     178*                GO TO 5874
```

```
00257     179*         873 CONTINUE
00260     180*             U=ABS(DTCR)
00261     181*        5973 CONTINUE
00262     182*             IF (U*DTIM-0.1) 973,973,974
00265     183*         974 DTIM=DTIM*0.5
00266     184*             GO TO 5973
00267     185*         973 CONTINUE
00270     186*             TIMX=TIMX+DTIM
00271     187*             TIME=TIME+DTIM
00272     188*             TSK=TSK+DTSK*DTIM
00273     189*             TCR=TCR+DTCR*DTIM
00273     190*       C
00273     191*       C     SYSTEME  DE  CONTROLE  PHYSIOLOGIQUE
00273     192*       C     VASOMOTRICITE = DILAT  ET  STRIC
00273     193*       C     SUDATION = REGSW
00273     194*       C
00274     195*             SKSIG=(TSK-34.1)
00275     196*             IF(SKSIG) 900,900,901
00300     197*         900 COLDS=-SKSIG
00301     198*             WARMS=0.0
00302     199*             GO TO 902
00303     200*         901 COLDS=0.0
00304     201*             WARMS=SKSIG
00305     202*         902 CRSIG=(TCR-36.6)
00306     203*             IF(CRSIG) 800,800,801
00311     204*         800 COLDC=-CRSIG
00312     205*             WARMC=0.0
00313     206*             GO TO 2310
00314     207*         801 WARMC=CRSIG
00315     208*             COLDC=0.0
00316     209*             IF(ACCLIM-1.)2310,2320,2320
00321     210*        2310 STRIC=0.5*COLDS
00322     211*             DILAT=75.*WARMC
00323     212*             GO TO 2330
00324     213*        2320 STRIC=0.5*COLDS
00325     214*             DILAT=150.*WARMC
00326     215*        2330 SKBF=(SKBFN+DILAT)/(1.+STRIC)
00327     216*             IF(ACCLIM-1.) 2340,2350,2350
00327     217*       C
00327     218*       C     REGSW   EN  (G/SQ.M*HR)
00327     219*       C
00332     220*        2340 REGSW=(200.*((COEF*WARMS)+((1.-COEF)*WARMC)))*
00332     221*            $EXP(SKSIG/10.7)
00333     222*             IF(REGSW) 2390,2390,2391
00336     223*        2390 REGSW=0.0
00337     224*             GO TO 3000
00340     225*        2391 IF(REGSW-350.) 2392,2392,2393
00343     226*        2392 GO TO 3000
00344     227*        2393 REGSW=350.
00345     228*             GO TO 3000
00346     229*        2350 REGSW=250.*((COEF*WARMS)+((1.-COEF)*WARMC))*
00346     230*            $EXP(SKSIG/10.7)
00347     231*        2360 IF(REGSW) 2370,2370,2380
00352     232*        2370 REGSW=0.0
00353     233*             GO TO 3000
00354     234*        2380 IF(REGSW-500.) 2394,2394,2395
00357     235*        2394 GO TO 3000
```

```
   00360     236*          2395 REGSW=500.
   00361     237*          3000 ERSW=0.7*REGSW
   00362     238*               EMAX=2.2*CHC*FPCL*(PTTBL(TSK)-RH*PTTBL(TA))
   00362     239*     C
   00362     240*     C         PWET = FRACTION  DE  PEAU  MOUILLEE
   00362     241*     C
   00363     242*               IF(ERSW-EMAX) 3001,3001,3002
   00366     243*          3001 PRSW=ERSW/EMAX
   00367     244*               PWET=(0.06+0.94*PRSW)
   00 70     245*               EDIF=PWET*EMAX-ERSW
   00371     246*               EDRIP=0.0
   00372     247*               EV=ERES+ERSW+EDIF
   00373     248*               GO TO 3003
   00374     249*          3002 PRSW=1.
   00375     250*               PWET=1.
   00376     251*               EDIF=0.0
   00377     252*               EDRIP=ERSW-EMAX
   00400     253*               EV=ERES+EMAX
   00401     254*          3003 CONTINUE
   00402     255*               DRY=CTC*(TSK-TA)*FCL
   00403     256*               STORE=RM-EV-DRY-WK
   00404     257*               STORC=STORE*SURF/POIDS*0.97
   00405     258*               ITIMX=TIMX*60.+0.005
   00406     259*               IF(ITIMX.LT.NTX) GO TO 600
   00410     260*               DTIM=0.01666666667
   00411     261*               TWET=TA
   00412     262*          1204 E=RH-(PTTBL(TWET)-0.00066*760.*(TA-TWET)*
   00412     263*              $(1.0+0.00115*TWET))
   00412     264*              X/PTTBL(TA)
   00413     265*               IF(E) 1203,1202,1202
   00416     266*          1203 TWET=TWET-0.10
   00417     267*               GO TO 1204
   00420     268*          1202 TIMX=0.0
   00421     269*          1100 FORMAT (1X,10F10.2)
   00422     270*               ATIME=TIME*60.
   00423     271*               PRINT 1100,TSK,TCR,STORE,STORC,EDRIP,ERES,EDIF,
   00423     272*              $ERSW,EMAX,ATIME
   00437     273*               IF(TIME-EXPOS) 600,2300,2300
   00442     274*          2300 CONTINUE
   00444     275*          2200 CONTINUE
   00446     276*               STOP
   00447     277*               END

   00101       1*               FUNCTION PTTBL(TC)
   00103       2*               TF=TC*1.8+32.
   00104       3*               X=(459.67+TF)/100.
   00105       4*               Y=16.386396+0.00137804*TF-5656./(100.*X)-
   00105       5*              $3.560573*LOG(X)
   00106       6*               Z=Y*2.302585
   00107       7*               PTTBL=25.4*EXP(Z)
   00110       8*               RETURN
   00111       9*               END

          END OF COMPILATION:          NO  DIAGNOSTICS.
```

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