BRITISH OCCUPATIONAL HYGIENE SOCIETY

ISBN 0 948237 29 5

British Occupational Hygiene Society

Technical Guide No. 12

The Thermal Environment (Second edition)

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1996

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The views expressed in the *General Guide* are those of the Authors and are not necessarily those of the Society.

Acknowledgements are given for valuable technical comments and editing assistance by Donald Hughes, Series Editor and Peter Dewell, Chairman, BOHS Technology Committee.

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

ISBN 0 948237 29 5

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Preface to the First Edition

The main objective of controlling the thermal environment in relation to humans is to match activities to response in order to optimise health, comfort, safety and performance.

A number of factors interact within the thermal environment. Ultimately, it is the individual's physiological and psychological responses which indicate whether a particular combination of these factors produce too much heat gain or loss and results in unacceptable physiological, psychological or subjective states.

The values providing criteria of unacceptable strain are based upon research that has shown that the physical and psychological performance of an increasing proportion of the population will be less effective as these criteria are exceeded in extreme conditions. This document examines the range of human responses to thermal conditions and the means by which environments can be monitored and controlled.

The Guide is written for persons who are involved in investigating or assessing thermal environments in the work place, whether from considerations of comfort or of stress (hot or cold). It is not directed at any specific discipline, as involvement in the thermal environment may arise from many areas, including occupational hygiene, ergonomics, medicine, engineering, biology or management.

The document is not intended to be a working manual as this would render it too voluminous - rather it attempts to cover all the relevant areas in this field in order to provide a basis for investigation and assessment. Other documentation relevant to specific areas is extensively referenced. As many of the references are common to different sections of the Guide, they appear together at the end of the document.

The guidance provided in this document is of a general nature only and views expressed are those of the authors and not necessarily of the Society itself.

1990

Preface to the Second Edition

The original BOHS Technical Guide No. 8 The Thermal Environment (TG8) was published in 1990, following several years of activity from the working group involved. Since that time there have been considerable developments in the subject area and revisions and changes of status to the standards applying (in particular adoption of ISO Standards as British and European Standards).

In late 1994 the BOHS Technology Committee proposed that the TG8 working group should be reconvened to address these changes. This was duly undertaken under the chairmanship of Tony Youle with only one change from the previous working group, namely Tony Mulhall (of the Health and Safety Executive) to replace Jim Sykes (of the same organisation).

The working group set out during 1995 to both update and broaden the scope of the Guide, leading to completion in 1996. This has coincided, appropriately, with the publication of the new standard BS EN ISO 11399: 1995 "Ergonomics of the thermal environment : Principles and application of relevant International Standards", otherwise known to those involved as the 'umbrella' standard, as it brings together all the various standards relating to ergonomics of the thermal environment. This document originated from the British Standards Committee chaired by Ken Parsons, with which several others of the working group are also associated.

Changes and additions have been made to all sections of the Technical Guide. The sections on Comfort, Heat Stress, Cold Stress and Measurement have all been updated and new issues included. Extensive revisions and additions have been made to Chapter 7 (Contact Injuries), Chapter 8 (Performance), Chapter 9 (Statutory Requirements) and to the References.

Although most of the experimental and applied work referred to in the Guide is based on fit, young, male subjects, the principles may be said to apply to both male and female workers.

The broad context and aims of the document remain as described in the Preface to the First Edition.

A. Youle,
April 1996

1

MAN AND HIS THERMAL ENVIRONMENT

1.1 Thermoregulation

Human beings are homeotherms and able to maintain a constant internal temperature within arbitrary limits of ±2°C despite much larger variations in ambient temperature. In a neutral environment at rest, deep body temperature may be kept within a much narrower band of control (±0.3°C). The main physiological adjustments involve changes in heat production, especially by shivering or voluntary muscular activity during physical exertion, and alterations in heat loss by vasomotor changes which regulate heat flow to the skin, and increased evaporative heat loss by sweating. Evaporation of sweat from the body surface provides man with one of the most effective methods of heat loss in the animal kingdom. Even so, temperature extremes can only be tolerated for a limited period depending on the degree of protection provided by shelter, the availability of clothing insulation in the cold and fluid replacement in the heat. By behavioural responses, human beings are able to avoid the effects of such extremes without recourse to excessive sweating or shivering. Repeated exposure to heat (and to a lesser extent to cold) can result in acclimatisation, which involves reversible physiological changes that improve the ability to withstand the effects of temperature stress. A permanent adaptation to climate can occur by the natural selection of beneficial changes in body form and function ascribable to inherited characteristics.

1.1.1 Central nervous control of body temperature

Thermoregulation is integrated by a controlling system in the central nervous structures of the body which respond to the heat content of tissues. Thermoreceptors sensitive to thermal information from the skin, deep tissues and central nervous system provide the feedback signals to the central controller (*eg* in the hypothalamus) as illustrated by the loop system in Figure 1.1.

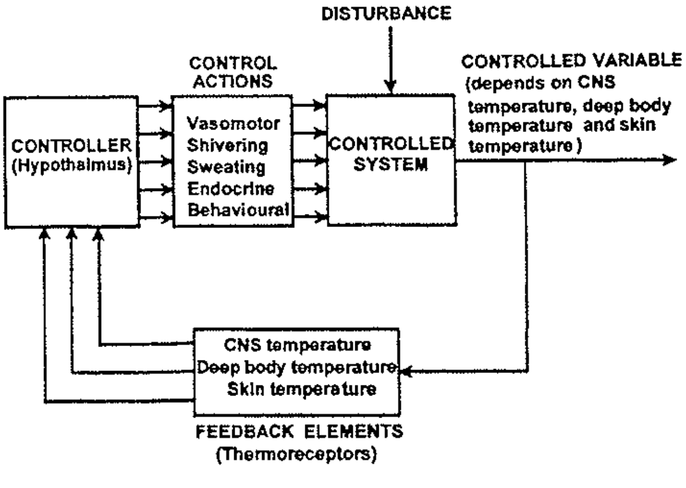


Figure 1.1: Schematic diagram of the feedback control of temperature regulation in man with the controlled variable an integrated value of multiple temperatures.

The temperature of the blood perfusing the hypothalamus in the brain is a major physiological drive to thermoregulation, but inputs to the controller also come from thermosensitive end-organs in the skin and deep tissues. Neural thermosensors in the skin provide an input of temperature information to the hypothalamus that enables it to anticipate the ambient thermal load and to prevent any actual deviation of core temperature. Beyond this zone of control, higher thermal loads induce changes in core temperature which then create a powerful additional blood-borne temperature stimulus to the hypothalamus.

An essential role in processing thermal signals is ascribed to areas in the posterior hypothalamus and in the pre-optic region of the anterior hypothalamus, described as the 'heat gain' and 'heat loss' centres since they are considered to control shivering/vasoconstriction and sweating/vasodilatation respectively. Cross-inhibition by nerve connections between these two centres has been shown. The integration of incoming and outgoing information and the 'set-point' or 'gain' at which the hypothalamic centres operate form the basis of the central nervous control of human thermoregulation (*eg* Newburgh, 1968; Clark and Edholm, 1985).

1.2 Physiological Measurements

1.2.1 Core temperature

The deep body or core temperature is normally maintained within a narrow range around 37°C. Core temperature represents a composite temperature of the deep tissues, but even in the core, temperature is not uniform because organs such as the liver and active muscles have a higher rate of heat production than other deep tissues.

Conventionally, core temperature is measured by a thermometer placed in the mouth (BS 691: 1987). Errors arise if there is mouth breathing or talking during measurement, or if hot or cold drinks have been taken just previously, or if the tissues of the mouth are affected by cold or hot external environments. The rectal temperature is a slowly equilibrating but more reliable measurement of deep body temperature and on average about 0.5°C higher than mouth temperature. Cold blood from chilled legs and warm blood from active leg muscles will affect the rectal temperature. The temperature of the urine is a reliable measure of core temperature providing it is possible to void a volume of 100 ml or more. For continuous measurement of core temperature, thermoelectric devices may be placed in the ear or the temperature in the intestine may be monitored by telemetry using a temperature-sensitive transmitter in the form of a pill that can be swallowed.

The internal temperature of warm-blooded animals including man does not stay strictly constant during the course of a day even when keeping constant the generation of heat from food intake and physical activity. In humans it may be 0.5-1.0°C higher in the evening than in the early morning due to an inherent circadian temperature rhythm. Another natural internal temperature variation occurs in women at the time of ovulation when core temperature rises by 0.1-0.4°C until the end of the luteal (post-ovulatory) phase of the menstrual cycle.

1.2.2 Skin temperature

Across the shell of the body, from the skin surface to the superficial layers of muscle, there is a temperature gradient which varies according to the external temperature, the region of the body surface, and the rate of heat conductance from the core to the shell. When an individual is thermally comfortable, the skin of the toes may be at 25°C, that of the upper arms and legs at 31°C, the forehead temperature near 34°C while the core is maintained at 37°C. Average values for skin temperature can be obtained by applying thermistors or thermocouples to the skin and using weighting factors for the different representative areas. Regional variations can be visualised and recorded more comprehensively by infra-red thermography.

1.2.3 Other measurements

A number of other physiological parameters apart from core and shell temperatures are of value in interpreting the components of thermal strain. These include peripheral blood flow to measure vasomotor changes, sweat loss, shivering responses, cardiovascular responses such as heart rate, blood pressure and cardiac output and metabolic heat production. The choice of measurements will depend largely on the nature of the thermal stress, the requirements and limits set by those responsible for the health and safety of employees, and the degree of acceptance of the methods by the subjects. Assessment of the physiological strain in a person subjected to thermal stress is usually related to two measurements of physiological function - the core temperature and the heart rate. Tolerance limits for work in adverse temperature conditions are commonly based on acceptable 'safe' levels of these two functions - in the heat a limit of 38.0°C core temperature and 180 beats per minute heart rate in normal healthy adults, and in the cold 36.0°C core temperature. Close monitoring and greater restriction of these limits may need to be applied to older workers and unfit personnel.

In field studies, techniques for measuring physiological parameters include telemetry procedures for ambulatory monitoring. A comparison of some of the standard methods available for measuring core temperature, skin temperature, heart rate and total body sweat loss, with an appraisal of their technical limitations and the discomfort and risks they involve, can be found in ISO 9886 (1992).

1.3 Thermal Balance

The body's core temperature remains constant when there is an equilibrium between internal heat production and heat loss from the surface. Thermal balance is expressed in the form of an equation

$$M \pm W = \pm K \pm C \pm R - E \pm S$$

where M is the rate of metabolic heat production, W the external work performed by or on the body, K, C and R the loss or gain of heat by conduction, convection and radiation, E the evaporative heat loss from the skin and respiratory tract and S the rate of change in the store of body heat (= 0 at thermal equilibrium).

Respiratory heat loss (RES) occurs in cool environments because expired air is warmer and has a higher absolute humidity than inspired air. For a person expending energy at 400 $W.m^{-2}$ in an air temperature of minus 10°C, the RES will be about 44 W (25 $W.m^{-2}$). For normal indoor activities (seated/standing) in 20°C ambient temperature, the heat loss by respiration is small (2 to 5 $W.m^{-2}$) and hence is sometimes neglected.

1.3.1 Metabolic heat production (M)

The human body may be considered to be a chemical engine, and foods with different energy content, the fuel. At rest, some of the chemical energy of food is transformed into mechanical work *eg* in the heart beat and respiratory movements. This accounts for less than 10% of the energy produced at rest, the remainder being used in maintaining ionic gradients in the tissues and in chemical reactions in the cells, tissues and body fluids. All this energy is ultimately lost from the body in the form of heat and the balance of intake and loss maintained during daily physical activity. In general, energy intake from food balances energy expenditure, except in those cases where body weight is changing rapidly. In the absence of marked weight changes, measurement of food consumption may be used in assessing habitual activity or energy expenditure, though in practice, energy balance is only achieved over a period of more than one week.

Energy released in the body by metabolism can be derived from measurements of oxygen consumption using indirect calorimetry (see BS EN 28996: 1994; Determination of metabolic heat production). The value of metabolic heat production in the basal state with complete physical and mental rest is about 45 $W.m^{-2}$ (*ie* per m^2 of body surface area) for an adult male of 30 years and 41 $W.m^{-2}$ for a female of the same age. Maximum values are obtained during severe muscular work and may be as high as 900 $W.m^{-2}$ for brief periods. Such a high rate can seldom be maintained and performance at 400-500 $W.m^{-2}$ is very heavy exercise but an overall rate that may be continued for about one hour. Metabolic heat is largely determined by muscle activity during physical work but may be increased at rest in the cold by involuntary muscle contractions during shivering.

In the heat balance equation given previously, $M - W$ is the actual heat gain by the body during work, or $M + W$ when negative work is performed. In positive work, some of the metabolic energy appears as external work so that the actual heat production in the body is less than the metabolic energy produced. With negative work *eg* 'braking' while walking downstairs, the active muscle is stretched instead of shortening so that work is done by the external environment on the muscles and appears as heat energy. Thus the total heat liberated in the body during negative work is greater than the metabolic energy production.

1.3.2 Conduction (K) and Insulation (I)

Heat is conducted between the body and static solids or fluids with which it is in contact. The rate at which heat is transferred by conduction depends on the temperature difference between the body and the surrounding medium, the conductance (k) and the area of contact. This can be expressed as

$$K = k\,(t_1 - t_2)$$

where K is the heat loss in watts per surface area of the body ($W.m^{-2}$), t_1 and t_2 the temperatures of the body and environment respectively (°C), and k is a constant, conductance ($W.m^{-2}.°C^{-1}$).

In considering conductance at the body surface it is usually more convenient to refer to insulation (I), the reciprocal of k, where I is a measure of resistance to heat flow ($m^2.°C.W^{-1}$).

For the human body there are three different components of I. I_{ti} is the insulation of the tissues affecting the flow of heat from the core at a temperature t_{co} to the skin at temperature t_{sk}, and I_{cl} and I_a the insulation of clothing and air affecting the heat flow from the skin to air at temperature t_a.

An arbitrary unit of insulation, the clo, is used for assessing the insulation value of clothing. By definition 1.0 clo is the insulation provided by clothing sufficient to allow a person to be comfortable when sitting in still air at a temperature of 21°C. 1.0 clo is equivalent to an I_{cl} of 0.155 $m^2.°C.W^{-1}$. Examples of typical clothing insulation values are given in Table 1.1.

Table 1.1

Basic insulation values, I_{cl}, of a range of clothing ensembles (adapted from Fanger, 1970)

For full listings of ensembles and individual garments see BS ISO 9920: 1995

Clothing ensemble	**I_{cl} (clo)**
Nude	0
Shorts only	0.1
Light summer clothing	0.5
Typical indoor clothing	1.0
Heavy business type suit	1.5
Business clothes, overcoat plus hat	2.0
Polar weather suit	3 to 4

When a person is fully vasoconstricted, I_{ti} is about 0.6 clo. When fully vasodilated at rest in the heat I_{ti} falls to 0.15 clo and when exercising hard in the heat it may fall to about 0.075 clo. These figures show that increasing tissue insulation by vasoconstriction can play only a small part relative to clothing in protecting an individual against cold, but decreased tissue insulation significantly helps the loss of heat in a hot environment. The amount of subcutaneous fat is an important variable determining cooling rate by tissue insulation and it is especially effective in cold water immersion. The thermal conductance of 10 mm thickness of freshly excised human fat tissue is reported to be 16.7 $W.m^{-2}.°C^{-1}$ (Beckman, Reeves and Goldman, 1966). The thickness and distribution of the subcutaneous layer of fat differs from person to person, but for a mean thickness of 10 mm the insulation value would be equivalent to 0.96 clo.

1.3.3 Convection (C)

Normally, the surface temperature of a person is higher than that of the surrounding air so that heated air close to the body will move upwards by natural convection as colder air takes its place. The expression for heat exchange by convection is similar to that for conduction and is given by

$$C = h_c (t_1 - t_2)$$

where C is the convection loss per unit area, h_c is the convective heat transfer coefficient and t_1 and t_2 the temperature of the body surface and the air respectively. The value of h_c depends on the nature of the surrounding fluid and how it is flowing. Natural (free) convection applies in most cases when the relative air velocity is < 0.1 $m.s^{-1}$. The transfer coefficient depends then on the temperature difference between clothing (t_{cl}) and air (t_a) (in °C) as given (in units of $W.m^{-2}.°C^{-1}$) by

$$h_c = 2.38\ (t_{cl} - t_a)^{0.25}$$

Relative air velocity is increased when the arms or legs are moved through the environment as for example in walking. The convective heat transfer coefficient is increased further when air movement induced by a fan or draught causes forced convection. For forced convection over a range of air speeds up to 4 $m.s^{-1}$ the best practical value for the mean convective heat transfer coefficient is given by

$$h_c = 8.3\ (v)^{0.5}$$

where v = air velocity in $m.s^{-1}$.

1.3.4 Radiation (R)

Radiant heat emission from a surface depends on the absolute temperature T (in Kelvin, K *ie* °C + 273) of the surface to the fourth power *ie* proportional to T^4. The radiation transfer, R, (in $W.m^{-2}$) between similar objects 1 and 2 is then given by the expression

$$R = \sigma\, \varepsilon\, (\, T_1^4 - T_2^4\,)$$

where σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}\ W.m^{-2}.K^{-4}$) and ε is the emissivity of the objects.

An approximation is often permissible where the rate of heat transfer between surfaces is related to their temperature difference and the first power of this difference may then be used in the same form as that for heat transfer by conduction and convection

$$R = h_r (t_1 - t_2)$$

where R is radiant heat transfer per unit area, h_r the radiant heat transfer coefficient and t_1 and t_2 the temperatures of the two surfaces. h_r depends on the nature of the two surfaces, their temperature difference and the geometrical relationship between them.

For many indoor situations the surrounding surfaces are at a fairly uniform temperature and the radiant environment may be described by the mean radiant temperature (see also Section 6.2.2). The radiant heat exchange between the body surface area (clothed) and surrounding surfaces in $W.m^{-2}$ is given by

$$R = \sigma\, \varepsilon\, f_{eff}\, f_{cl}\, [\, (t_{cl} + 273)^4 - (t_r + 273)^4\,]$$

where ε is the emissivity of the outer surface of the clothed body; f_{eff} is the effective radiation area factor *ie* the ratio of the effective radiation area of the clothed body to the surface area of the clothed body; f_{cl} is the clothing area factor *ie* the ratio of the surface area of the clothed body to the surface area of the nude body; t_{cl} is the clothing surface temperature (°C) and t_r the mean radiant temperature (°C).

The value of f_{eff} is found by experiment to be 0.696 for seated persons and 0.725 for standing persons. The emissivity for human skin is close to 1.0 and most types of clothing have an emissivity of about 0.95. These values are influenced by colour for short wave radiation such as solar radiation.

The mean radiant temperature t_r is defined as the temperature of uniform surrounding surfaces which will result in the same heat exchange by radiation from a person as in the actual environment. The mean radiant temperature is estimated from the temperature of the surrounding surfaces weighted according to their relative influence on a person by the angle factor between the person and the radiating surface. t_r is therefore dependent on both a person's posture and their location in a room.

1.3.5 Evaporation (E)

At rest in a comfortable ambient temperature an individual loses weight by evaporation of water diffusing through the skin (insensible cutaneous water loss) and from the respiratory passages (RES). Total insensible water loss in these conditions is approximately 30 $g.h^{-1}$. Water diffusion through the skin will normally result in a heat loss equal to approximately 10 $W.m^{-2}$.

The latent heat of vaporisation of water is 2453 $kJ.kg^{-1}$ at 20°C and a sweat rate of 1 litre per hour will dissipate about 680 W. This value of heat loss is only obtained if all the sweat is evaporated from the body surface; sweat that drips from the body is not providing effective cooling.

Evaporation is expressed in terms of the latent heat taken up by the environment as the result of evaporative loss and the vapour pressure difference which constitutes the driving force for diffusion

$$E = h_e (p_{sk} - p_a)$$

where E is the rate of heat loss by evaporation per unit area of body surface ($W.m^{-2}$), h_e the mean evaporation coefficient ($W.m^{-2}. kPa^{-1}$) and p_{sk} and p_a the partial pressures of water vapour at the skin surface and in the ambient air (kPa).

The direct determination of the mean evaporation coefficient (h_e) is based on measurement of the rate of evaporation from a subject whose skin is completely wet with sweat. Since the production of sweat is not even over the body surface this requires that total sweat rate must exceed evaporative loss by a considerable margin - a state that is difficult to maintain for any length of time.

Air movement (v) and body posture are also important in making the measurement, and in surveying the results of various researchers, Kerslake (1972) recommended that for practical purposes h_e (in units of $W.m^{-2}.kPa^{-1}$) be represented by

$$h_e = 124 (v)^{0.5}$$

for v in the range 0.1 to 5.0 $m.s^{-1}$.

If the actual rate of evaporation E_1 is less than the maximum rate possible E_{max}, at the prevailing h_e, p_{sk} and p_a, the ratio E_1/E_{max} can be used as a measure of skin wettedness. The skin surface may be considered as a mosaic of wet and dry areas. With a wettedness value of 0.5 the rate of evaporation achieved would be equivalent to half the skin surface being covered with a film of water, the other half being dry. For insensible cutaneous water loss the value is about 0.06 and at the maximum value 1.0 the skin is fully wet.

1.3.6 Heat storage (S)

The specific heat of the human body is 3.5 kJ.kg^{-1}. If a 65 kg individual has a change in mean body temperature of 1°C over a period of 1 h, the rate of heat storage is 230 kJ.h^{-1}, or 64 W. In the equation for thermal balance (Section 1.3), S can be either positive or negative, but in determining storage the difficulty is to assess the change in mean body temperature. The change in mean deep body temperature alone is not acceptable because of the different weightings contributed by the core and shell.

Various formulae have been suggested to combine measurements of skin and core temperature to give a mean body temperature *eg*

$0.90\ t_{core} + 0.10\ t_{skin}$ in hot conditions and

$0.67\ t_{core} + 0.33\ t_{skin}$ in cold conditions.

The volume of the warm core during vasoconstriction in cold surroundings is effectively reduced thereby altering the weighting coefficients.

1.3.7 Interpretation of core temperature

Reference has been made in Section 1.2.3. to the limiting values of core temperature which are regarded as 'safe' in adverse temperature conditions *eg* in the heat, 38.0°C is usually stated as the body temperature at which work should cease. In practice, there are usually two principal situations which lead to raised core temperature.

(a) Extreme heat stress.

Extreme heat stress due to hot environmental conditions when little physical work is performed (environmental heat stress). Core temperature (t_c) might eventually reach 38°C when mean skin temperature (t_{sk}) has risen to perhaps 35°C or higher. Under these conditions, maximum sweating (E_{max}) is achieved as the result of the combined central nervous drive from high t_c and high t_{sk}.

(b) Exertional heat strain.

In work situations in cooler climates, physical activity often provides the main stimulus to increasing the t_c (exertional heat strain). Under these circumstances, t_c may also reach 38°C because of a high internal heat production, but the mean skin temperature may not rise higher than, say, 28°C because of skin cooling brought about by sweating in a cool environment. In this case the drive to produce E_{max} may not have been reached and this may safely allow a limiting t_c of 38.5 to 39.0°C.

1.4 Thermal Imbalance

If the human body is not able to maintain a balance of heat flows then over a period of time the core temperature will rise or fall from the steady state value and lead to heat stress or cold stress effects. These are described in Chapters 4, 5 and 11. Alternatively, sudden changes in localised temperatures can lead to localised damage to the body, as described in Chapter 7.

Chapter 11 also discusses the effects of chemicals (*ie* drugs) on the thermoregulation mechanism.

2 CLIMATE AND THE BUILT ENVIRONMENT

2.1 Introduction

A wide range of climates exists on our planet. Conditions are such as to have allowed life forms to evolve and occupy many regions of the Earth. The typical extremes of conditions experienced range in temperature from -50°C to +50°C. Human beings evolved initially in relatively warm climates, but they now occupy large areas of the planet.

For humans to survive and function efficiently and successfully they must invariably provide for themselves some form of protection from the prevailing 'weather' conditions. Long-term protection is created in the form of built enclosures. Simple buildings provide 'passive' temperature control internally, by smoothing out external temperature fluctuations and providing physical protection from the sun, wind and precipitation. 'Active' control may also be introduced through heating and/or cooling systems, allowing 'artificial climates' to be generated within buildings (*eg* Weller and Youle, 1981).

Clothing or protective suits provide the same type of function at a different level of control.

2.2 Climate

In order to provide appropriate internal conditions, designers of buildings must first establish the extremes and variations that are likely to occur in external conditions, *ie* the local climate. Of particular concern are the maxima and minima in air temperature and the variations of solar intensity, both on a daily and seasonal basis.

Standard meteorological data are usually available for most parts of the world enabling these basic external design conditions to be established (*eg* CIBSE, 1987).

As an example, for the southern part of the UK, the design external air temperature for winter heating requirements is usually taken as –1°C for buildings heated during the day only, and –5°C for those with 24 hour heating. In summertime the design external maximum air temperature is usually taken as 28°C (with 55% relative humidity). Standard solar data are also available but the effect on the building performance is dependent on many factors such as the orientation, form, fabric and areas and types of glazing.

The extremes in external conditions will influence the performance requirements of both the building fabric and the heating/cooling systems in order to provide a stable internal thermal environment.

Buildings are not usually designed to cope with the extreme upper and lower annual peaks in external conditions, and therefore internal conditions may fall outside the specified parameters for some of the time. For instance, again for the UK, statistical data indicate that summer external air temperatures will exceed 24°C for 2.5% of the time (*ie* 9 days per year) and 28°C for 1% of the time (*ie* 3 days per year). Hence, depending on the design parameters selected, internal temperatures may exceed those specified on a certain number of occasions if there is no excess capacity in the cooling plant.

In some countries (*eg* Holland) standards are set for office buildings at their design stage limiting the maximum period for which comfort conditions are not achieved during occupancy, due to an inability of the building and/or its heating/cooling systems to cope with extreme external conditions. Typically this is a total of a certain number of hours per annum on both the hot side and cold side of comfort. These standards are applied *via* approved computer simulation models of the building whilst it is still on the drawing board. This approach is currently the subject of a new ISO work item relating to standards for thermal environments.

Possible climatic changes taking place on a relatively short term basis (*eg* global warming through the 'green-house' effect) may alter the extremes of temperature that have to be tolerated in the climate in general, and controlled by buildings. Existing building stock may be deficient in this respect.

2.3 Building Enclosure

Heat transfer through the building fabric is governed by the thermal insulation or 'U-value' of the fabric. Maximum U-values for different building types (*ie* giving maximum heat or energy loss values) are specified for the UK in the Building Regulations (see Chapter 9).

Thermal insulation will not only affect heat losses and energy running costs for a building, but will also govern internal surface temperatures. For instance, an uninsulated factory roof in winter time may have a surface temperature of only 10-12°C (with an internal air temperature of 16-18°C), with consequences to thermal comfort. If the roof is well insulated the surface temperature will be typically only 1°C less than the internal air temperature. The opposite effect can occur in summertime due to solar gain to the roof.

Areas of glazing are also limited by the Building Regulations, for reasons of heat loss. In summertime possible overheating due to solar gain into buildings is governed particularly by the area, orientation and type of glazing (*eg* CIBSE, 1987). Additional solar control can be provided by temporary or fixed shading devices, preferably external to the building. Internal shading systems such as blinds can protect personnel from the direct effects of solar radiation (including glare) but the space as a whole will have received the thermal gain, potentially leading to general overheating.

The mass of a building, combined with thermal insulation (and the position of the insulation within the construction) will affect the rate of change of internal temperature conditions. For instance, a cathedral responds very slowly to changes, a wooden hut quickly. The mass may be increased significantly by stored products as in a warehouse. Lightweight buildings such as modern offices with insulating internal finishes (*eg* carpets and fabrics) may fluctuate rapidly in temperature, especially when influenced by solar gain, with consequences to the comfort and stress of occupants. In recent years the widespread introduction into existing offices of computing equipment, with associated heat output (typically 10-120 $W.m^{-2}$ floor area), has contributed to tipping the balance in relation to the incidence of summertime overheating. Solutions to overcome such problems can be complex and expensive.

The movement of air through the building fabric, either as natural ventilation or air leakage, will also affect conditions. The 'air tightness' of construction (with respect to external wind conditions) is important in terms of minimising unwanted air passage and heat losses. In recent years, for reasons of energy consumption, more emphasis has been placed on such factors, but with possible consequences to resulting internal ventilation rates.

The ability of a building to provide acceptable internal conditions (thermally and for ventilation) without the consumption of energy from fuels, *ie* by harnessing natural (or ambient) energy *eg* from the sun and wind, is generally known as 'passive' control. Environmental and energy conservation pressures have led to particular interest and development of such 'passive' means, attempting to reduce reliance on 'active' measures.

2.4 Active Control

Although a building may be able to provide a certain degree of passive control, invariably for some (or even all) of the time it is necessary to consume energy in heating, cooling and/or ventilation systems to provide full control of internal thermal conditions. This may be for the needs of occupants or for control of processes (*eg* electronics or pharmaceuticals production) or stored items (*eg* food). Typically, conditions for occupancy are specified to ±2°C, *eg* 22°C°±2°C. Conditions may drift within the range depending on the season. Humidity may also require to be controlled for general health and comfort reasons; too low a relative humidity (*eg* <30%) can lead to drying of mucous membranes and raised dust levels resulting in irritation of eyes and throat; too high a value (*eg* >70%) can lead to mould growth, condensation and associated health issues. For processes, control may require to be more stringent than for people *eg* to ±1.0°C or ±0.5°C, with relative humidity to *eg* ±5% with a set point of 50%.

Modifying the temperature in buildings can be achieved by altering the air temperature or radiant conditions (*ie* surface temperatures) or a combination of both. Heating systems can operate either principally by air temperature control *eg* a fan convector, or principally by radiant control *eg* high temperature element such as an electric bar fire or radiant strip heater, or by a combination of both *eg* a conventional hot water 'radiator/convector'. Cooling systems usually rely on altering the air temperature, although some systems (*eg* chilled ceilings) affect mainly the radiant conditions.

Heating/cooling systems may also be used to control ventilation, air movement and air quality, together with relative humidity. A system which provides full control (*ie* of heating, cooling, humidity and ventilation) is usually described as 'full air conditioning'.

Control of air quality is normally confined to varying the proportion of fresh air to recirculated air, and filtering the air of particulate matter by fabric filtration (to whatever standard is required).

Removing gas/vapour contaminants is not normally undertaken as it is a relatively complex and costly process.

General issues relating to conditions in buildings and health of occupants have recently been reviewed by the UK Building Research Establishment, BRE (1995). The significance of the health risks involved are compared; thermal conditions (termed 'hygrothermal') are midway in the risk hierarchy.

2.5 Sizing of Systems and Control

The sizing of cooling systems is often a less precise procedure than the sizing of heating equipment, as the size of heat gains can be difficult to predict precisely. There are a number of sources of gains: external conditions, particularly solar radiation; internal artificial lighting; people; and equipment, in particular process plant or office equipment. Total gains may exceed 100 $W.m^{-2}$ floor area, but they may vary as the use of the building varies.

The maximum requirement for heating, on the other hand, is taken for an unoccupied building at the design winter external conditions, a typical value being 30-40 $W.m^{-2}$ floor area (excluding ventilation losses). When the building is being used, internal gains contribute to heating and the control systems should hence reduce the heat output from the heating system accordingly. The main uncertainties in sizing heating plant are in determining the ventilation losses, and in establishing excess plant capacity required for the heat-up period *ie* bringing the building up to occupancy temperature within a reasonable time particularly after a weekend or holiday period.

It is important that adequate control of active systems is incorporated to ensure that conditions are maintained reasonably stable (*eg* to ±1.5°C for comfort conditions). Energy conservation and the need to reduce fuel consumption have led to rapid developments and increased complexity of control systems in recent years. This in turn has led to greater potential for incorrect or faulty performance. Hence, if temperature conditions are considered inappropriate in a building, then control systems should always be checked as a first priority.

The number and positioning of internal temperature sensors for space temperature control are important in terms of achieving uniform and appropriate temperatures throughout a space. Consideration should be given to whether users should have individual control of conditions, or whether there should be an overall control system. The former is generally considered to provide greater user satisfaction, but is likely to be more complex and costly to install and may lead to greater energy consumption. Future likely change of use or layout of space may also need to be taken into account.

Control systems provide the key to successful operation of heating/cooling plant, but can be the source of unsatisfactory conditions leading to complaints and dissatisfaction. Further discussions on these aspects appear in Section 3.4.

The task of ensuring that commercial buildings provide appropriate conditions for occupants in all aspects of comfort falls within the remit of the buildings or estates facilities manager, see *eg* Park (1994).

3 THERMAL COMFORT

3.1 Subjective Evaluation

Asking people how warm they feel must be one of the most prevalent forms of psychophysical activity. In studies of the thermal environment, it is normal practice to assess individual reaction by asking the respondents to indicate their thermal sensation on a rating scale which consists of a number of named categories; the Bedford (rating sensation and comfort) and modified ASHRAE (thermal sensation) 7 point scales are the most widely and frequently used and are illustrated in Table 3.1.

Table 3.1
The Bedford and modified ASHRAE seven-point scales
(Chrenko, 1974; ASHRAE, 1993)

Bedford Scale		**ASHRAE Scale**	
Much too warm	7	Hot	+3
Too warm	6	Warm	+2
Comfortably warm	5	Slightly warm	+1
Comfortable	4	Neutral	0
Comfortably cool	3	Slightly cool	–1
Too cool	2	Cool	–2
Much too cool	1	Cold	–3

These two scales are similar and, in general, are not affected by immediately previous thermal experience.

Field studies of warmth using seven point scales show a wide range of neutral temperatures in different climates, in contradiction to the invariance of group preferred temperature found in chamber studies. It has been demonstrated that the centre point of the scale (neutral) is not necessarily the preferred temperature. In general, people in cold climates prefer a temperature sensation which they describe as on the warm side of neutral, while people in warm climates prefer a sensation on the cool side of neutral. These findings help in reconciling the apparently contradictory findings of different experimental techniques. A warmth vote is not a physical quantity like temperature and the measurement of sensation is by no means straightforward.

The categories of the scale are assigned numbers, which conventionally run from 1 to 7 or from –3, through 0, to +3. Logically, the symmetrical scale is better, but since the use of negative numbers sometimes causes confusion, there is good practical argument for using the 1 to 7 scale. The purpose of assigning numbers to the warmth votes is so that statistical analysis may be carried out; regression analysis is the most widely practised technique for dealing with the variation of warmth vote with temperature. Scales of warmth are not, however, ratio scales; it cannot be said that a vote of 3 implies a sensation 3 times stronger than a vote of 1.

Different people give different warmth votes from each other (even in identical environmental conditions) due to normal biological variation and if the voting is repeated at a later time, the individual may give a different vote on the second occasion. It is this scatter of voting that necessitates the use of statistical analysis to disentangle the effects of physical variables from the random variations produced by people themselves. The votes obtained at given temperatures can be plotted as a frequency distribution where it is found that they follow the well-known Gaussian distribution curve (Fishman and Pimbert, 1982).

Seven point semantic differential scales have also been used. These are 7 point scales with only the end points named, *eg* hot (7) and cold (1). The subject is asked to choose the number between 1 and 7 that best describes his or her feelings at that moment in time. The regression of vote on temperature produces a lower correlation coefficient than either of the two named scales and the semantic differential scale seems to have no advantages over the conventional category scales.

A variation on the seven point scale is shown in Table 3.2. A 6 cm vertical line is marked with 7 equal divisions, each of which is labelled with the appropriate ASHRAE scale name.

Table 3.2
Continuous form of the ASHRAE scale
(reduced to half scale)

How do you feel at this moment?

Hot
Warm
Slightly warm
Neutral
Slightly cool
Cool
Cold

Put a mark anywhere on the line to describe your thermal sensation

Subjects respond by placing a mark at a point on the line corresponding to their thermal comfort vote. They are thus free to vote at any point on the line and can indicate small changes in thermal sensation. These continuous forms of the warmth scale are particularly useful when dealing with only small changes of sensation.

Further information can be obtained if subjects are asked their preference on a 3-point scale:

I would like to be:

Warmer No change Cooler

This is asked in addition to the Bedford scale and has an advantage of avoiding any confusion over which of the three central categories of the seven point scale are preferable.

The execution of a survey requires extreme care, especially where subjective responses are involved. Questions should always be as specific as possible, *eg*

> ***'Do you have a cold now?'*** is a better question than,
>
> ***'Do you suffer from colds?'*** which in turn is better than,
>
> ***'Does the air conditioning give you colds?'***

Questionnaires should be clear and unambiguous. If the questionnaire is to be administered, staff must be well trained so as not to influence the results by asking leading questions or by misinterpreting the answers given. It is always better if they are unaware of the purpose of the investigation (*ie* double-blind study).

A further method of obtaining subjective responses is by the use of an individual diary or log, whereby the individual records at regular intervals, over a period of time, answers to a set of standard questions, responses to scales of warmth or other relevant observations. Such questionnaires require very careful design, but have the advantage that the replies provide detailed information over a period of time and may be coded for subsequent computer analysis. They are of particular value for use in field observations.

3.2 Examples of the Use of Subjective Scales

It is often useful, in the ergonomic assessment of thermal environments, to complement objective assessments of individuals' thermal environments which are based on physical measures such as air temperature *etc* with subjective measures; see, for example, BS EN ISO 7730: 1995: 'Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort'. (PMV, Predicted Mean Vote, and PPD, Predicted Percentage Dissatisfied, are terms based on subjective responses from individuals, as will be described below.) This approach has the advantage of providing information directly from the working population of interest about such things as thermal sensation, comfort, satisfaction *etc*. The design of the subjective scales will depend upon the specific areas of application. There are however a number of principles which can usefully be followed and it is helpful to have examples of subjective forms which have been successfully used in practice.

Forms 1 and 2, which are illustrated below, were designed to supplement objective data which involved measuring the physical environment and using procedures for assessing its suitability for workers. The forms were not meant to be detailed questionnaires, and in both studies more detailed questionnaires were used in an overall assessment of the working environments.

3.2.1 Form 1

Form 1 was used in a moderate office environment where employees had been complaining about general working conditions. The assessment of the thermal environment formed part of an overall environmental ergonomics study. Details about individuals characteristics, location *etc* were collected separately. The thermal environment was assessed by the method described in BS EN ISO 7730 and the form was handed to workers for completion at their workplace.

In Form 1:

Question 1: Determines the worker's sensation vote on the ASHRAE scale. (Note that this can be compared directly with the measured PMV as described in BS EN ISO 7730, Section 3.3.1).

Question 2: Provides an evaluative judgement. For example, Question 1 determines subject's sensation (*eg* warm). Question 2 compares this sensation with how the subject would like to be.

Questions 3 & 4: Provide information about how workers generally find their thermal environment. This is useful where it is not practical to survey the environment for long periods.

Questions 5 & 6: Are catch-all questions about worker satisfaction and any other comments. Answers to these questions will provide information about whether more detailed investigation is required. Answers will also indicate factors which are obvious to the workers but not obvious to the investigator.

Form 1

Please answer the following questions concerned with YOUR THERMAL COMFORT.

1. **Indicate on the scale below how you feel NOW.**

Hot
Warm
Slightly Warm
Neutral
Slightly Cool
Cool
Cold

2. Please indicate how you would like to be NOW.

Warmer　　No change　　Cooler

3. Please indicate how you GENERALLY feel at work:

Hot
Warm
Slightly Warm
Neutral
Slightly Cool
Cool
Cold

4. Please indicate how you would GENERALLY like to be at work:

Warmer　　No change　　Cooler

5. Are you generally satisfied with your thermal environment at work?

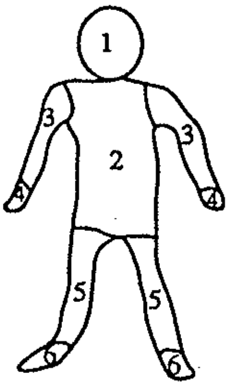
Yes　　No

6. Please give any additional information or comments which you think are relevant to the assessment of your thermal environment at work (*eg* draughts, dryness, clothing, suggested improvements *etc.*)

Thank you

Form 2

Please answer the following questions concerned with YOUR THERMAL COMFORT.



1. With reference to the above diagram please indicate on the scales below how you feel NOW.

	OVERALL	HEAD 1	TRUNK 2	ARMS 3	HANDS 4	LEGS 5	FEET 6
Very Hot							
Hot							
Warm							
Slightly Warm							
Neutral							
Slightly Cool							
Cool							
Cold							
Very Cold							

2. Please indicate how you would like to be NOW.

   Warmer   No change   Cooler

3. Are you generally satisfied with your thermal environment?

   Yes   No

4. Please give any additional information or comments which you think are relevant to the assessment of your thermal environment at work (*eg* draughts, dryness, clothing, suggested improvements *etc.*)

Thank you

3.2.2 Form 2

Form 2 was used in a cold environment. The suitability of clothing and working practices in cold environments was investigated as part of an ergonomics assessment of the working environment. It may be noted that physiological measures (including mean skin and core temperatures) were also measured in this study.

In Form 2:

Question 1: Determines the worker's sensation vote overall and for six areas of the body.
The nine point scale allows the extremes of 'very hot' and 'very cold' to be recorded. It is particularly important in cold environments to record sensation votes at the extremities (hands and feet).

Question 2: Provides an overall evaluative judgement.
It allows comparison of the worker's sensation with how he would like to be.

Questions 3 & 4: Are catch-all questions about worker's satisfaction and other comments.
Answers to these questions will provide information about whether or not more detailed information is required. Answers will also indicate factors which are obvious to workers but not obvious to the investigator.

3.3 Thermal Indices

A useful tool for describing, designing and assessing thermal environments is the ***thermal index***. The principle is that factors that influence human response to thermal environments are integrated to provide a single index value. The aim is that the single index value varies as human response varies and can be used to predict the effects of the environment.

The principal factors that influence human response to thermal environments are:

- air temperature,
- radiant temperature,
- air velocity,
- humidity and
- the clothing and activity of the individual.

A comprehensive thermal index will integrate these factors to provide a single index value. Numerous thermal indices have been proposed for assessing heat stress, cold stress and thermal comfort. The indices can be divided into three types, rational, empirical and direct.

3.3.1 Rational thermal indices

Rational thermal indices use the principle of heat balance which has been employed widely in methods for assessing human response to hot, neutral and cold environments. If a body is to remain at a constant temperature then the heat inputs to the body need to be balanced by the heat outputs.

Heat transfer can take place by:

- conduction (K),
- convection (C),
- radiation (R) and
- evaporation (E).

In the case of the human body an additional heat input to the system is the metabolic heat production (M) generated within the body.

Using the above, the following body heat equation can be proposed (see also Section 1.3 which expresses the equation in a different form):

$$M \pm K \pm C \pm R - E = S$$

If the net heat storage (S) is zero then the body can be said to be in heat balance and hence internal body temperature can be maintained. The analysis requires the values represented in this equation to be calculated from a knowledge of the physical environment, clothing, activity, *etc.* Rational thermal indices use heat transfer equations (and sometimes mathematical representations of the human thermoregulatory system) to 'predict' human response to thermal environments.

A comprehensive mathematical and physical appraisal of the heat balance equation represents the approach taken by Fanger (1970) which is the basis of ISO Standard BS EN ISO 7730: 1995 'Moderate thermal environments- Determination of the PMV and PPD indices and specification of the conditions for thermal comfort'. The purpose of this Standard is to present a method for predicting the thermal sensation, Predicted Mean Vote (PMV), and the degree of discomfort (thermal dissatisfaction), Predicted Percentage Dissatisfied (PPD), of people exposed to moderate thermal environments and to specify acceptable thermal environmental conditions for comfort.

This International Standard applies to healthy men and women. It was originally based on studies of North American and European subjects but also agrees well with recent studies of Japanese subjects exposed to moderate thermal environments. The Standard is expected to apply with good approximation in most parts of the world, but ethnic and national-geographic deviations may occur and require further studies. The Standard applies to people exposed to indoor environments where the aim is to attain thermal comfort, or indoor environments where moderate deviations from comfort occur. In extreme thermal environments other International Standards apply (see Chapters 4 and 5). Deviations may occur for sick and disabled people. The present International Standard may be used in the design of new environments or in assessing existing ones. The Standard has been prepared for working environments but can be applied to any kind of environment.

BS EN ISO 7730: 1995 provides a method of assessing moderate thermal environments using the PMV thermal comfort index, Fanger (1970). The PMV is the Predicted Mean Vote of a large group of persons, if they had been exposed to the thermal conditions under assessment, on the +3 (hot) to –3 (cold) through 0 (neutral) scale, see Section 3.1.

The PMV is calculated from:

- the air temperature,
- mean radiant temperature,
- humidity and air velocity of the environment and
- estimates of metabolic rate and clothing insulation.

The PMV equation involves the heat balance equation for the human body and additional conditions for thermal comfort. The PPD index is calculated from the PMV and provides the Predicted Percentage of thermally Dissatisfied persons. The Annex of the Standard gives recommendations that the PMV should lie between –0.5 and +0.5, giving a PPD of less than 10%.

Tables and a computer program are provided in BS EN ISO 7730 to allow ease of calculation and efficient use of the standard. This rational method for assessing moderate environments allows identification of the relative contribution different components of the thermal environment make to thermal comfort (or discomfort) and hence can be used in environmental design. It is important to remember that this Standard standardises the *method* and not the *limits*. The recommendations made for thermal comfort conditions are produced in an annex which is for information and not part of the standard.

Heat balance is not a sufficient condition for thermal comfort. In warm environments sweating (or skin wettedness), and in cold environments mean skin temperature, must be within limits for thermal comfort. Rational predictions of the body's physiological state can be used with empirical equations which relate mean skin temperature, sweat rate and skin wettedness to comfort. Recommendations for limits to air movement, temperature gradients, *etc* are given in BS EN ISO 7730 (see also Section 3.3.5).

3.3.2 Empirical indices

Empirical thermal indices are based upon data collected from human subjects who have been exposed to a range of environmental conditions. Examples are the Effective Temperature (ET) and Corrected Effective Temperature (CET) Scales. These scales were derived from subjective studies on US marines; environments providing the same sensation were allocated equal ET/CET values. These scales take into account dry bulb/globe temperature, wet bulb and air movement; two levels of clothing are considered (*eg* Chrenko, 1974).

For this type of index, the index must be 'fitted' to values which experience predicts will provide 'comfort'.

3.3.3 Direct indices

Direct indices are measurements taken on a simple instrument which responds to similar environmental components to those to which humans respond. For example a wet, black globe with a thermometer placed at its centre will respond to air temperature, radiant temperature, air velocity and humidity. The temperature of the globe will therefore provide a simple thermal index which with experience of use can provide a method of assessment of hot environments. Other instruments of this type include the temperature of a heated ellipse and the integrated value of wet bulb temperature, air temperature and black globe temperature (WBGT).

An engineering approach employing what is known as the dry resultant temperature (CIBSE, 1987) is to use simply the equilibrium temperature of a 100 mm globe thermometer placed in the environment. The temperature of the globe approximates to an average of the air temperature and mean radiant temperature. The index needs to be corrected for air movement greater than 0.1 $m.s^{-1}$, and assumes that relative humidity lies in the range 40–60%.

A review of indices is given in McIntyre (1980) and Parsons (1993).

3.3.4 Selection of appropriate thermal indices

A first step in the selection of a thermal index is to determine whether a heat stress index, comfort index or cold stress index is required. There are numerous thermal indices and most will provide a value which will be related to human response (if used in the appropriate environment). An important point is that experience with the use of an index should be gained in a particular industry. A practical approach is to gain experience with a simple direct index; this can then be used for day to day monitoring. If more detailed analysis is required a rational index can be used (again experience should be gained in a particular industry) and if necessary subjective and objective measurements can be taken.

3.3.5 Thermal comfort/discomfort

Thermal discomfort can be divided into whole-body discomfort and local thermal discomfort (*ie* of part of the body). Thermal comfort is subjective and has been defined by ASHRAE as 'that condition of mind which expresses satisfaction with the thermal environment'. Comfort indices relate measures of the physical environment to the subjective feelings of sensation comfort or discomfort.

It is generally accepted that there are three conditions for whole-body thermal comfort. These are that the body should be in heat balance, and that the sweat rate (or skin wettedness) and the mean skin temperature are within limits for comfort. Rational indices such as the predicted mean vote (PMV - BS EN ISO 7730) use the criteria to allow predictions of thermal sensation. In many instances a simple direct index, such as the temperature of a black globe, will be sufficient. The dry resultant temperature is related to this.

BS EN ISO 7730 considers issues relating to local thermal discomfort, such as vertical temperature gradients and radiation asymmetry. Recommended values are given in the Annex of the Standard to limit these effects. Discomfort caused by draught is also examined. Draught is defined as an unwanted local cooling of the body caused by air movement. A method for predicting the percentage of people affected by draught is provided in terms of air temperature, air velocity and turbulence intensity (*ie* a measure of the variation of air movement with time). The model applies over a specified range of thermal conditions and for people performing light, mainly sedentary activity, with a thermal sensation for the whole body close to neutral.

Guidance is provided on how to determine acceptable thermal conditions for comfort based on the methods provided in the Standard.

The occurrence of such discomfort conditions often results from poor building design or inadequate design or control of mechanical services systems, see Section 3.4.

3.3.6 Subjective judgement scales

BS ISO 10551: 1995 'Assessment of the influence of the thermal environment using subjective judgement scales' provides a set of specifications on direct expert assessment of subjective thermal comfort/discomfort expressed by persons subjected to thermal stress. The methods supplement physical and physiological methods of assessing thermal loads.

Subjective scales are useful in the measurement of subjective responses of persons exposed to thermal environments. They are particularly useful in moderate environments and can be used independently or to complement the use of objective methods (*eg* thermal indices). This Standard presents the principles and methodology behind the construction and use of subjective scales and provides examples of scales which can be used to assess thermal environments. Examples of scales are presented in a number of languages.

Scales are divided into the five types illustrated by example questions:

- ***Perceptual*** - How do you feel now?
- ***Affective*** - How do you find it?
- ***Thermal preference*** - How would you prefer to be?
- ***Personal acceptance*** - Is the environment acceptable/unacceptable?
- ***Personal tolerance*** - Is the environment tolerable?

The principle of the Standard is to provide background information to allow ergonomists and others to construct and use subjective scales as part of the assessment of thermal environments. Examples of the construction, application and analysis of subjective scales are provided in the Annex to the standard.

3.3.7 Comfort standards; theory and practice

Thermal comfort has been defined as 'that condition of mind which expresses satisfaction with the thermal environment'. It is therefore a *psychological* phenomenon and not a *physiological* state. It will be influenced by individual differences in mood, personality, culture and other individual, organisational and social factors. It is not surprising, therefore, that methods for predicting thermal comfort conditions will never be perfect. Whether standard methods are, or will ever be, adequate, or universally acceptable and what their appropriate form should be, are continually debated topics.

An important issue to be addressed is whether present standardised methods for determining thermal comfort conditions are sufficient for practical application or, if methods are to be established for world wide use, a new approach or philosophy is required. Some researchers have called into question both the philosophy and accuracy of current international standards, methods and recommended limits. It is through such questioning that standards will be improved.

Thermal comfort has been the subject of much international research over many years. A great deal is known about principles and practice and some of the knowledge has been incorporated into international standards. These include BS EN ISO 7730. 'Moderate thermal environments - calculation of the PMV and PPD thermal comfort indices', and the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 55-1992, 'Thermal environmental conditions for human occupancy'. Such has been the acceptance and use of the standards that the observer could conclude that all questions concerning thermal comfort standards have been answered, and that neither laboratory nor field research is required.

However, many studies have demonstrated that knowledge is not complete and that problems have not been solved. People in buildings suffer thermal discomfort, and this is not a minor problem for the occupants of the buildings nor for those interested in productivity and the economic consequences of having a dissatisfied workforce. Is the problem because standards have not been correctly updated or are they not correctly used and there is a presentation and training issue? Maybe all of these apply. Field studies provide practical data but when designing buildings to provide thermal comfort, can we improve upon current standards? Are the standards applicable universally or do individual factors, regions and culture, for example, greatly influence comfort requirements? Are people more adaptable and/or less predictable than the standards suggest (depending on circumstances). Are we consuming more capital and running cost resources in buildings to provide recommended levels of thermal comfort than is really needed? If current standards are being brought into question, what can be used instead; guidance of some kind is required for building designers, owners and operators.

Issues relating to this debate were reviewed recently by the Building Research Establishment, UK (BRE, 1994) and at a conference in Windsor, England in 1994 (Nicol *et al*, 1995).

3.4 Control

Much attention has been concentrated in recent years on the 'quality' of internal environments, particularly offices (*eg* WHO, 1984; HSE, 1995). Buildings themselves and active control systems can influence conditions detrimentally (*eg* Youle, 1986). Those factors which are likely to influence the thermal conditions occurring within a space or building are described here. This is by no means a comprehensive treatment, but represents typical problem areas. Any one, or combination, of these factors may require attention to improve thermally unsatisfactory conditions (see also Sections 2.3 and 2.4).

It is likely that a range of personnel will be required for such investigations, in particular those responsible for the design, operation and maintenance of mechanical services plant (*ie* building services engineers).

3.4.1 Building fabric

The fabric of a building can influence thermal conditions in a number of ways:

- Poor thermal insulation will result in low surface temperatures in winter, and high values in summer, with direct effect on radiant conditions. Variations and asymmetry of temperature will also be influenced.

- Single glazing will take up a low internal surface temperature when it is cold externally causing potential discomfort and radiation asymmetry. The effects are reduced (but not eliminated) with double glazing.

- Cold down draughts from glazing (due to cold window surfaces) can be counteracted by the siting of heat emitters under glazing, or by installing double or triple glazing.

- Direct solar gain through glazing is a major source of discomfort. This can be reduced/controlled by for example:
    - modification of glazing type (*eg* 'solar control glass' or applied tinted film)
    - use of internal blinds (preferably of a reflecting colour); this provides localised protection for individuals, but the majority of the solar heat gain still enters the space
    - use of external solar shading devices (by far the most effective method).

It should be noted that the glazing itself may absorb heat and therefore rise in temperature causing an increase in mean radiant temperature. This is particularly relevant with 'solar control glasses'. Also use of such glass often means that internal natural lighting levels are reduced, leading to more use of artificial lighting and associated heat gain into the space, which could contribute to thermal discomfort.

- Unwanted air movement (and local low air temperatures) in winter time can arise from poor window and fabric seals, external doors, *etc*. Draught-proofing techniques can be employed to reduce this effect.

- The siting and nature of internal partitions can affect local conditions. If the interior of a space has high thermal mass (thermal capacity) then temperature fluctuations are reduced.

3.4.2 Heating systems

A range of factors needs to be checked to ensure that a heating system is designed and functioning appropriately. Advice from suitably qualified engineers may be required. Examples are:

- Overall output from central boiler plant or local output from heat emitters in individual spaces needs to match the building and its requirements.

- The position of heat emitters can assist in counteracting discomfort *eg* siting of radiators under windows counteracts cold window surfaces and cold down draughts.

- Poor siting can lead to radiation asymmetry and increased draughts.

- Noise (*eg* from fan units and grilles) can be a contributing nuisance factor.

- The heat output from emitters should be appropriately controlled. Control systems may vary from a simple thermostat in one room to multiple sensing systems and computer control throughout the building.

3.4.3 Ventilation systems (heating only)

When assessing a system pertinent points to note are:

- Identify air input grilles/diffusers to the room and check volume flow, velocity, circulation and distribution of supply air.

- Check the value of the supply air temperature. Note that increased air movement may mean higher air temperature requirements for given comfort conditions.

- Look for air temperature gradients, particularly arising from air distribution patterns. If the supply temperature is too high, buoyancy effects may lead to large temperature gradients, and poor supply air distribution.

- Air volumes : if ventilation is providing heating, then air volume flow (and air temperature) must be sufficient to counteract heat losses in the space.

- Ensure local adjustments in one area do not adversely affect adjacent areas or overall plant operation.

- Low values of relative humidity may result during winter heating. Humidification may be provided in central plant. If so, check that it is operating and being controlled correctly.

3.4.4 Air conditioning systems (heating, cooling and humidity control)

'Full air conditioning systems' can be very complex and sophisticated and it is likely that specialist expertise is required in their assessment. The types of point to be questioned or require checking are:

- What is the principle of operation? There are many types *eg*:

    Fixed air volume, variable temperature;
    Variable air volume (often referred to as VAV), fixed temperature;
    Fan assisted terminals;
    Fan coil unit - local control;
    Induction units;
    Twin duct;
    Chilled ceilings, chilled beams;
    Displacement ventilation; floor air supply.

These issues fall into the domain of the building services engineer - but the basic principle of operation and control needs to be established.

- If conditions are not satisfactory check for under- or over- capacity in both main plant and local emitters. This is particularly relevant with cooling systems, which usually have little capacity in hand.

Also check, or have checked, the operation of local valves to heater and chiller batteries; these may jam, let-by or operate incorrectly, *eg* in reverse to that expected.

- Assess the temperature and velocity of air leaving grilles. Are the values likely to lead to local discomfort, and is there sufficient air distribution?

Adjustments made for summer conditions (*eg* enhancing air movement) may lead to discomfort in winter (and *vice versa*).

Also the air distribution pattern is likely to differ for cooling and heating modes.

- Establish whether relative humidity is being controlled (humidification and/or dehumidification). Measure values. Check control logic and sensors and whether plant is in operation/operational. Humidity sensors are prone to drift and malfunction.

3.4.5 Control systems (heating, cooling, humidity and airflow)

Again, many questions will need to be asked to establish the principle of operation of control systems, and whether they are actually performing as intended. Much of this will necessitate consultation with other experts.

- What is the mode of control? Space sensors, return air sensors? How many sensors are involved? Do they operate independently or do they average detected readings?

- Are sensors suitably positioned to control the occupied space? Are they responding primarily to air or surface temperatures?

- Are sensors set at appropriate control values, *eg* return air sensor control set point should be higher than the room temperature required. What are the set-point values?

- Control may be fully automatic, localised or operated by individuals.

- The type of control provided may influence 'perceived' comfort *eg* adjustment of a thermostat may induce a perceived improvement of conditions even if the thermostat is disconnected and has no effect on control.

- Check functioning and calibration *etc* of sensors, particularly relative humidity and duct air pressure sensors (in variable air volume, VAV, systems).

- Plant may be controlled by an 'Energy/Building Management System'. Functional logic needs to be established.

Overall plant control, start up times, temperature values, *etc* are often controlled by such systems or by a localised optimum start and stop controller. Check set-point values and operational logic.

3.4.6 Plant maintenance

Plant must be checked and maintained on a regular basis to ensure correct operation. Daily inspection is recommended for large plant. Air handling systems (including ductwork) require periodic inspection and cleaning (see *eg* HSE, 1995).

- Plant should be fully documented so that the nature of operation, and system and control logic can be ascertained.
- Maintenance and condition monitoring records should be kept and be available for inspection. Building management systems are of value here, although sometimes too much information becomes available.
- There may be difficulty in obtaining all the explanations/answers required concerning the building and its services. In this case the services and expertise of outside consultants may be required to assess the systems.
- It may be necessary to recommend complete reassessment and recommissioning of the mechanical systems (although this will be an expensive process).

The organisation in the UK providing reference data in this field is the Chartered Institute of Building Services Engineers (CIBSE, 1987); their reference data have received considerable review and revision since 1987 and new editions are due to be published in 1996. Further information on systems can be found in Croome-Gale & Roberts (1975) and Jones (1985) whilst discussion of overall issues relating to comfort, control and energy efficiency can be found in *eg* BRE IP (1995).

3.5 Comfort Case Study

3.5.1 Practical assessment of a moderate environment

(a) General

A common request to the Occupational Hygienist is to assess an indoor climate such as an office. The practical method used in an actual case is outlined below, although some adjustment to the results has been made to illustrate points.

The workers in a large office were complaining that their thermal environment was unacceptable. The Occupational Hygienist was asked to assess the environment, quantify the problem and make recommendations for improvement if necessary. One day was allowed for the assessment and a total of four days for the whole project, including analysis and final report.

(b) Worker relations

Complaints about working environments can be stimulated by other work related problems and it is important for the investigator to gain an impression of the physical, social and organisational environment in general. In addition it is useful to have the co-operation and understanding of management and workers. The workers' representative was therefore contacted and the investigator introduced. It was explained that the objective of the investigation was to improve the thermal environmental conditions. The physical and subjective measures which were to be taken were also demonstrated to the workers' representative who then passed on the information to the office occupants.

(c) Where, when and what to measure

The question of where and when to measure is a question of statistical sampling (*eg* BOHS, 1989). The thermal environmental conditions will vary throughout a space and also with time (during the day, night and seasons). The more measuring points in the room and the more measuring times, in general, the more accurately the environment can be quantified. This is a question of resources.

Only one day was allowed for measurement so a plan of the office was obtained and workplaces identified. Measurements should be taken at the positions of the workers. Ankle, chest and head heights were chosen as measuring points at each workplace. Ten workplaces were 'evenly spread' throughout the office. The ventilation systems were noted and set to 'normal' working. Measurements were then taken over a three hour period under 'typical' conditions throughout the morning when complaints had been received. Outside weather conditions were also recorded. Chapter 6 gives further details of instrumentation.

A 150 mm diameter globe thermometer was placed at each workplace (only two were available so they had to be moved around) and allowed at least twenty minutes to come to thermal equilibrium before readings were taken.

Using a hot-wire anemometer with combined temperature sensor, air velocity and air temperature were measured at ankle, chest and head height of the worker.

A whirling hygrometer was used at chest height to measure wet and dry bulb temperatures (dry bulb was used as a cross check for air temperature with the air temperature sensor on the hot-wire anemometer).

The occupants' clothing and activity were noted, and movements throughout the room were also noted.

Subjective evaluation forms (see Section 3.2) were handed to each worker and collected centrally (*ie* the working position was noted but a degree of anonymity was maintained). The subjective forms allowed some information to be collected regarding time variations and general satisfaction.

3.5.2 Analysis

(a) Physical measures

Analysis of the physical measurements is in two parts. The first part is to obtain for each measurement point air temperature, mean radiant temperature, relative humidity and air velocity from the instrument readings and also to determine metabolic heat production and clothing insulation values.

The second part is to predict the degree of discomfort. The subjective measures were analysed separately and complemented the physical measures.

The air temperature and air velocity were measured directly using the hot-wire anemometer. The mean radiant temperature (t_r) was obtained from globe temperature (t_g) corrected for air temperature (t_a) and air velocity (v). If the mean radiant temperature is within a few degrees of room temperature then McIntyre (1980) suggests that :

$$t_r = t_g + 2.44\,(v)^{0.5}\,(t_g - t_a)$$

where temperatures are in °C and air velocity in $m.s^{-1}$. Relative humidity is determined from the dry bulb (air temperature) and aspirated (whirled) wet bulb of the whirling hygrometer. Useful information is provided by presenting all physical data in a table, or on the office plan, in the final report.

(b) Prediction of whole-body thermal discomfort

Despite some theoretical limitations, one of the most useful thermal comfort indices is the Predicted Mean Vote (PMV) of Fanger (1970) which is used in BS EN ISO 7730: 1995. Using the PMV, the air temperature, mean radiant temperature, air velocity, humidity, clothing and activity values can be integrated to predict the mean thermal sensation vote of a large group of people on a seven point thermal sensation scale (Section 3.1).

The values range from PMV = 3 (hot) through PMV = 0 (neutral) to PMV = –3 (cold). PMV = 0 provides comfort conditions. From the PMV value a Predicted Percentage Dissatisfied (PPD) value can be calculated. This is related to the percentage of people likely to complain about the thermal conditions.

The results for all the workplaces will not be presented here, however the PMV and PPD values for each workplace were calculated and labelled on a copy of the plan of the office, for the final report. This showed the predicted whole-body thermal sensation (comfort) pattern over the office and also the areas of likely complaint.

A calculation example for one workplace is given below. For the workplace the physical measurements were:

t_a = 18°C
t_r = 18°C
v = $0.15\ m.s^{-1}$
rh = 50%

Clothing insulation = 0.65 clo
Metabolic rate = $70\ W.m^{-2}$

These give PMV = −1.7, and PPD = 62%
(see tables or calculation methods in BS EN ISO 7730 or Fanger, 1970).

That is, the prediction is that on average a person will be between slightly cool and cool at this position and that 62% of the population would be dissatisfied (compared to 10% as recommended in BS EN ISO 7730). For the parameters involved an increase in t_a from 18°C to 24°C would give a PMV of 0. This could be a recommendation, or a recommendation could be made in terms of increased clothing insulation *etc*.

(c) Local thermal discomfort

As well as overall or whole-body thermal sensation, thermal conditions can provide effects on local areas of the body. For example, cold air moving around the workers' ankles can cause a draught. The most common forms of local discomfort are caused by cooling due to air movement, heat losses due to asymmetric radiation (*eg* a 'radiant' draught caused by workers sitting next to cold walls or windows) and thermal gradients.

There is some debate about conditions which produce discomfort; however, cool air movements (especially if fluctuating) should be avoided above 0.15 $m.s^{-1}$ (especially for exposed skin areas or if the subject is already cool).

Radiant asymmetry should not exceed 10°C (5°C in the case of heated ceilings) and vertical temperature gradients should not be greater than 3°C from head to foot. General observation of the workplace and air velocity measurements at the three heights together with mean radiant temperatures will provide an indication of possible local thermal discomfort.

A sensation of dryness is probably related to humidity, air velocity and air and radiant temperatures. It is usually associated with the evaporation of fluid from the eyes, nose and mouth and can lead to problems with contact lenses for example. However, dustiness of the air can cause similar effects.

These factors, as well as general (dis)satisfaction with the overall environment, should be assessed by subjective methods.

In a study of this kind the performance of mechanical services should also be assessed as appropriate to ascertain their influence on internal conditions (Section 3.4).

(d) Subjective responses

Analysis of subjective responses involves determining average and variation in response. The responses of how workers felt at the time of measurement can be compared with predicted responses. In general, subjects used a wider range on the scale than predicted values. The subjective values were also presented on a plan of the office in the final report. On average, workers were between slightly cool and cool with some subjects cold and some neutral. Draughts were reported in some areas. Most workers wished to be warmer and people were generally dissatisfied with the thermal environment.

3.5.3 Case study: conclusions and recommendations

The above measurements and analysis allowed recommendations to be made in a final report which was related to the original objectives. An average increase in air temperature was recommended with some specific recommendations about draughts at particular workstations. It was also noted that the high level of dissatisfaction indicated may be due to general dissatisfaction with working conditions and not simply related to thermal conditions.

4 HEAT STRESS

4.1 Medical Effects

The effects on the body of exposure to, or work at, high temperatures varies from mild, reversible symptoms to acute, life endangering illness. They range from fainting when exposed to a hot environment ('heat syncope') to the potentially fatal 'heat stroke' when the body's thermoregulatory system fails and body temperature soars. There are many other effects lying between these extremes, as described in Chapter 11. This Chapter concentrates on the assessment and control of heat stress.

4.2 Heat Stress Indices and Standards

Heat stress indices provide a means of assessing hot thermal environments to predict their likely effect on people. As with comfort indices, in theory a heat stress index will take account of all environmental factors to produce a single index number which, when considered in relation to a person, their clothing and metabolic rate, will enable the stress, strain or risk to them to be assessed.

Indices generally fall into two groups: those which have been ***empirically*** derived and substantiated by assessing the physiological effects on a test group of people under varying environmental conditions, and those which have been derived by ***theoretical*** consideration of the effects of the environment *etc* on the body's heat balance. Empirical indices do not readily allow detailed consideration of the individual components of the thermal environment but, being practically derived, they are more widely used as the basis for standards. Theoretically derived standards allow detailed consideration of the factors controlling the body's heat balance and are therefore useful when assessing changes *etc*, but they are not based on so much practical data and thus only one such theoretical index has been used for standard-setting (ISO 7933: 1989).

A number of indices have been used to assess heat exposure. It is important to note that these are principally intended for protection against heat stroke; they do not protect against the milder or chronic effects of heat. Their primary object is to prevent the deep body temperature from exceeding 38°C, either by limiting environmental conditions in which exposure or work is permitted, or by permitting exposure to more extreme conditions but for limited periods only.

No index or standard is universally applicable since all are affected to differing degrees by components of the thermal environment, clothing and metabolism. The application of different indices or standards to a particular environment often produces differing results. Also, a standard which is intended to provide a safe environment for all people will be far more restrictive than one aimed at young fit people.

A number of the more commonly used indices are described.

4.2.1 Empirical indices

(a) Wet bulb globe temperature (WBGT)

WBGT is the most widely accepted index and forms the basis of many standards, most notably the Threshold Limit Value (ACGIH, 1995) and BS EN 27243 (1994) *ie* ISO 7243 (1989).

WBGT is calculated from

$$\text{WBGT} = 0.7\ \text{WB} + 0.3\ \text{GT} \qquad \text{(indoors)} \quad \text{or}$$

$$\text{WBGT} = 0.7\ \text{WB} + 0.2\ \text{GT} + 0.1\ \text{DB} \qquad \text{(outdoors)}$$

(the outdoors formula reduces the influence of the globe contribution from direct sun)

where: WBGT is the Wet Bulb Globe Temperature

WB is the wet bulb temperature (natural)

GT is the globe thermometer temperature (150 mm diameter globe)

DB is the dry bulb temperature.

WBGT was originally derived to reduce heat casualties in the USA during military training. It takes account, albeit empirically, of radiant and air temperatures, humidity and low air velocities (below 1 m.s^{-1}).

Table 4.1 and Figure 4.1 reproduce the standards for exposure as specified by ISO 7243 using WBGT. These figures are generally conservative and indicate a level which is likely to be safe for most people. The ACGIH (1995) have introduced guidance on the effect of clothing on the use of the WBGT index. Standard clothing for which the index is applied directly is light clothing with a clo value of 0.6. For alternative clothing a correction factor can be used, *eg* for additional cotton overalls it is recommended that the WBGT index value is corrected by –2°C, and for heavier protective clothing the correction may be up to –6°C. Care must always be applied particularly if clothing restricts vapour movement or is completely impervious as with chemical protective clothing (Smith *et al*, 1995); see also Section 9.3 on risk assessment. Guidance on clothing is not included in ISO 7243.

WBGT is also used as the basis for another exposure limit, the Physiological Heat Exposure Limit (PHEL) (Dasler, 1977). This permits exposure for short periods of time to temperatures higher than those permitted by ISO 7243.

PHEL is expected to be safe for 95% of fit young men under 45 years old and is limited to metabolic rates of 85-150 W.m^{-2} and WBGTs of 31-50°C. It therefore needs to be applied with great caution and, since by inference 5% of fit workers will not be safe, with medical agreement and under good supervision.

Table 4.1
Reference values of WBGT heat stress index from ISO 7243 (1989) (BS EN 27243 : 1994)
(reproduced by permission of ISO)
(Note: the values given relate to a maximum rectal temperature of 38.0°C)

Metabolic rate class	Metabolic rate, *M*		Reference value of *WBGT*			
	Related to a unit skin surface area W.m^{-2}	Total (for a mean skin surface area of 1.8 m^2) W	Person acclimatised to heat °C		Person not acclimatised to heat °C	
0 (resting)	$M \leq 65$	$M \leq 117$	33		32	
1	$65 < M \leq 130$	$117 < M \leq 234$	30		29	
2	$130 < M \leq 200$	$234 < M \leq 360$	28		26	
3	$200 < M \leq 260$	$360 < M \leq 468$	No sensible air movement 25	Sensible air movement 26	No sensible air movement 22	Sensible air movement 23
4	$M > 260$	$M > 468$	23	25	18	20

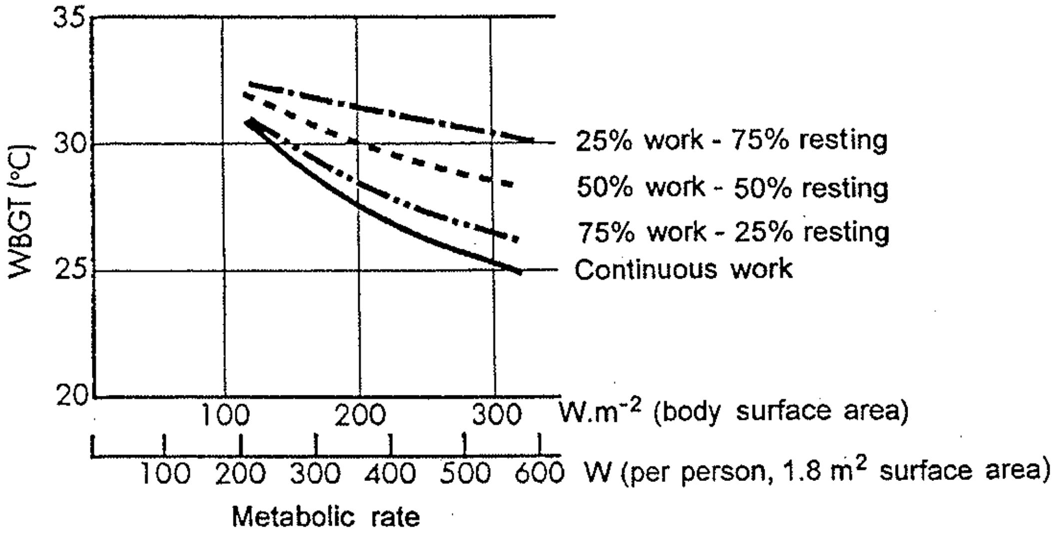


Figure 4.1: Curves showing reference values of WBGT established for various work/resting cycles for acclimatised persons (adapted from ISO 7243).
(Note that the rest area is assumed to have a WBGT value similar to the work area and the work/rest cycles take place within hourly periods.)

(b) Wet bulb temperature

Wet bulb temperature alone may be used in certain limited circumstances. For example, BS 6164 (1990) stipulates a maximum wet bulb temperature of 27°C for tunnelling work where radiant heat is rarely a problem but humidity is often high. Regulations applying to the cotton industry, where humidity is also often high, prohibit work in weaving sheds when wet bulb temperatures exceed 27°C (see Chapter 9).

(c) Effective temperature (ET) and corrected effective temperature (CET)

Effective temperature (ET) was originally derived for predicting comfort rather than heat stress, taking account of wet bulb temperature, dry bulb and air velocity. The corrected effective temperature (CET) was 'corrected' to take into account radiation conditions by incorporating the globe (150 mm) thermometer temperature in place of the dry bulb temperature. CET is not generally used to predict heat stress although it has been applied in the coal mining industry in the UK, where it formed the basis for thermal environment standards.

(d) Oxford Index (WD)

The Oxford Index (Kerslake, 1972) predicts tolerance time for fit men working for short periods in extreme conditions. It was derived from tolerance times of mines rescue personnel at different metabolic rates (up to 180 $W.m^{-2}$) and is calculated from:

$$WD = 0.15\ DB + 0.85\ WB$$

where

WD = Oxford Index

DB = Dry Bulb temperature

WB = Wet Bulb temperature

Tolerance times are given with the index. As with PHEL, great caution needs to be exercised in the use of this index as some people will be at risk at these temperatures.

(e) Predicted four-hour sweat rate, P4SR

The P4SR index (MacPherson, 1960) enables a nominal sweat rate (*ie* strain) to be predicted from criteria relating to the environment and individual. Limiting values for various circumstances are recommended by different organisations. The index is determined *via* measurement of appropriate environmental factors, adjustments for activity and clothing and use of the P4SR chart (nomogram).

4.2.2 Rational/analytical indices

(a) ISO 7933: 1989 Hot environments - analytical determination and interpretation of thermal stress using calculation of required sweat rate

Various indices and methods have been developed to predict thermal strain on the body by balancing heat input from the environment and metabolic heat generation against heat loss by sweat evaporation. The most notable of these is given in ISO 7933 (1989), which can be used for predicting heat strain from a very wide range of factors by determining the required sweat rate. Whilst being the most extensive and detailed of the methods for predicting heat strain and the effects of the different components of the thermal environment, ISO 7933 is complex and difficult to use and does not lend itself to occasional or casual use.

The standard specifies a rational method for assessing hot environments by calculating and interpreting a parameter termed the required sweat rate (S_{req}). The S_{req} index is a development of the heat stress index (HSI) and the index of thermal strain (ITS) - see the following Section. It is derived from the work of Vogt *et al* (1981) in the CNRS laboratories in Strasbourg, France and after further development it was published as an ISO Standard in 1989.

Measurement of the hot environment is made in terms of air temperature, mean radiant temperature, humidity and air velocity, together with estimates of factors relating to clothing, metabolic rate and posture. These are then used to calculate the heat exchange between a standard person and the environment. This allows the calculation of the required sweat rate (for the maintenance of the thermal equilibrium of the body) from the following adaptation of the basic heat balance equation (see Section 1.3).

$$E_{req} = M - W - C_{res} - E_{res} - K - C - R$$

combined with

$$S_{req} = E_{req}/r_{req}$$

where

M = metabolic power
W = mechanical power
C_{res} = respiratory heat loss by convection
E_{res} = respiratory heat loss by evaporation
K = heat exchange on the skin by conduction
C = heat exchange on the skin by convection
R = heat exchange on the skin by radiation
S_{req} = required sweat rate for thermal equilibrium
E_{req} = required evaporation for thermal equilibrium
r_{req} = evaporative efficiency at required sweat rate.

Metabolic and mechanical power are estimated, although W is often taken as zero if detailed information about the task is not known. They can be determined using methods provided in BS EN 28996 (1994). K is regarded as having negligible effect. The remaining terms are calculated from expressions similar to (but more complex than) those in Section 1.3, using measured parameters of the environment (see the Standard for details).

Predicted values for evaporation from the subject (E_p), sweat rate (Sw_p) and skin wettedness (w_p) are determined for the standard subject. Predictions are made taking into account required values (w_{req}, E_{req} and S_{req}) and limit values (w_{max}, Sw_{max}). The required sweat rate is compared with the maximum limit values for skin wettedness (w_{max}) and sweat rate (Sw_{max}) which can be achieved by persons. These are given in the Standard for acclimatised and non-acclimatised persons at work and rest.

In the case where thermal equilibrium is not maintained heat storage will occur and hence the body core temperature will rise. Limiting values are presented for warning and danger, in terms of heat storage. They are also presented in terms of the maximum allowable water loss compatible with the maintenance of the hydromineral equilibrium of the body.

The predicted sweat rate can be determined from the required sweat rate and the limit values. If the required sweat rate can be achieved by persons and it will not cause unacceptable water loss, then there is no time limit due to heat exposure, over an eight-hour shift. If this is not the case, then an allowable exposure time - duration limited exposure (DLE) - can be calculated from appropriate equations.

If the DLE is determined by a heat storage criterion then the worker must rest until there is no longer a risk of heat stress. If the DLE is determined by dehydration factors then no further exposure is allowed during the day.

If workers carry out a number of types of work during the day and under different thermal conditions, ISO 7933 provides a method for assessing sequences of 'tasks' (including work and rest) based on a time weighting of E_{req} and E_{max} values.

If E_{max} is negative (*ie* condensation will occur) or if exposure time is short (*ie* less than 30 mins), the method used in ISO 7933 is inappropriate. Physiological measurements on individuals should then be taken according to ISO 9886 (1992). A computer programme is provided to allow ease of calculation and efficient use of the Standard. The Standard does not allow for modifications of clothing.

This rational method of assessing hot environments allows identification of the relative importance of different components of the thermal environment and hence can be used in determining appropriate engineering environmental control measures.

(b) Heat Stress Index (HSI) and Index of Thermal Stress (ITS)

Other analytical indices include the Heat Stress Index (HSI) (Belding, 1972) and the Index of Thermal Stress (ITS) (Givoni, 1976). These indices have practical limitations but they enable the individual components of the thermal environment to be considered. The method for calculating the Heat Stress Index (HSI) is set out in Table 4.2 and is included as it represents a similar but simpler approach to ISO 7933.

HSI is expressed as a number on a 0 to 100 scale, representing stress and hence indicating strain. Conditions giving an HSI of below 40 are not considered to pose a risk to health; above 40 the risk increases and 100 is the maximum tolerated by fit, acclimatised young men. Over 100 the body is unable to lose heat and body temperature will continue to rise unless the exposure time is limited. The maximum allowable exposure time (AET) can be calculated from:

$$\text{AET (minutes)} = (2440)/(E_{req} - E_{max})$$

(where the terms are as defined in Table 4.2).

HSI cannot be applied if temperature and humidity are both high because E_{max} becomes negative. However, AET is still valid.

Reviews of indices and standards are given in NIOSH (1986), Olesen (1985), Graveling *et al* (1988), ECSC (1988), Malchaire (1990) and Parsons (1993).

Table 4.2
Calculation of Heat Stress Index (HSI)

$$\text{HEAT STRESS INDEX} = \frac{E_{req}}{E_{max}} \times 100$$

where:

E_{req} = Required evaporative (*ie* sweat) loss (W.m^{-2})
= M - R - C (see below)

E_{max} = Maximum evaporative (*ie* sweat) loss (W.m^{-2})
= $7.0\,v^{0.6}\,(56 - p_a)$ ......clothed
= $11.7\,v^{0.6}\,(56 - p_a)$ ......unclothed

with upper limit of 390 W.m^{-2}

M = Metabolic rate (W.m^{-2})

R = Radiation loss (W.m^{-2}) = $4.4\,(35 - t_r)$ ......clothed
= $7.3\,(35 - t_r)$ ......unclothed

C = Convection loss (W.m^{-2}) = $4.6\,v^{0.6}\,(35 - t_a)$ ......clothed
= $7.6\,v^{0.6}\,(35 - t_a)$ ......unclothed

and
p_a = water vapour pressure (mb)
t_r = mean radiant temperature (°C)
t_a = dry bulb (*ie* air) temperature (°C)

4.2.3 The use and application of indices

No index predicts working conditions which are completely safe since even at moderately elevated temperatures there will be some risk of the milder medical effects.

For most applications, ISO 7243 (BS EN 27243) provides a relatively safe baseline, below which the risk of serious medical effect is very small to most people, whether working continuously or for short periods. However, even the conservative standards of ISO 7243 will not provide sufficient protection in all cases. In particular ISO 7243 cannot be assumed to apply to work or activities carried out in impervious protective clothing, and it may not fully reflect the risk if radiant temperature or air temperature and velocity are high.

In circumstances where ISO 7243 does not apply or where exposure to more extreme environments is considered, other indices may be used but since the risk increases with temperature they should be applied with great caution and in conjunction with other precautions, particularly medical screening, supervision and, if advised by a doctor, medical monitoring.

The most appropriate index or indices which take adequate account of all relevant environmental conditions, clothing, metabolism *etc* should be used. If possible, a comparison of several indices should be made. ISO 7933 will allow the most comprehensive assessment of conditions although other indices may have practical benefits in particular situations.

An example of the general practical application of heat stress standards, in asbestos removal operations, is given in HSE (1992), EH 57.

4.3 Control Procedures

4.3.1 Planning

Exposure to elevated temperatures should be avoided or minimised by careful planning whenever possible. This applies in particular to work activities such as maintenance and repair of hot equipment, replacement of insulating materials *etc* and other work of short duration which can often be planned ahead.

If exposure is unavoidable then the risk should be controlled to an acceptable level, preferably by environmental control. Figure 4.2 illustrates the points to be considered when planning hot work. Where, despite all reasonable environmental controls, temperatures continue to exceed ISO 7243 recommendations, then additional precautions will be required to reduce personal risk including:

- medical preselection and acclimatisation
- supervision and training
- restriction of work periods (work-rest regimes)
- conditioned protective clothing.

4.3.2 Environmental control

Control of the temperature of the environment is of primary importance in reducing risk. The methods selected will be dictated by the nature of the workplace or environment and, in particular, of the heat source.

(a) Control of the source

Where heat is released by a particular process or by other readily discernible sources, the temperature of the source itself should be reduced. This may be done by:

(i) Temperature reduction

This is most practicable for operations of short duration such as maintenance of hot equipment or replacement of insulating materials where, for example, air and radiant temperatures at working positions can be improved by reducing steam and hot water temperatures in pipework and plant. Temperature reduction is particularly important if surface temperatures are very high and radiant heat transfer is a problem.

(ii) Insulation

Hot surfaces should be insulated wherever possible in order to reduce surface temperatures and heat emission from the surface. (However, plant may rely on these heat losses for operation so care should be exercised with such measures.) Various insulating materials are available. Where permanent insulation has been damaged or is being replaced, temporary insulation may be used. However, care should be taken if existing insulation is likely to contain asbestos since work with such material is only permitted to contractors licensed by the Health and Safety Executive.

(iii) Radiant heat control

Thermal radiation plays an increasingly significant part in heat transfer as the surface temperature increases. Radiant heat emission depends on the nature of the surface itself. In general, bright surfaces have lower emissivities (*ie* lower radiant heat output) than dark or dull surfaces at equivalent temperatures. For example, the emissivity of oxidised aluminium is 0.10 whilst that of rusted iron is 0.85 and rough brickwork is 0.93. Radiant heat emission from iron or brick surfaces can therefore be considerably reduced by cladding them with aluminium. However, if such cladding becomes dirty or discoloured the emissivity, and hence the rate of heat transfer, will rise.

Data on heat emission from pipework and other surfaces, the properties of insulating materials, and emissivity of various materials, are given in Weller and Youle (1981) and CIBSE (1987).

(b) Ventilation, air conditioning and air movement

Ventilation can be used for thermal environment control in two ways:

(i) By removing or diluting hot / humid air and replacing it with cooler/drier air.

This is most efficient if air is removed from the hottest area, for example, from above the heat source itself or at high level in the building. Make-up air will normally be taken from a cool place outside or, if the heat load is high and the area to be cooled is limited, it may be mechanically chilled. The position and design of the make-up air system is important; cool air should normally be introduced into occupied areas in a way that will ensure mixing without causing unacceptable cold draughts. Maintenance of adequate ventilation is especially important in confined and enclosed spaces where temperatures can rise quickly and escape may be difficult.

(ii) By increasing air movement.

In general, the rate of heat loss from the body by convection and evaporation increases with air velocity, so increased air velocities are generally beneficial. However, at temperatures over 35°C, convective heat transfer will become a gain to the body. Unless humidity is high, evaporative heat loss still outweighs convective heat gain but at very high temperatures and/or humidities, this is reversed. The nett effect of increasing air velocity can be calculated from indices such as ISO 7933 and HSI. As a rule of thumb, if the wet bulb temperature is below 36°C, increasing air velocity is beneficial; if above 36°C, it is detrimental.

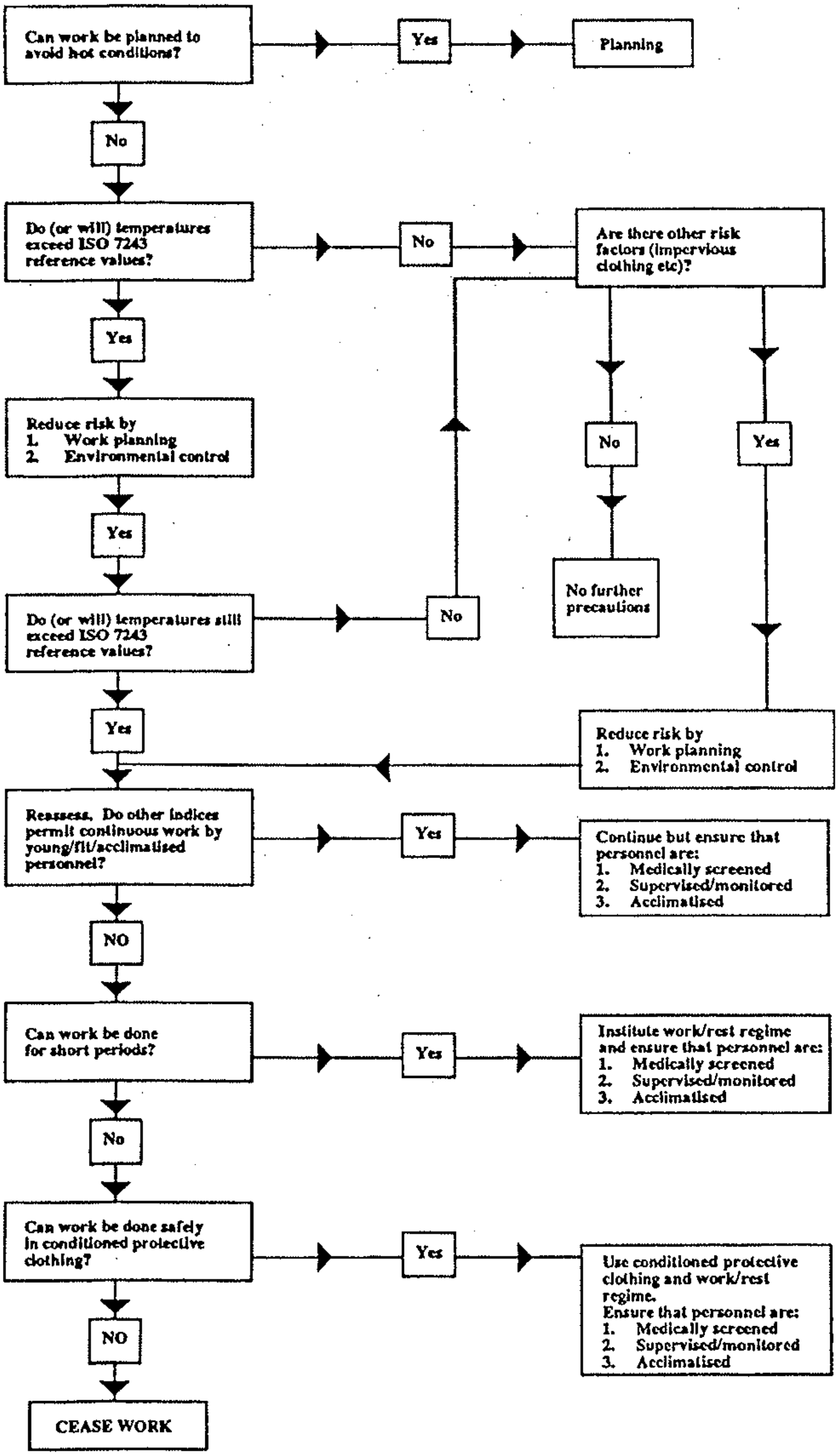


Figure 4.2:
Planning for hot work

(c) Evaporative cooling

Evaporative cooling is a means of reducing air temperature by spraying water into the airstream or passing the air over a wetted element. Evaporative coolers are also available for localised cooling in which water is sprayed into the airstream of a fan directed towards the person. Whilst evaporative cooling can reduce the air temperature, it also increases humidity and these two factors must be balanced when evaluating the potential benefits.

(d) Radiation barriers

Where it is not possible to reduce radiant heat at source, radiation barriers positioned between the source and the subject will reduce direct radiation. Ideally, such barriers should be of a material with good insulating properties and have surfaces of low emissivity (*ie* high reflectivity) so that they do not themselves become hot, reradiate and present a contact hazard. Reflected radiation from the heat source should be directed so as to avoid contributing to the heat load. Transparent materials such as partially silvered glass or selectively absorbing clear plastics can be used where it is necessary to view the heat source itself. Cold water 'radiators' can also be used as radiation 'sinks' (*cf* radiant cooling systems in offices).

4.3.3 Managerial aspects of control

(a) Supervision and training

A high standard of supervision is essential whenever work is to be carried out in hot environments to ensure that potential heat casualties are detected quickly and immediately removed to a place of safety. No person should be allowed to work alone and unsupervised in such conditions.

The degree of supervision will depend on circumstances. In some cases, a 'buddy' system may be acceptable where two or more workers supervise each other. However, a formal system of supervision is to be preferred.

Supervisors and workers should be trained to recognise symptoms of impending heat strain, both in themselves and in others and should be trained in appropriate emergency and first aid procedures. Health and Safety Executive Guidance Note, MS 16 (HSE, 1978) gives advice on this subject. For work in extreme thermal environments a formal permit to work system and medical supervision may be necessary.

(b) Restricted work periods (work-rest regimes)

In conditions where continuous work cannot be tolerated, work may be permitted for short periods. The time limit for such exposure is set to ensure that the body's temperature is not allowed to rise beyond a predetermined point, usually 38°C. Once the time limit has been reached, the worker will then either rest for a predetermined period or, in severe environments, move to a cool place to recuperate.

The same criteria should be used in selecting a work-rest regime index as an index for continuous exposure (see Section 4.2). ISO 7243 can be used in most circumstances. Where work is contemplated in more extreme conditions not covered by ISO 7243 then an alternative index may be consulted provided that other precautions are also taken to protect susceptible individuals. Greater emphasis will need to be placed on precautions such as medical screening and supervision because at the higher temperatures involved, the risk is correspondingly greater and rise in body temperature would be correspondingly more rapid.

Estimation of rest periods is often difficult. ISO 7243 quotes work and rest periods as a percentage of total exposure time (using a one-hour time base) and it is therefore simple to calculate both the work and rest periods in moderate environments. (Note: the rest area in ISO 7243 is assumed to be at the same WBGT value; for cooler rest areas recovery would be expected to be more rapid.) Whilst other indices allow the maximum exposure period to be calculated, they do not stipulate rest periods.

The time theoretically required to lose body heat can be calculated using ISO 7933 or other analytical indices. However, a more pragmatic approach based on physiological monitoring is usually appropriate, prohibiting return to the hot workplace until temperature or pulse rate has returned to a safe level, *eg* using Brouha's guide (NIOSH, 1973). Rest periods should be spent in a cool place. Workers should continue to be supervised when resting and should not be permitted to leave, even to return home, until pulse rate or temperature has returned to a safe level as symptoms of heat stress are not always immediately apparent.

4.3.4 Protective clothing and equipment

Clothing, especially protective clothing, often has an adverse effect on the body's heat balance in hot environments by insulating the body and reducing evaporative heat loss. Impervious clothing particularly impedes heat loss and the wearing of such clothing may present some risk if physically demanding work or exercise is carried out at air (dry bulb) temperatures as low as 21°C, especially if the wearer is not acclimatised, is unfit or otherwise susceptible.

The use of a respirator may also affect the wearer's ability to tolerate hot environments since, whilst the effect on heat balance is relatively small, the respirator can cause discomfort and rashes and can restrict respiratory airflow, thus further increasing the cardiovascular strain. Where it is necessary to wear a respirator in hot environments, this should preferably be of a positive pressure type, *ie* supplying air under pressure to the mask or across the face; this can enhance local cooling.

In some circumstances, clothing may provide protection against heat. Protective clothing, especially if made of natural fibre, will provide some protection against contact burns and radiation. For protection against contact with very hot surfaces, or molten metal, special clothing assemblies as specified in BS EN 366 (1993) are necessary and the use of materials with aluminised surfaces and reflective visors gives protection against radiation.

Heat resistant protective clothing will only give protection for limited periods and may have a detrimental effect if exposure continues. If continued exposure is necessary in circumstances where it would not otherwise be permitted, the use of cooled or conditioned protective clothing may allow longer periods of exposure. Various types of clothing have been developed but for practical purposes only two are generally used, ice-cooled jackets and air-cooled suits.

(i) Ice-cooled jackets

These permit exposure for short periods, the length of exposure being limited by the severity of the environment and the capacity of the jacket. Ice-cooled jackets are relatively simple, comprising a cotton waistcoat either with integral ice packs or with pockets for ice packs, but their bulk may give rise to discomfort and restrict movement. Other cooling media such as dry ice may be employed. It is necessary to wear a light garment under the waistcoat to prevent contact between the ice pack and the skin, and an insulated overjacket. Ice-cooled jackets are not suitable for extreme environments, and carrying the jacket can contribute to the metabolic rate and thermal strain.

(ii) Air-cooled suits

These suits are cooled by air supplied through the connecting hose. The air may be supplied directly at outside temperature or it may be cooled by a venturi cooler, usually worn on a belt or harness attached to the suit. The balance of air volume and temperature is important. Air-cooled suits can be worn for long periods at high temperatures but the hose may restrict access to some spaces. Aluminised overgarments can also be used where radiant heat is an additional problem.

(iii) Liquid (water)-cooled suits

These are also used in some circumstances, particularly where work stations are fixed, where cooling loads are high and where heating may also be required, *eg* for drivers of tractors in hot climates and aerospace applications. The temperature of the coolant is important as if it is too low vasoconstriction at the body surface can occur, leading to reduced heat loss and increasd risk of the body core temperature rising.

Because cooled or conditioned clothing is used in circumstances where exposure would not otherwise be permitted, its use should be restricted to those who are medically fit and there should be a high standard of supervision since, in the event of its failure, the user will be exposed to an unacceptable environment and will need to be removed immediately.

5 COLD STRESS

5.1 Effects of Cold

5.1.1 Immediate effects

Exposure to cold brings about an immediate stimulation of nerve receptors in the skin to cause a reflex vasoconstriction of skin blood vessels. The resultant reduction in blood flow has the effect of increasing body surface insulation. Though there is considerable variation between individuals, heat transfer from deep body tissues to the skin may be 60 $W.m^{-2}$ when peripheral blood vessels are fully dilated and approximately 10 $W.m^{-2}$ in the vasoconstricted state. The nervous reflex vasoconstriction is enhanced by a direct constrictor effect of the cold environment on blood vessels of exposed skin. Skin vasoconstriction, aided by a reflex sympathetic nervous drive to the heart can also produce a large increase in arterial blood pressure.

Skin temperature gradually falls and increased insulation of the shell of the body maintains deep body temperature, but with more prolonged cold stress internal heat production may then increase. This is brought about by an involuntary reflex increasing muscle tone that eventually results in shivering. During bursts of intense shivering total oxygen consumption can increase by up to 5 times the basal level. Voluntary movement and muscular exercise tend to inhibit shivering, partly by raising deep body temperature. In very cold conditions, if movement is limited, a contracted posture is usually adopted, with the arms folded over the body and the legs drawn up. Such behavioural responses to cold can reduce the surface area exposed for heat loss by up to 50%.

Heat is lost from the body surface by evaporation of water and by radiation, conduction and convection. The conductive element may become large when an individual rests on the ground in snow, ice or very cold conditions. The amount of water evaporated from the skin can also be importantly large. Further heat is lost by way of the respiratory tract, the quantity depending on the temperature and humidity of the air and on respiratory ventilation rate. At a resting ventilation rate of 5 litres per minute respiratory heat loss may be 18 W in extreme cold and during heavy exercise more than 100 W. Dehydration may occur insidiously in the cold because of the increased water loss from the skin and respiratory tract and renal cold diuresis.

Although a mean skin temperature falling progressively below 33°C is associated with increasing cold discomfort, the physiological responses, adequate clothing and physical activity enable most healthy people to maintain a constant deep body temperature in a wide range of cold environments. Mean skin temperatures as low as 12°C are tolerated without a fall in body temperature in fat individuals, but only as low as 25-30°C if the individual is thin and lacks good subcutaneous insulation. Most adults can maintain deep body temperature when lightly clothed (1 clo) for several hours in still air at 5°C, but not in much colder air, or if clothing insulation is reduced by immersion in water or by wind or rain. Even fat people are prone to cool in water below 12°C, since cold paralysis of the peripheral blood vessels results in cold vasodilatation with concomitant rapid loss of heat.

5.1.2 Chronic exposure to cold

There is little clear evidence of a general form of cold acclimatisation in man that can be regarded as similar to the physiological adaptations that accompany repeated exposure to heat. There are some experimental observations to suggest that cold acclimatisation may take the form of a delayed shivering response and a decrease in the amount of vasoconstriction, but these effects have not been satisfactorily confirmed. The thermal conductivity of fat is considerably less than that of skin or muscle. Ordinary body fat, in contrast to brown fat (a metabolically active tissue which is found in significant amounts as a source of thermogenesis only in newborn infants), has a poor blood supply. Thus, a fat person will be better insulated, but there is no convincing evidence that this means of cold defence is developed by individuals habitually exposed to cold.

Human beings do, however, appear to possess the ability to adapt to cold by changes in local responses in the extremities such as hands and feet. Those who habitually work with their hands exposed to cold develop the ability to maintain local blood flow in conditions that would cause extreme discomfort and loss of dexterity in unacclimatised people. After an initial vasoconstriction on placing the hands in cold water, further cooling can lead to vasodilatation and increased blood flow. People whose hands are regularly exposed to cold show a local adaptation of this response, the initial vasoconstriction is less severe and the dilation occurs more rapidly and lasts longer.

Medical effects are covered in further detail in Chapter 11.

5.2 Principles of Control

Thermal protection necessary to ensure comfort and well-being in the cold is determined by two sets of factors, personal and environmental. Personal factors include bodily activity (metabolic rate), clothing insulation worn and available, and duration of the exposure. Environmental factors are ambient temperature, wind velocity, radiant temperature of surroundings including the earth and sky, the presence of rain or snow, solar radiation and atmospheric pressure.

5.2.1 Environment

The cooling effect of the environment is increased by wind to the extent that wind disturbs the thin boundary layer of air next to the outside of the clothing and may also penetrate the clothing. If air velocity at the work site is increased by wind, draught or ventilating equipment, the increased cooling power of the air can be reduced by either shielding the work area and/or wearing an additional windbreak layer garment. The equivalent cooling power of wind speed is shown in Table 5.1.

Table 5.1

Cooling power of wind on exposed flesh expressed as equivalent chilling temperature under low wind speed (1.8 $m.s^{-1}$) conditions

(adapted from ACGIH, 1995)

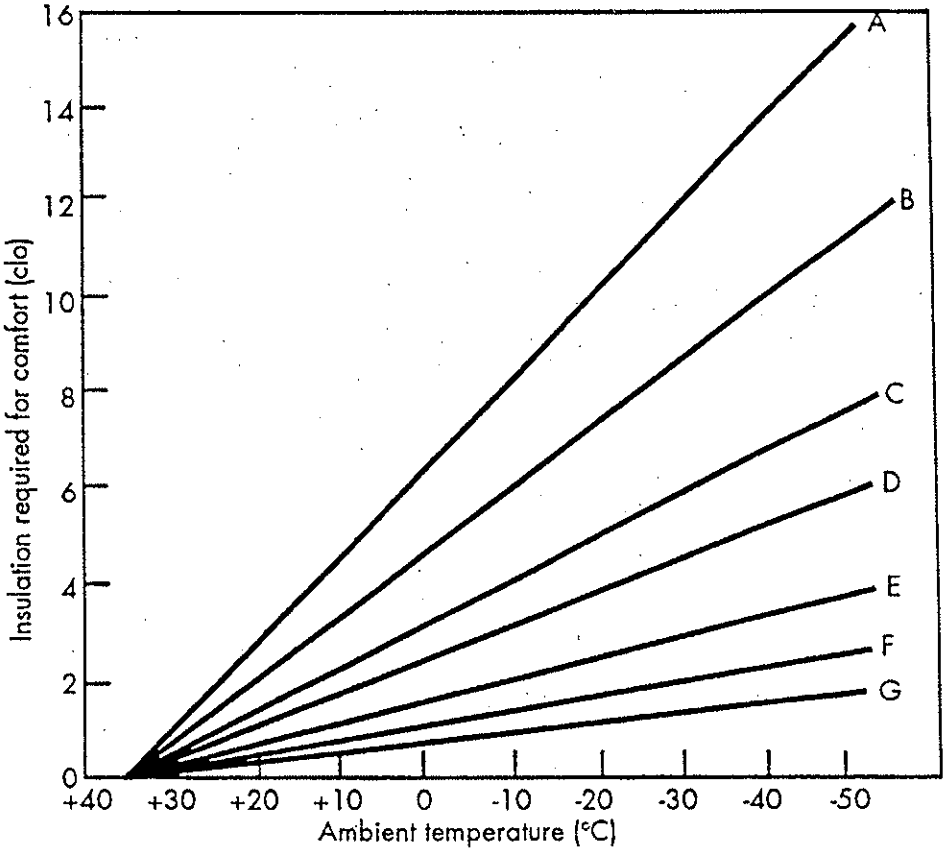
Equivalent chilling temperature (⁰C)

Wind speed		Actual thermometer reading °C											
mph	$m.s^{-1}$	+10	+5	−1	−7	−12	−18	−23	−29	−34	−40	−46	−50
calm		+10	+5	−1	−7	−12	−18	−23	−29	−34	−40	−46	−50
5	2.2	+9	+3	−3	−9	−15	−21	−26	−32	−38	−44	−50	−56
10	4.5	+5	−2	−9	−16	−23	−30	−36	−43	−50	−57	−64	−71
15	6.7	+2	−6	−13	−21	−28	−38	−43	−50	−58	−65	−73	−80
20	8.9	0	−8	−16	−23	−32	−40	−47	−55	−63	−71	−79	−87
25	11.2	−1	−9	−18	−26	−34	−42	−51	−59	−67	−76	−83	−92
30	13.4	−2	−11	−19	−28	−36	−44	−53	−62	−70	−78	−87	−96
35	15.6	−3	−12	−20	−29	−37	−45	−55	−63	−72	−81	−90	−98
40	17.9	−3	−12	−21	−30	−38	−47	−56	−65	−73	−82	−91	−100

The amount of radiant heat exchange taking place between men working outdoors and the sky and earth is an important environmental consideration. Up to 95% of incident radiant energy can be absorbed by a man wearing a black outer covering and as little as 30% by a white reflecting garment. Altitude affects protection requirements. A reduced air density at high altitudes will decrease the thermal resistance of the boundary air layer and require more clothing to be worn. On the other hand the intensity of solar radiation for heat gain is greater at high altitudes.

5.2.2 Work activity

Figure 5.1 predicts the total insulation required for prolonged comfort at various activities in the shade as a function of environmental temperature (see also I_{REQ}, Section 5.3). Short exposures can be tolerated in temperatures colder than those predicted for equilibrium conditions in the Figure. In calculating these relationships it has been assumed that heat available for loss by convection, conduction and radiation is 0.75 of the metabolic heat production and that 33°C is a satisfactory mean skin temperature to achieve thermal comfort. Thus a worker dressed for thermal comfort during periods of inactivity will be overdressed for hard work and hence the problem of providing clothing for operatives engaged in intermittent work schedules can present some difficulty.



A:	45 W.m^{-2}	Sleeping
B:	58 W.m^{-2}	Sitting quietly
C:	93 W.m^{-2}	Working at desk, driving *etc*
D:	116 W.m^{-2}	Standing with light work
E:	174 W.m^{-2}	Moderate work, walking on level at 2.5 mph
F:	230 W.m^{-2}	Harder work, walking on level at 3.5 mph
G:	350 W.m^{-2}	Hard work, walking on level at 3.5 mph with 20 kg load.

Figure 5.1
Total insulation required (clo) for prolonged comfort at various activities in shade and still air
(adapted from Burton and Edholm, 1955)

The metabolic rates quoted in the Figure 5.1 correspond to the reference value classes defined in Table 4.1, Section 4.2.1, relating to hot environments:

Metabolic rates: A=class 0 C=class 1 E=class 2 G=class 4
B=class 0 D=class 1 F=class 3

5.2.3 Clothing

In the absence of shelter, clothing is the most important means of protection against cold stress for people living in natural cold environments. The thermal insulation provided by clothing is due to the air trapped between layers of clothing and in the fibrous structure. Insulation is proportional to the thickness of still air enclosed in the garments, on the capacity to trap air and on the compressibility of the fabric when in use. Clothing also has to protect against wind which can penetrate and destroy the insulating property of the trapped air. It is therefore necessary for an effective cold-weather assembly to be wind-proof by having an outside layer made of tightly woven or impermeable material.

Whole body protection must be provided in cold air or cold water immersion primarily to prevent the onset of hypothermia (core temperature <35°C). The aim is to maintain a core temperature above 36°C if possible. The equivalent wind chill temperature (Table 5.1) should be used when estimating the combined cooling effect of wind and low temperature on exposed skin or when determining insulation requirements to maintain deep core temperature (Figure 5.1).

Efficiently water-proofed clothing is essential in cold, wet environments because of the rapid cooling produced by combined evaporative and wind chill. A serious disadvantage of impermeability is that the clothing is also impermeable to water vapour escaping from the skin surface. If it cannot escape, water vapour from the skin will condense beneath the impermeable layer in cold weather and eventually eliminate the insulation provided by trapped air. This effect is increased if the individual is physically active and sweating. In environmental temperatures below 0°C, water trapped in clothing may freeze. Apart from necessary protection against wet conditions, impermeable clothing is mainly useful in cold, dry conditions for people who are not very active. Loosely fitted with openings round the neck, impermeable garments rely on a bellows effect to reduce water vapour concentration. For more severe work the outer layer should be water repellent but capable of allowing vapour movement so that water vapour can escape. (The outer layer should be changed if it becomes wetted due to water repellency properties being lost.) If adequate protective clothing is not available to prevent the development of hypothermia or cold injury, work practices should be modified or suspended until adequate clothing is available or weather conditions improve.

The other important clothing consideration is protection of the extremities and head. Thick insulating gloves are of little use when fine hand movements are required, and, furthermore, insulation round small diameter cylinders like the fingers is difficult to achieve. Mitts, with all the fingers enclosed together and only the thumb separate, provide more effective insulation. Under survival situations these weaknesses in insulation can be overcome by withdrawing the hands and arms into the body of the jacket (ensuring that loose sleeves are constrained and made air tight).

Cold-protection clothing technology has developed to overcome many of these problems by the use of special fabrics (*eg* Gortex) which allow passage of water vapour while remaining wind- and water-proof, and by the use of electrically heated suits and gloves (*eg* Morris, 1975; Mekjavic *et al*, 1988). However, as with all personal protective equipment, the performance provided can deteriorate with time, use, wear and materials ageing processes; hence protective clothing should be examined and tested regularly.

5.2.4 Local cold injury

Cold injury to the hands and face is especially likely to occur since these areas are the most frequently exposed. Special attention should be paid to keeping workers' hands warm if fine work is performed for more than 20 min at air temperatures below 16°C. Warm air jets, radiant heaters and contact warm plates are useful control measures. Metal handles or tools should be covered by thermal insulating material for work at temperatures below −1°C. Gloves should be worn by workers when fine manual dexterity is not required, for sedentary situations in air temperatures below 6°C, for light work (120 W.m^{-2}) below 4°C and for moderate work (170 W.m^{-2}) below −7°C. Anti-contact gloves should be worn to prevent contact frostbite when cold surfaces below −7°C are within reach (see also Section 7.4). Care is required in the handling of petrol, alcohol, cleaning fluid or other cryogenic fluids with a boiling point only just above ambient temperature, at air temperatures below 4°C. Cold injury can result from the rapid evaporative cooling associated with splashes or from clothing contaminated by these liquids.

5.2.5 Work/rest regimes

For work performed continuously in a cold environment with an equivalent chill temperature below −7°C, warm shelters should be available for rest and recovery. During rest pauses it is recommended that dry clothing be provided as necessary and body fluids replaced (preferably by warm, sweet drinks and soups) to combat dehydration. Alcohol and caffeine-containing beverages have adverse diuretic and circulatory effects (see Chapter 11).

In environments of −12°C or below *ie* in many cold stores, it is necessary for workers to be under constant protective observation or supervision (see also BS 4434, 1995). Work rates should not be so high as to cause heavy sweating, but if this is unavoidable, more frequent rest pauses in the warm for changing into dry clothes should be taken. Sitting or standing still for long periods in the cold should be avoided. Air movement should be minimised by properly designed air distribution systems and should not exceed 1 m.s^{-1} at the work site. Out of doors in snow or ice-covered terrain, eye protection should be provided from blowing ice crystals. Safety goggles are needed to protect against UV radiation and glare.

For light to moderate hard work (*eg* 230 W.m^{-2} walking at 3 mph on level ground) in environments below −26°C, warm shelters should be used at regular intervals and rest pauses arranged according to the schedule in Table 5.2. There are usually significant subjective and physiological differences between operatives, especially in the reactions of the hands and feet to cold. Natural work/rest routines vary for workers of different age and because of the metabolic cost of different tasks. It is therefore unwise to insist on a rigid work/recovery routine for all operatives. Further advice on control of cold environments and 'Work-warming Regimen' is given in ACGIH (1995) whilst the HSE provide guidance on cold-room working (HSE, 1994) and on construction work in cold weather (HSE, 1985).

5.3 Cold Stress Standards and Indices

Standards relating to the performance of work, thermal balance and exposure duration in cold environments are less well validated than those for heat. It is generally more difficult to assess the stress of cold climates, possibly because of the potentially greater part played by behavioural thermoregulation in maintaining body core temperature equilibrium. The objectives of cold exposure standards are to avoid core temperature falling below 35°C and to prevent cold injury to the extremities. Cold stress should therefore be evaluated in terms of both general cooling of the body (Still-Shade Temperature, Required Clothing Insulation) and local cooling of the exposed extremities (Wind Chill Index).

Table 5.2

Periods of work (min) after which a 10 min rest pause should be taken in a warm shelter during a 4-h work shift in temperatures of –26°C and below for outdoor environment with clear sky

(adapted from ACGIH, 1995)

Wind Speed	Still Air		5 mph (2.2 m.s^{-1})		10 mph (4.5 m.s^{-1})		15 mph (6.7 m.s^{-1})		20 mph (8.9 m.s^{-1})	
Work Rate*	A	B	A	B	A	B	A	B	A	B
Air Temp. (°C)			Work Period (min)							
-26 to -28	110	110	110	75	75	55	55	40	40	30
-29 to -31	110	75	75	55	55	40	40	30	30	**
-32 to -34	75	55	55	40	40	30	30	**	**	**
-35 to -37	55	40	40	30	30	**	**	**	**	**
-38 to -39	40	30	30	**	**	**	**	**	**	**
-40 to -42	30	**	**	**	**	**	**	**	**	**
below -43	**	**	**	**	**	**	**	**	**	**

* Work Rate A = 230 W.m^{-2}, moderately hard work, walking at 3.5 mph on level

B = 145 W.m^{-2}, light to moderate work, alternatively standing and walking at 2.5 mph on level

** Non-emergency work should cease.

5.3.1 Still-Shade Temperature (S.S.T.)

This is an 'equivalent' temperature intended for outdoor situations with no solar heat exchange and no wind effect (Burton and Edholm, 1955).

The correction applied for the solar heat absorbed by the body can be expressed as a 'thermal radiation increment' (in full sunshine this can amount to 2 or 3 times the resting metabolic rate). In calculating this factor, numerous corrections need to be made for solar heat absorbed by clothing, the posture of the subject, reflecting power of the surface, absorption by moisture and dust in the air and by clouds, scattered radiation, diffuse reflection *etc*, but in spite of this it is possible to arrive at a useful average figure for the radiation incident on the body. The radiation increment (T_R in °C) is thus defined by:

$$T_R = 0.42\ (1 - 0.9\ x)\ a.\ I_A$$

where

x = 'average cloudiness' (meteorological system, *eg* 3/10 cloudy)

a = % absorbtivity of clothing (88% for black, 57% khaki and 20% for white)

I_A = insulation of air, where $I_A = I_{SA} - W$

(I_{SA} is standard value for still air, W the decrement of insulation for different wind velocities.)

The thermal radiation increment to be added to the temperature to give the equivalent shade temperature is shown in Figure 5.2 (adapted from Burton and Edholm, 1955).

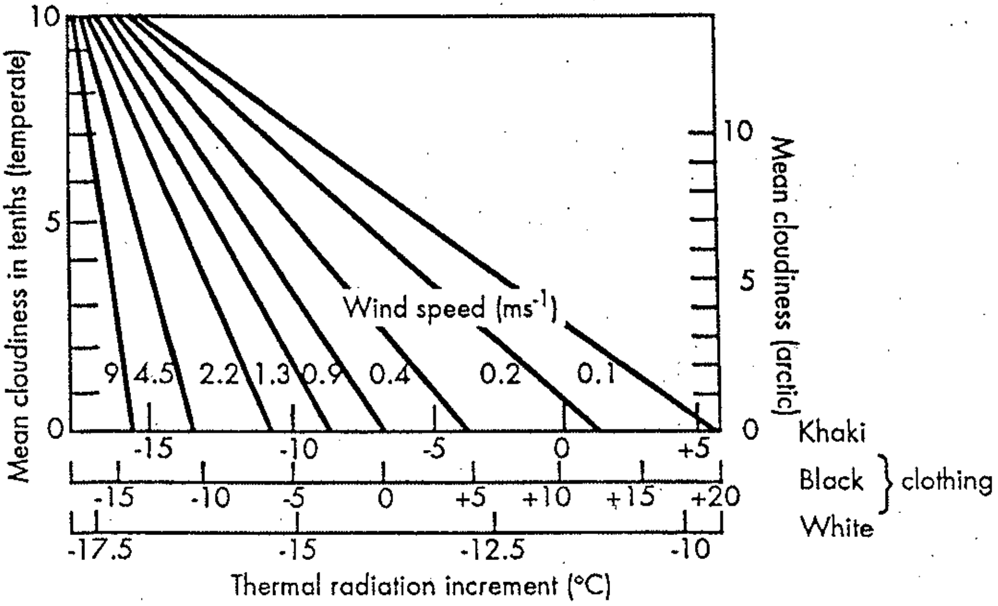


Figure 5.2: Still-shade temperature:
thermal radiation increment for various degrees of cloudiness, clothing and wind speed

The equivalent still-air temperature or thermal wind decrement can be calculated if the metabolic rate of the individual is known. Since it is not possible to include metabolic rate in a unitary scheme, separate standards must be applied for men with different degrees of activity (Figure 5.3).

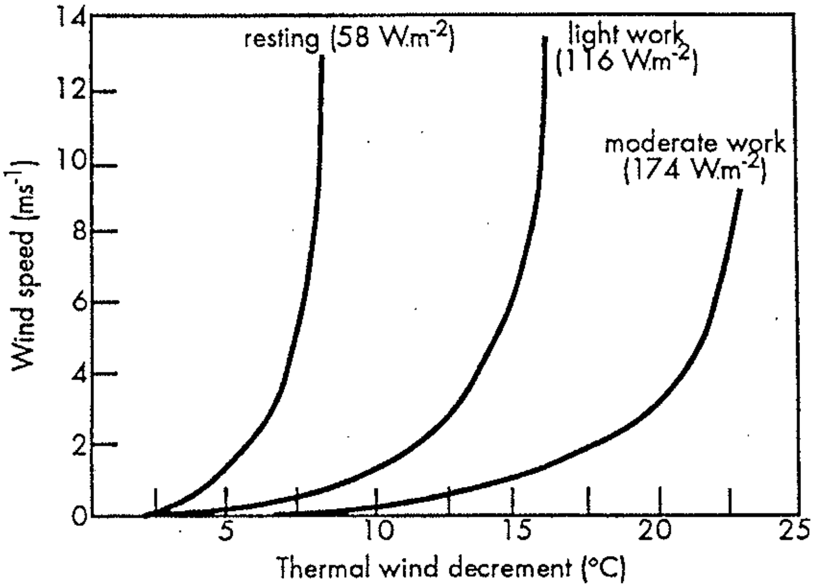


Figure 5.3: Still-shade temperature:
thermal wind decrement for resting, light and moderate work
(adapted from Burton and Edholm, 1955)

The thermal wind decrement (°C) is given by H x W / (0.11) where H is the total heat and W the decrement of insulation to be subtracted from the insulation of still air in correcting for air movement ($I_A = I_{SA} - W$).

The equivalent 'still-shade temperature' is thus derived by subtracting the thermal wind decrement (°C) and adding the radiation increment (°C). The windspeed enters into both of these corrections to increase the wind decrement and decrease the radiation increment and thus in outdoor conditions of sunshine the wind speed becomes of great importance in determining comfort and endurance.

5.3.2 Wind Chill Index (WCI)

The Wind Chill Index (WCI) is an index of heat loss from the body and is not the same as the wind chill correction factor applied to environmental conditions (Table 5.1). WCI was developed (Siple and Passel, 1945) in order to identify the potential risk resulting from the combined cooling effect of wind and cold conditions. It is, nevertheless, based on an artificial model for the human, *ie* on the cooling characteristics of a warm (33°C) water-filled tin cylinder hoisted on a pole in a station in Antarctica under different conditions of wind speed and temperature. The index is found to correlate well with human reactions to cold and wind and is successful in identifying conditions of potential danger when skin surfaces are exposed. It is of particular value in estimating the ***local*** cooling of hands, feet and head that may produce deterioration of physical performance and cold injury.

The relationship between wind speed and cooling power is not linear; the greatest increase of cooling is produced by air movement increasing from calm to 2 $m.s^{-1}$, while from 9 to 14 $m.s^{-1}$ there is no great increase (Figure 5.4). An important criticism of the WCI is that the amount of clothing worn, which is theoretically necessary to express the effect of wind on heat loss of subjects, is not taken into account. The proven usefulness of the WCI in practice is probably because tolerance of cold conditions, given adequate nutrition, is ultimately determined by the reaction of parts of the unprotected body. Complete protection of exposed areas, by the use of suitable face mask and gloves would, in effect, make the WCI redundant.

The WCI as defined by Nishi & Gagge (1977) is:

$$K_o = (33 - t_a)(10v^{0.5} - v + 10.45)$$

where K_o is the cooling power of the environment, the original units being $kcal.m^{-2}.h^{-1}$, t_a the ambient temperature (°C) and v the air velocity in $m.s^{-1}$. Values are given in Table 5.3 and Figure 5.4, with conversions to units of $W.m^{-2}$ also quoted. There are, however, different versions of the formula and descriptions relating to the values, as reviewed by Dixon and Prior (1987).

Table 5.3 also gives a practical interpretation of the WCI *ie* the 'chilling temperature' (t_{ch}) defined as the ambient temperature which, under calm conditions (<1.8 $m.s^{-1}$ wind speed), produces the same cooling power as the actual environmental conditions. t_{ch} is derived from WCI by

$$t_{ch} = 33 - WCI/22 \text{ where WCI is in units } kcal.m^{-2}.h^{-1} \text{ or}$$
$$t_{ch} = 33 - WCI/25.5 \text{ where WCI is in units } W.m^{-2}.$$

Table 5.3
A practical interpretation of the WCI is the 'chilling temperature' (t_{ch}) defining the ambient temperature which, under calm conditions (<1.8 m.s^{-1} wind speed), produces the same cooling power as the actual environmental conditions.

Note: the WCI values in the table are rounded to the nearest 100.
(Source: ISO/TR 11079, 1993 - see Appendix A)

WCI kcal.m^{-2}.h^{-1}	**WCI** W.m^{-2}	t_{ch} °C	**Effect**
1 000	1 200	–14	Very cold
1 200	1 400	–22	Bitterly cold
1 400	1 600	–30	Exposed flesh freezes within 1 h
1 600	1 800	–38	
1 700	2 000	–45	Exposed flesh freezes within 1 min
1 900	2 200	–53	
2 100	2 400	–61	Exposed flesh freezes within 30 s
2 200	2 600	–69	

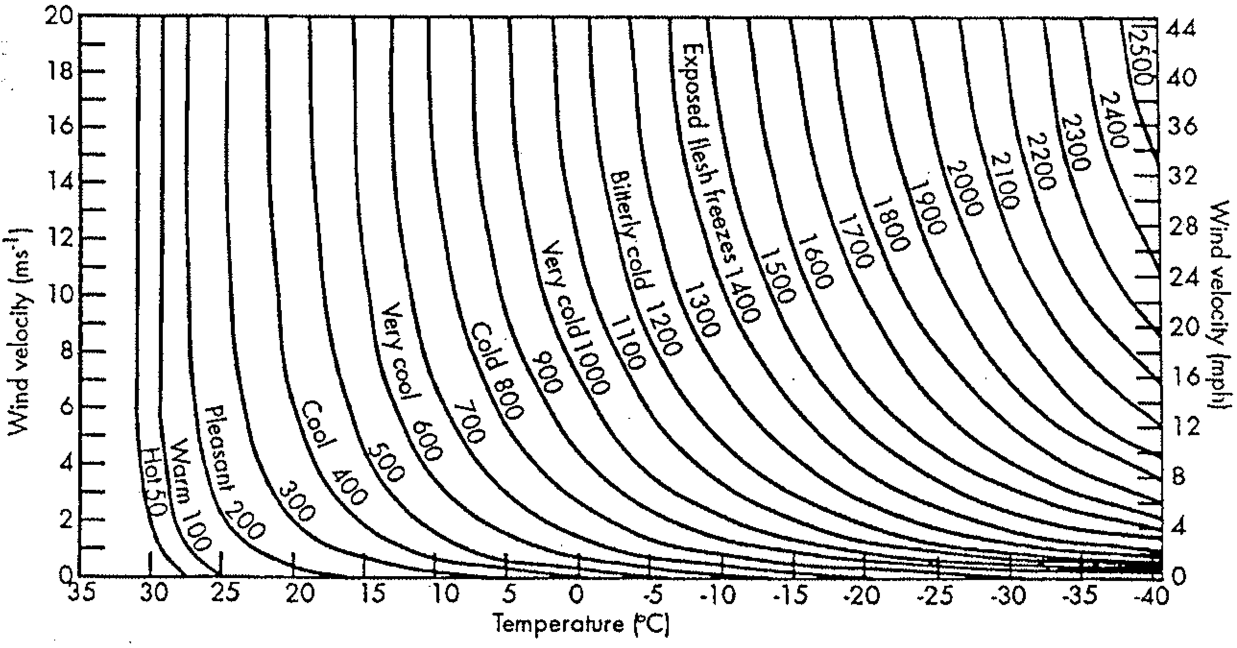


Figure 5.4: Wind Chill Index (WCI) showing the rate of cooling in kcal.m^{-2}.h^{-1} (x 1.16 to convert to W.m^{-2}) at different combinations of wind velocity and temperature

5.3.3 Required Clothing Insulation (IREQ)

IREQ is defined as the resultant clothing insulation required to maintain the body in thermal equilibrium under steady-state conditions when sweating is absent and peripheral vasoconstriction is present. The important role of clothing insulation, omitted in the Wind Chill Index, is used in IREQ to express cold stress in terms of general body cooling and the insulation required to maintain thermal balance (Holmer, 1984). Thus, the higher the value of IREQ at any given activity level, the greater the cooling power of the environment, and an increase in energy expenditure will act to reduce IREQ.

IREQ differs from I_{cl} (see Section 1.3.2.) which is a static insulation value of clothing that does not take into account the effects of posture, wind speed and body motion. I_{cl} is the basic insulation of an assembly usually directly measured on a static manikin, and it may be reduced by as much as 50% by the combined effect of body activity and wind speed.

Since there is an upper limit to the amount of clothing insulation possible, a duration limited exposure (DLE) based on acceptable levels of body cooling may be calculated for the available clothing. During exposure of a few hours, a certain reduction in body heat content (Q_{lim}) is acceptable and can be used to calculate the allowable duration of exposure when the rate of heat storage (S) is known, where

$$DLE = Q_{lim}/S$$

After exposure to cold, a recovery period should be allowed to restore normal body heat balance. Recovery time (RT) may be calculated in the same way as DLE if S is the rate of heat storage for the thermal conditions during the recovery period.

Thermal equilibrium can be achieved at different levels of thermoregulatory strain (defined in terms of mean skin temperature, sweating and change in body heat content) and, for practical purposes, IREQ is applied at two different levels of physiological strain:

$IREQ_{(min)}$: a minimal thermal insulation to maintain body thermal equilibrium at a subnormal level of mean body temperature

$IREQ_{(neutral)}$: a neutral level of insulation required to provide body thermal equilibrium at a normal level of body temperature.

In occupational work, $IREQ_{(min)}$ represents the highest index of cold stress admissible for body cooling (Figure 5.5).

IREQ provides the basis for an ISO Technical Report (ISO/TR 11079, see Appendix A) which outlines the more recent methods and strategies to evaluate the stress of cold environments. At present, ISO/TR 11079 is not regarded as an International Standard, but rather a prospective standard for provisional application so that experience of its use in practice may be gained (*eg* O'Leary and Parsons, 1994). A computer program developed by Holmer and Nilsson for calculating IREQ, DLE, RE and WCI is given in the ISO/TR. Protective clothing is discussed in general terms in Section 5.2.3; detailed information on the estimation of the thermal insulation and evaporative resistance of clothing is given in BS ISO 9920: 1995.

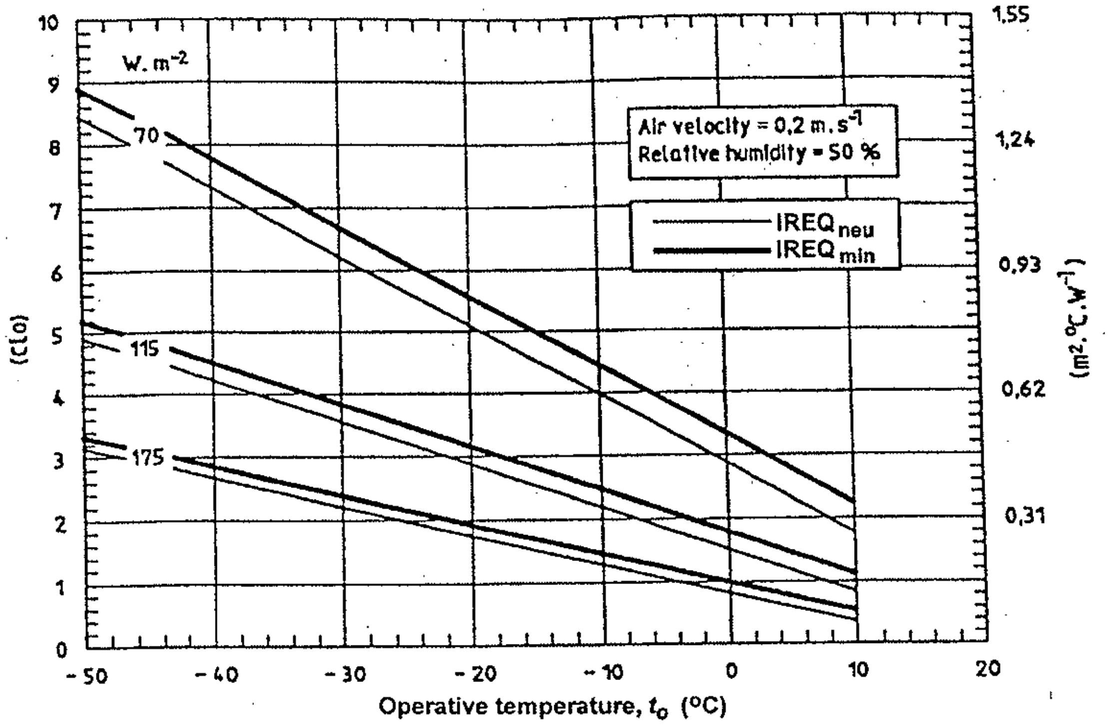


Figure 5.5: Comparison of IREQ$_{(min)}$ and IREQ$_{(neutral)}$ at three levels of metabolic heat production (ISO/TR 11079:1993)

(The operative temperature is the integrated value of the air temperature and mean radiant temperature weighted according to values of the convective and radiation transfer coefficients respectively.)

6 SURVEYING THE THERMAL ENVIRONMENT

6.1 Objective Measurements and Instrumentation: Introduction

The determination of thermal comfort or stress indices requires the accurate knowledge of physical quantities of the thermal environment. The fundamental parameters are:

- air temperature (°C)
- mean radiant temperature (°C)
- absolute humidity of the air (kPa.kg^{-1} or kg.kg^{-1})
- air velocity (m.s^{-1})

Methods of measuring these parameters are given in BS EN 27726 (1994) *ie* ISO 7726 (1985), 'Thermal environments - Instruments and methods for measuring physical quantities', which is currently under revision (*ie* at 1996).

The thermal environment in typical occupied spaces varies with time due to the action of controls or the influence of varying external conditions. Also, there are likely to be variations throughout the space, particularly near to windows and air inlet and extract grilles. Most heating systems impose temperature gradients. Measurements therefore should be made at various positions throughout a room and at 3 heights - ankle height (0.1 m) abdomen level (0.6 m sitting areas, 1.1 m standing areas) and head height (either 1.1 m or 1.7 m). Measurements should be carried out over the cycling period of the controls and, where external solar conditions affect the internal environment, at different times during the day.

In cases of heat and cold stress, individual circumstances need to be taken into account when selecting positions for measurement. In general, the position should reflect the thermal load on the individual concerned. The concept of 'personal' monitoring, where equipment is attached to the individual to monitor the 'local' conditions, is not currently routinely applied in the thermal environment for practical reasons, but may be undertaken in special circumstances *eg* fire fighting.

6.2 Instrumentation

6.2.1 Air temperature

This is the temperature of the air and affects the convection heat transfer from an individual. It can be measured by a mercury-in-glass thermometer, a thermocouple, a platinum resistance thermometer or a thermistor. Table 6.1 shows the relative merits and accuracy of the various sensors (see also Hardy, 1975).

Care must be taken to prevent the thermometer from being affected by radiation from heat sources. This can be achieved by:

- Reducing the emissivity of the sensor.
- Shielding the sensor from heat sources *eg* by placing a polished metal tube or film around the sensor - the shield should be separated from the sensor by an air space large enough to allow air to circulate.
- Increasing the air velocity around the sensor by forced ventilation.

Some commercially available equipment use all 3 methods simultaneously.

Table 6.1
Instrumentation for temperature measurement
(Acknowledgement to National Physical Laboratory: Report Qu48 1978)

Property	Thermo-couple *	Thermistor	Platinum resistance thermometer	Semi-conductor junction **	Mercury in glass
Long-term stability	variable	ages	stable	stable	stable
Signal for 1°C change	10-60 μV	1% of resistance (linearised)	40 μV (at 1 mA current)	2.3 mV	-
Speed of response	fast	fast	moderate	moderate	slow
Relative cost ***	1	4	5	2	3
Mechanical stability	robust	moderate	moderate	robust	poor
Reproducibility	moderate	good	very good	poor	very good
Linearity	moderate	linearised versions required	good	good	good
Accuracy (typical)	±2°C	±1°C	±0.1°C	±1°C	±0.1°C NPL calibrated

* cold junction or compensated circuit required
** high self-heating effect
*** relative cost: 1: cheap
5: expensive

All thermometers need time to reach equilibrium. The smaller the probe and the faster the air circulation around it, the quicker the response. Moderate to quick response is essential when monitoring heating/ventilation systems.

In some circumstances temperature probes are required to assess surface temperatures. This may be in relation to the temperature of touchable surfaces or to investigate, for instance, radiation sources, control measures and effectiveness of insulation. In such cases the thermometer sensor requires to be mounted in a suitable probe which provides good surface contact (*eg* spring loaded), good conductivity (*eg* copper mounted) and fast response *via* low thermal mass. Most suitable are electrical sensors in purpose-designed probes.

6.2.2 Mean radiant temperature (MRT)

This is the temperature of a uniform imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual enclosure. It can be measured by instruments which allow the heterogeneous radiation from the walls of the enclosure to be integrated into a mean value.

The mean radiant temperature (MRT) can be measured directly using a two-sphere radiometer. In this method two spheres with different emission coefficients (one black and one polished copper) are used. The two spheres are heated to the same temperature so that they will be exposed to the same convective heat loss. As the emittance of the black sphere is higher than that of the polished one, there is a difference in the heat supplied to the two spheres to maintain the same temperature. This is a measure of the incoming radiation.

The mean radiant temperature can be calculated as given in Table 6.2.

Table 6.2

Calculation of the mean radiant temperature (MRT) for a two-sphere radiometer

$$(t_r + 273)^4 = (t_s + 273)^4 + \frac{(P_p - P_b)}{\sigma\ (E_b - E_p)}$$

where

t_r = mean radiant temperature (°C)
t_s = sensor temperature (°C)
P_p = heat supplied to polished sphere ($W.m^{-2}$)
P_b = heat supplied to black sphere ($W.m^{-2}$)
E_p = emissivity of the polished sphere
E_b = emissivity of the black sphere
σ = Stefan Boltzmann constant, $5.67 \times 10^{-8}\ W.m^{-2}.K^{-4}$

Alternatively, the MRT can be derived from the readings of a black globe thermometer. Apart from its simplicity, the advantage of using a black globe thermometer is that the globe temperature can also be used directly as a thermal index, or as a parameter within an index (Sections 3.3 and 4.2), and it can operate without an electrical power supply.

The black globe thermometer consists of a hollow black globe usually made of copper (because of its high conductivity) in the centre of which is placed a temperature sensor such as the bulb of a mercury thermometer, a thermocouple or a resistance probe.

The globe can in theory have any diameter but as the formulae or nomograms used in the determination of the MRT depend upon the diameter of the globe, a diameter of 150 mm, specified for use with these formulae, is generally recommended, although other sizes are commercially available.

It should be noted that the smaller the diameter of the globe, the greater the effect of the air temperature and air velocity, thus causing a reduction in the accuracy of the measurement of the MRT. However, smaller globes (*eg* 40 mm) have the practical advantage of reaching thermal equilibrium with the environment more quickly.

The black globe is placed in the actual enclosure where the MRT is to be measured. The globe tends towards a thermal balance under the effect of the exchanges due to the radiation coming from the different heat sources of the enclosure and under the effect of the exchanges by convection.

The MRT can be calculated from the globe value as given in Table 6.3, or determined from standard nomograms (Ellis *et al*, 1972).

As the radiation of an enclosure is frequently one of the main factors in contributing to the thermal stress of an environment, an incorrect determination of MRT can lead to errors in the assessment of stress.

When the radiation is heterogeneous, the measurement of a black globe temperature carried out at a single point is not representative of the overall radiation field to which the subject is exposed. It is, therefore, necessary to place black globes at the 3 heights quoted in Section 6.1, in such a way that the radiation received by each of the globes is very close to the radiation received by each part of the body located at the same level.

For normal environments the MRT is the mean of all 3 values, but for stressful environments the abdomen reading has twice the weighting of the head and ankle values.

The response time for a black globe thermometer is about 20 to 30 minutes according to the physical characteristics of the globe and the environmental conditions. Successive readings of the globe temperature enable the thermal balance to be registered. Because of its high inertia, the black globe thermometer cannot be used to determine the radiant temperature of environments which vary rapidly.

The accuracy of measuring the MRT using a black globe can vary to a great extent according to the values for the other thermal parameters of the environment.

The use of a black globe thermometer for the assessment of the MRT as experienced by an individual is an approximation due to the difference in shape between a person and a globe. In particular, the radiation coming from a ceiling or a floor will be over-estimated by the globe in relation to that received by an individual.

Table 6.3
Calculation of the mean radiant temperature (MRT) from the globe thermometer reading

The temperature, t_g, of the globe at thermal equilibrium allows the mean radiant temperature (mrt) t_r to be determined.
For natural convection (150 mm globe)

$$t_r = \left[(t_g + 273)^4 + 0.4 \times 10^8 (t_g - t_a)^{0.25} \times (t_g - t_a)\right]^{0.25} - 273$$

or for forced convection

$$t_r = \left[(t_g + 273)^4 + 2.5 \times 10^8 \times v^{0.6} \times (t_g - t_a)\right]^{0.25} - 273$$

where:-
t_r = mean radiant temperature (°C)
t_g = black globe temperature (°C)
t_a = air temperature (°C)
v = air velocity (ms^{-1})

In order to decide whether the equations for natural or forced convection should be used it is first necessary to evaluate the coefficient of heat transfer.

For natural convection:-

$$h_{cn} = 1.4 \left[\frac{t_g - t_a}{D}\right]^{0.25} \qquad (W.m^{-2}.°C^{-1})$$

For forced convection:-

$$h_{cf} = 6.3 \frac{v^{0.6}}{D^{0.4}} \qquad (W.m^{-2}.°C^{-1})$$

If $h_{cn} > h_{cf}$ use natural convection formula

If $h_{cf} > h_{cn}$ use forced convection formula

where:-
h_{cn} = coefficient of heat transfer for natural convection
h_{cf} = coefficient of heat transfer for forced convection
D = diameter of globe (m)
t_g, t_a, v as above.

If a non standard sized globe is used, then the appropriate equations are :-

for natural convection

$$t_r = \left[(t_g + 273)^4 + \frac{0.25 \times 10^8}{\varepsilon} \left(\frac{t_g - t_a}{D}\right)^{0.25} (t_g - t_a)\right]^{0.25} - 273$$

for forced convection

$$t_r = \left[(t_g + 273)^4 + \frac{1.1 \times 10^8 v^{0.6}}{\varepsilon D^{0.4}} (t_g - t_a)\right]^{0.25} - 273$$

where:-
D = diameter of globe (m)
ε = emissivity
t_r, t_g, t_a, v as above.

The globe thermometer is not suitable for assessing localised sources of radiation. Direct radiation effects from individual surfaces can be obtained by measuring the temperature of the surface directly with a suitable contact probe, or measuring emission with an infra-red, non-contact thermometer.

6.2.3 Humidity

There are many ways of measuring the humidity of the air. A fundamental technique is to determine the **dew point**, *ie* the temperature at which the air becomes saturated. This is done by cooling a surface until water vapour begins to condense on it. The onset of condensation is sensed optically by shining a light onto the surface and detecting the scattering of the light by the moisture droplets.

An alternative method is to use a material that changes its dimensions as the relative humidity (rh) changes. Human or horse hair is the most commonly used hygroscopic material and is the basis of the **hygrograph**. As the length of the hair alters the change is transmitted by a magnifying linkage to a recording pen. The pen writes on a chart driven by clockwork (or a quartz clock) to give a continuous recording of the humidity.

Hygrometers frequently incorporate a second pen connected to a bimetallic element to record temperature as well as humidity. Both the humidity and air temperature readings need regular calibration. Although it is only accurate to ±5% rh and ±1°C the instrument is robust and simple to use and because it needs no external power supply can be used in a wide range of locations. The response to rh becomes non-linear at high and low values.

Some humidity sensors rely on their change in electrical properties with changes in moisture content in response to changes in atmospheric humidity level. The sensors are based on either changes in resistance or capacitance. **Resistance probes** are particularly sensitive to atmospheric pollutants and cannot tolerate any condensation and so are restricted to clean environments where the relative humidity is less than 90%. **Capacitance** types are tolerant to condensation and not so affected by air quality as long as it is breathable. The sensors are generally made of plastic and can be interfaced to a wide range of recording instruments. Their accuracy is typically ±3%; calibration is important.

A fourth class of instrument relies on the cooling produced by water evaporating from a fabric sleeve surrounding a thermometer bulb. These are known as **psychrometers.** A psychrometer consists of two thermometers and a device to ensure ventilation of the thermometers at a velocity greater than 4 m.s^{-1}. The thermometer can be any sensor, as previously described.

The air movement is generated either by rapidly moving the thermometers through the air as in a whirling psychrometer or by sucking air over the thermometer by a fan driven electrically or mechanically *eg* the Assman hygrometer. Static hygrometers are also available which rely upon natural ventilation of the thermometers, but their usefulness is fairly limited (although it should be noted that this version is required for the WBGT index, Section 4.2.1). Terms used to describe the two types of wet bulb are:

natural - static, unaspirated, screen, sheltered, Mason's;
forced - aspirated, sling, whirling, psychrometric, Assman.

The first thermometer in the psychrometer is an ordinary thermometer indicating the air temperature. This is often referred to as the 'dry' bulb temperature of the air.

The second consists of a thermometer surrounded by a wet wick generally made from close-meshed cotton. The end of the wick lies in a container of water. The water is raised by capillary attraction from the container to the thermometer and then evaporates at a rate dependent upon the humidity of the air. This results in a greater cooling of the thermometer the drier the air (this cooling is limited by the heat transfer due to air convection). The temperature indicated by the thermometer surrounded by the wet wick is referred to as the 'wet bulb' temperature (psychrometric). The observed dry bulb temperature and wet bulb temperature are used with the psychrometric chart to determine both absolute and relative humidity. It is important to measure the temperature of the aspirated bulb immediately after aspiration (whirling) as the value will rise once air movement is reduced.

As with measuring air temperature, the thermometers should be shielded from radiation, while the water used should be distilled and the wick kept clean and free from grease.

A further instrument for rh measurement uses a **lithium chloride cell.** The active part of the sensor consists of a thin insulating tube covered with muslin glass, impregnated with lithium chloride solution. Two electrodes are connected to a low voltage supply. The resulting current causes the lithium chloride solution to heat up and the previously absorbed water to evaporate. Once the water has evaporated, the solution crystallises. The electrical conductivity, and hence the current between the two electrodes, is considerably reduced and the temperature falls once more. The lithium chloride solution can then absorb water vapour contained in the air, which has the effect of increasing its electrical conductivity. The current increases and causes the water to evaporate once more.

A balance is quickly established between the water vapour content of the air, the heating power and the temperature of the detector. This equilibrium temperature, which is measured using a thermometer, depends solely on the water vapour pressure of the air. It gives a direct measurement of the dew point or the absolute humidity, this being one of the advantages of lithium chloride hygrometers.

The inter-relation between the humidity parameters quoted, *ie* wet and dry bulb, relative humidity, absolute humidity and dew point is given on a psychrometric chart (*eg* CIBSE, 1987).

6.2.4 Air velocity

The air velocity affects the convective heat transfer and the evaporative heat transfer from a person. It can be measured by an omnidirectional probe *eg* a hot sphere anemometer or katathermometer or by a directional instrument *eg* a hot wire anemometer or rotating vane anemometer. Air flow may be visualised by the use of smoke.

The air velocity usually fluctuates considerably and the mean velocity should be quoted as this effectively governs the heat transfer between a person and the environment. However, large fluctuations may have an effect on the subjective sensation of air movement and thus these may need to be identified.

Both the **hot sphere** and **hot wire anemometers** rely on an electrical current heating the sensor to a temperature above ambient and being cooled by the air movement. The amount of cooling is dependent on the air velocity, the ambient air temperature and the characteristics of the heated element. All hot element anemometers should therefore have two temperature sensors, one to measure the hot element and the other to measure the air temperature.

One disadvantage with hot element anemometers is that if the temperature of the element is high, natural convection around the sensor will affect the measurement of low air velocities. The ***katathermometer*** (literally - 'down' or 'falling' thermometer, sometimes referred to simply as a 'kata') overcomes this disadvantage but is not suitable for automatic data recording systems. The katathermometer has a stem with an upper and lower graduation corresponding to a temperature drop of 3°C. In operation the thermometer is heated to above the temperature of the upper graduation, wiped dry and allowed to cool. The time taken to cool over the marked temperature interval is measured. Air velocity may then be derived by formula or nomogram from three known quantities *viz*: the cooling time, the dry bulb temperature of the air, and a calibration factor for the particular katathermometer which represents the heat loss per unit surface area, as the thermometer cools (*eg* Ellis *et al*, 1972).

The katathermometer has a long response time and hence averages air movement values over the measurement period. It is not suitable for detailed measurements of environments where large or rapid variations in air movement occur, nor for determining turbulence intensity (see Section 6.4.1).

For the detection and visualisation of draughts, localised air movement, air distribution patterns *etc*, a smoke tube, smoke bomb or smoke generator can be used. Care should be exercised in their use.

A range of British Standards apply to the equipment discussed (BSI, 1995).

6.3 Composite Instruments

Instruments are available that measure more than one parameter of the thermal environment. These either display the value of each individual parameter leaving the operator to combine them into any desired comfort or stress index or else the instruments are programmed to give automatically a direct read out of the relevant index.

6.3.1 Indoor climate analyser

This instrument measures and displays the 4 environmental factors - air temperature, radiant temperature, air velocity and humidity. It has a facility for storing the readings and these can be output to a chart recorder or computer for later analysis. It has been designed to satisfy the requirements of BS EN 27726 (1994) *ie* ISO 7726 (1985), 'Thermal environments - Instruments and methods for measuring physical quantities'.

Air temperature is measured by a platinum resistance thermometer. The sensor is designed to be shielded from radiation effects and for fast response; it is accurate to ±0.2°C. Besides the air temperature sensor the instrument can also have a surface temperature probe, again using a platinum resistance element. The small size of this sensor ensures that any change in surface temperature caused by the sensor pressing on the surface is minimised.

The radiant temperature transducer measures the plane radiation temperature simultaneously in two opposite directions and thus radiant temperature asymmetry can be measured. Each face of the transducer consists of a gold plated and black painted element of the same size. The black painted element is affected by radiation whilst the gold plated one is not. Therefore, the difference in temperature between the two elements is a function of the amount of radiation received. Although the MRT is not measured directly it can be calculated by measuring the plane radiant temperature in six directions, as represented by the six faces of a cube.

The air humidity sensor directly measures the dew point temperature. From this measurement and the value of air temperature, the relative humidity can be calculated. This is done automatically in the climate analyser. The transducer operates by cooling a mirror until dew is formed. When condensation occurs light from an LED is scattered by the moisture droplets onto a light sensitive transistor. The temperature of the mirror and hence the dew point temperature is measured by a platinum resistance element.

Air velocity measurement is based on the constant temperature anemometer principle. The probe has two ellipsoidally shaped bodies one of which is heated and one unheated. The power input to the heated element required to maintain a constant (15°C) temperature difference is a function of the air velocity. The sensor is non-directional and can react quickly to fluctuating velocities.

Details are given in Olesen and Madsen (1988). The measuring principles can be incorporated into an instrument for determining a range of heat stress/comfort parameters (Olesen, 1988).

6.3.2 Wet bulb globe temperature (WBGT) meter

One of the most widely used heat stress indices is the WBGT index, as defined in Section 4.2.1. The index requires measurement of natural wet bulb temperature, globe temperature (150 mm globe) and air temperature. Smaller globes (*eg* 40 mm) are sometimes used in practice; their readings should be corrected for globe size, but often the correction involved is sufficiently small to ignore. Wet bulb globe temperature meters thus have 3 sensors and automatically weight the individual readings to display the WBGT index. In some instruments there is the facility to connect 3 sets of sensors measuring the conditions at 0.1 m, 1.1 m and 1.7 m heights. These can be automatically combined to give an overall WBGT index with the abdomen reading (1.1 m) having twice the weighting of the other two. WBGT meters are used to evaluate heat stress in hot working environments and to ensure that relevant standards are met. They can also be used to evaluate the effect of any changes made to the working environment. Advantages of electrical composite instruments are that they can measure remotely, monitor continuously and be linked to alarm systems.

6.3.3 Thermal comfort meter

This meter is designed to give a direct reading of comfort and is based on Fanger's Predicted Mean Vote (PMV) (see Section 3.3). The ellipsoidal sensor is designed to simulate the thermal characteristics of a human body. It contains a surface temperature sensor and a surface heating element. The power to the heating element is automatically adjusted to maintain a surface temperature similar to that of a thermally comfortable person clothed as set on the instrument. When mounted with the major axis vertical the sensor simulates a standing person, whilst when inclined by 30° to the vertical it simulates a sitting person.

Besides setting the clothing level it is also necessary to set the activity level of the occupants of the space and the humidity. The instrument then integrates the effect of the air and radiant temperatures and of the air velocity surrounding the sensor to give a direct reading of PMV and PPD (percentage of people dissatisfied).

Although the instrument gives a direct reading of comfort as defined by Fanger's comfort equation it does not measure each parameter of the thermal environment directly. Therefore, if the comfort level is outside the permitted range, the instrument cannot be used as a diagnostic tool to determine what physical parameter should be changed.

NOTE: The accuracy (as opposed to the resolution) of commercially available instruments should always be checked prior to use and an instrument reading is no better than its calibration value.

6.4 Undertaking a Survey

6.4.1 Data required

Basic data required for any assessment of the thermal environment involve the following 6 parameters.

Four parameters related to the environment (Section 6.2):

1. **Air temperature (°C):** measured such as to avoid any influences of radiation sources.
2. **Radiation conditions (°C):** expressed *via* the globe temperature, or *via* surface temperature readings and/or the MRT (which can be derived from the globe temperature).
3. **Humidity conditions :** expressed as relative humidity (%); wet (sling or screen) and dry bulb (°C); vapour pressure (kPa); or absolute humidity (kg of moisture per kg of air).
4. **Air movement ($m.s^{-1}$)**

Plus two parameters related to the individual:

5. **Clothing:** usually measured or estimated as a 'clo' value or a clothing 'attire' (light, medium, *etc*).
6. **Metabolic rate/work rate :** usually estimated *eg* as light, medium or heavy, but can be assessed accurately (in W or $W.m^{-2}$) through physiological tests (BS EN 28996: 1994).

Not all six of the above parameters may be required in an assessment - this will depend on the nature of the assessment and the comfort/stress index being used.

For example, the globe thermometer may suffice as an averaging parameter for air temperature and radiation conditions (*eg* as in the CET scale). For comfort conditions humidity measurements are less important, assuming relative humidity lies in the range 40-60%. Clothing and metabolic rate may be assumed at fixed values in the index used, or typical values selected.

However, individual measurements of the six parameters quoted may not give a full picture of the thermal environment and a more detailed assessment may require information on the following:

(a) Air temperature gradients

These are particularly relevant from feet to head, and in tall spaces with mezzanine levels.

(b) Surface temperature measurements

These may be required to establish further information on, for instance, radiation transfer, sources of cold downdraughts or issues relating to touchable surfaces.

(c) Radiation asymmetry

This can occur for example in offices where large areas of glazing can be warmer or cooler than other surfaces, with heating systems (*eg* heated ceilings) or in industry with specific radiation sources (*eg* furnaces and reaction vessels). Measurement requires specialist equipment such as provided by the indoor climate analyser.

(d) Air movement

Localised air movement (*ie* draughts) can cause severe discomfort, arising as down draughts from windows, poorly sealed buildings, or from ventilation systems. These are best identified using smoke as a tracer, and then air velocity and temperature assessed locally. The perception of draughts is also considered to be dependent on the turbulent nature of the air movement (Fanger and Christensen, 1986) leading to the requirement to measure turbulence intensity to determine the 'draught rating' (BS EN ISO 7730, 1995); a suitable hot wire type anemometer is required for such assessments.

(e) Humidity conditions

Variations within a space are not normally problematic. Variations over a time period may occur with changing air temperatures or changing meteorological conditions. Extreme values are considered to cause discomfort other than thermal (*eg* dry eyes).

(f) Clothing and activity

These can vary throughout the day, for different tasks and for different personnel. Their values are usually approximated, but may be the source of localised discomfort/stress for certain individuals. Protective clothing can add to the thermal stress burden.

(g) Physiological measurements

In some circumstances (particularly for extreme conditions of heat) it is necessary to monitor an individual's physiological condition *eg via* heart rate or body temperature. Full information on such measurement is given in ISO 9886 (1992) 'Evaluation of thermal strain by physiological measurement' (see also Section 1.2). Equipment is available for continuous monitoring in the field. Such measurements should always be undertaken with appropriate medical supervision in relation to both the taking of the measurements and the interpretation of results.

In all survey work it is essential to ensure that all instrumentation is suitably and correctly calibrated. It is important also to ensure that the measurer does not distort readings, *eg* by influencing temperature or humidity by their own body or shielding the measuring point from the true conditions occurring.

6.4.2 Presentation of results

Results should be presented clearly and precisely together with sufficient background information and description of the activity or process to enable interpretation. The form of presentation will depend on the type of survey, whether the problem is one of thermal discomfort or of heat/cold stress, and the use to which the results are to be put. A short summary of key findings and recommendations is essential for effective communication to management.

Table 6.4
Example of table for presentation of results

FIRM

DATE

SHEET NO.

PROCESS

EXTERNAL CONDITIONS

REF	POSITION	TIME	TEMPERATURES °C (STATIC)						WBGT	SLING HYGROMETER °C				KATA (No.)			NOTES
			DRY BULB		WET BULB		GLOBE			DRY BULB		WET BULB		SECS			
			Range	Mean	Range	Mean	Range	Mean		Range	Mean	Range	Mean	Range	Mean	Vel ms^{-1}	
		i	— —		— —		— —			— —		— —		— —			
		ii	— —		— —		— —			— —		— —		— —			
		iii	— —		— —		— —			— —		— —		— —			
		i	— —		— —		— —			— —		— —		— —			
		ii	— —		— —		— —			— —		— —		— —			
		iii	— —		— —		— —			— —		— —		— —			
		i	— —		— —		— —			— —		— —		— —			
		ii	— —		— —		— —			— —		— —		— —			
		iii	— —		— —		— —			— —		— —		— —			
		i	— —		— —		— —			— —		— —		— —			
		ii	— —		— —		— —			— —		— —		— —			
		iii	— —		— —		— —			— —		— —		— —			

WORK / SAMPLING POSITIONS:

Where possible, results should be presented in standard tabular form as this will enable the data to be appraised quickly and easily, and ensure that none are omitted. Table 6.4 shows a typical presentation of results for a heat stress survey. Where appropriate, the form would be accompanied by a plan of the space or building to show where readings were taken. It is also important to note prevailing weather conditions at the time of the survey as these may influence the internal conditions, clothing worn *etc* (Fishman and Pimbert, 1982).

6.4.3 Analysis and interpretation

The primary object of the analysis of results is to determine whether the thermal environment is acceptable and if not, whether occupants of a space are likely to suffer from discomfort or from the more serious effects of heat or cold stress. If the thermal environment is shown to be unacceptable, it is then necessary to identify the reason or reasons so that remedial action can be taken.

Analysis involves converting the data into a form which can be readily interpreted. The first step is the selection of a suitable stress or comfort index which takes into account all relevant factors. These will include: the measured environment, clothing, work rate and physiological condition of personnel (fitness, age, acclimatisation *etc*).

The index chosen should be related to an accepted standard which has been validated by field trials. In practice, no index is universally applicable. For thermal comfort a variety of standards are available *eg* BS EN ISO 7730 (Section 3.3). The most commonly accepted heat stress index is the Wet Bulb Globe Temperature (WBGT) which is used as the basis of the Standard BS EN 27243 *ie* ISO 7243 (Section 4.2).

ISO 7243 forms a useful baseline. Other indices and standards permit work at higher temperatures or under more onerous conditions than those permitted by ISO 7243, and many people work at higher temperatures without undue harm. However, susceptibility to heat stress varies from individual to individual and whilst most people, especially the young and fit, can work at higher temperatures, a small number are liable to suffer adverse effects.

Indices other than WBGT can prove useful in particular circumstances. However, if they permit work at temperatures higher than those allowed in ISO 7243, care will be necessary to ensure that the workforce does not include persons who are susceptible to the effects of heat, and medical screening and/or monitoring may be required.

6.5 Outcome of Survey

6.5.1 Precautionary measures

Precautions may be required when temperatures exceed those recommended in BS EN 27243: ISO 7243, or the heat stress standard chosen. These fall into four categories:

1. Environmental control, *ie* measures to reduce temperatures to acceptable levels. This is the preferred solution; alternative precautions are only acceptable if it is not reasonably practicable to reduce temperatures to a safe level and, even so, the temperature should be reduced as far as is reasonably practicable.

2. Selection of persons who are fit to work in hot environments and, where necessary, medical or physiological monitoring.

3. Reduction of the working period (*ie* a 'work/rest regime') or selection of work methods which are less physically demanding and therefore involve a lower metabolic rate.

4. The use of 'conditioned' protective clothing or, where thermal radiation is a problem, reflective clothing.

6.5.2 Environmental control measures

General precautions which can be taken to reduce temperature and control environmental conditions include control or elimination of the source of heat. This is the preferred method and is usually the most effective and economical. This involves for example:

(a) Insulation of hot surfaces and pipework

(b) Shielding of radiant heat sources

(c) Maintenance of plant and pipework to eliminate steam leaks.

(d) Reduction of plant and pipework temperatures

(e) Increased ventilation, air movement and local cooling

6.5.3 Personnel selection and monitoring

In deciding whether a person is suitable for work in hot environments, the following points should be considered:

(a) Overweight and physically unfit people have an increased risk of ill-effect. Those over 45 years old are also more susceptible to hot conditions.

(b) Some chronic illnesses, especially those affecting the heart and circulatory system, may be aggravated by work at high temperatures. Chronic skin disorders may also be affected.

(c) People suffering from minor illnesses such as influenza, or hangovers (especially if they are habitual heavy drinkers), or who are receiving certain medical treatment should avoid working in hot environments.

(d) People who have previously suffered from heat stress are often more susceptible to further attacks.

People who may be required to work in very hot environments, *ie* where conditions exceed those recommended in ISO 7243 (*eg* WBGT exceeds 33°C), or who fall into the above categories, should first consult a doctor.

In addition, physiological monitoring is also necessary. The form of monitoring will be determined by the degree of risk. In moderately hot conditions, it may be sufficient to ensure that workers look out for each other so that if one is unwell, he can be removed from the hot environment and treated immediately. If the environment is very hot, supervision by a trained first aider or qualified nurse may be necessary, possibly including measurement of pulse rate, sweat loss or deep body temperature (ISO 9886, 1992). No person should be permitted to work alone in a hot environment.

6.5.4 Work/rest regimes

Work may be permitted at very high temperatures for short periods followed by a period of rest either in the work area or, if conditions are very hot, in a cooler environment. The body is able to accumulate a certain amount of heat before the deep body temperature reaches an unacceptable level, and if exposure ceases before that level is reached, there will be no harm.

Various indices have been derived to enable the maximum allowable work period to be predicted *eg* BS EN 27243; ISO 7243 (WBGT), PHEL, Oxford Index, HSI *etc* (Section 4.2).

ISO 7243 sets work/rest limits that are acceptable for most people based on WBGT; the rest area is assumed to be at the same WBGT value. Physiological Heat Exposure Limit (PHEL), based on WBGT, sets limits that are appropriate for 95% of fit young workers. This allows work at much higher temperatures than those allowed by ISO 7243, with a maximum of 50°C WBGT. Note however that a small percentage of workers will suffer adverse effects at these temperatures so medical or physiological monitoring of workers is important. The Oxford Index was derived from tolerance times for mines rescue teams. It is not appropriate where there is thermal radiation, and should only be applied to fit, young people.

For the Heat Stress Index (HSI) an allowable exposure time (AET) can be calculated. AET takes into account more factors than the other indices, but has been derived from theoretical rather than practical considerations.

6.5.5 Clothing

When it is necessary to work at temperatures which are so high that even very short exposure can lead to heat stress, then the workers themselves must be protected. Various types of heat protective clothing are available (*eg* Nunneley, 1988).

(a) Radiation protection

This is to prevent burns or excessive heat gain from radiant sources. If exposure is of short duration, a felted material may suffice, for example, during the opening of a furnace, and this also protects against molten metal splashes. However, if the heat is intense or if exposure is of long duration, clothing and head/face covering will need to be of low emissivity so that heat is reflected rather than absorbed. Aluminised clothing and equipment is used in these circumstances.

Whilst aluminised or reflective clothing protects against radiant heat, it does not protect against high air temperatures and may even prove detrimental if it restricts heat loss by sweat evaporation.

(b) Conditioned clothing

This protects the wearer from ambient heat by cooling the body, thereby permitting exposure to higher temperatures than would otherwise be acceptable or, in less extreme environments, allow the period of exposure to be extended. These include ice, liquid and air cooled suits, as described in Section 4.3.4.

Conditioned suits may also be coated with reflective material, or may be worn underneath reflective clothing where high air temperatures and high radiant temperatures occur together.

7 CONTACT INJURIES

7.1 Introduction

Contact of the body with hot surfaces, liquids, gases or steam or exposure to excessive radiant heat will cause localised overheating resulting in burns to the skin and, in severe cases, the underlying flesh.

The severity of a burn or scald depends on the temperature of the hot medium (or radiant intensity), the material involved, the time of contact and the size of the skin area affected. A burn may be superficial (*ie* it does not penetrate the epidermis, or outer layer of skin), partial thickness (*ie* it penetrates the outer but not the inner layer of skin or dermis) or full thickness (*ie* it completely penetrates the skin and damages tissue below). Superficial burns are self-healing, partial thickness burns may be self-healing in time, and full thickness burns require extensive medical treatment including skin grafting.

Figure 7.1 illustrates the relationship between time of contact and the temperature of hot metal surfaces at which burns will occur. Burns and scalds are possible at temperatures as low as 45°C if contact is maintained for long enough. In practice most people will react and break off contact within 0.25 seconds but some people, especially the very young and the old, are unable to react quickly and may therefore be at risk at moderate temperatures.

There is currently work being undertaken in European and International standards committees (see Appendix A) on the topic of acceptable surface temperatures (hot and cold) of touchable/handleable parts of machinery, taking into account the material, surface temperature and time of contact. For hot surfaces a European (and British) standard has been produced, BS EN 563 (1994).

7.2 Standards

In 1989 a European Ergonomics standards committee was formed to produce a standard concerned with hot surface temperatures. This was in anticipation of the common European Market to be established in 1992 and involved active participation from France, Germany, Sweden and the United Kingdom. The work was published as BS EN 563 1994 ‘Safety of machinery - Temperatures of touchable surfaces - Ergonomics data to establish temperature limit values for hot surfaces’. Discussions within CEN are now concerned with whether the standard can be applied to areas other than the safety of machinery. For domestic cookers, toasters, kettles, heating systems, toys and other products, for example, allowable surface temperatures can now be above those for industrial machines yet children, the aged and other relatively vulnerable populations can be exposed to these (see Parsons, 1993a).

Data are provided to allow the assessment of the risk of burning, based on early work involving the burning of the skin of young anaesthetised pigs, and more recently on the artificial finger (thermesthesiometer) studies of Siekmann (1989, 1990).

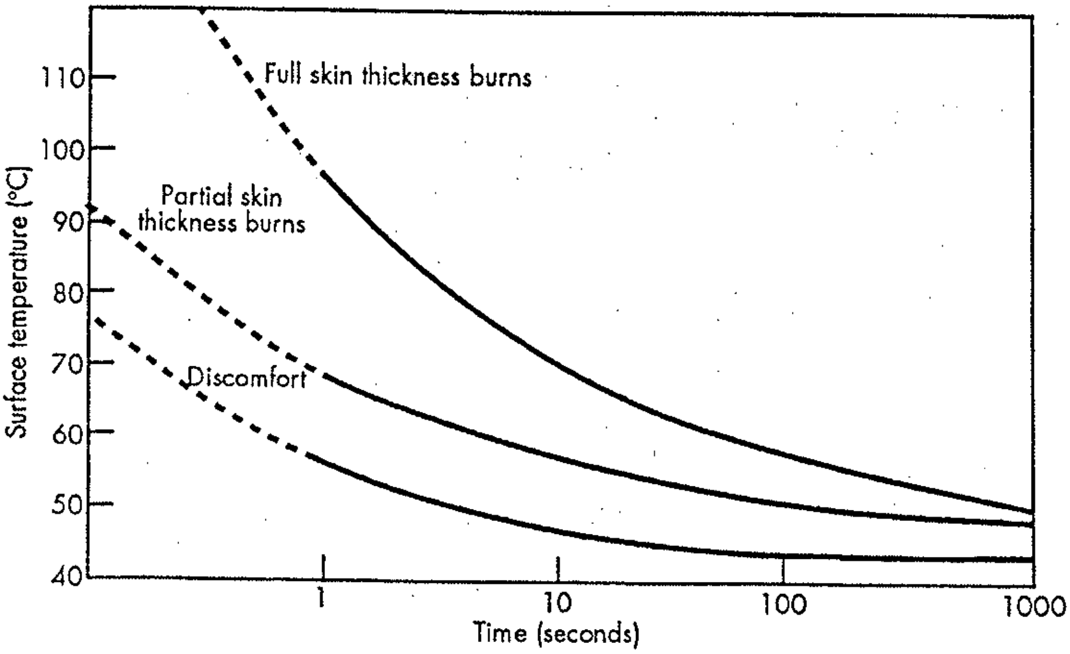


Figure 7.1: Relation between contact time and metal surface temperature to produce injury or discomfort
(Courtesy MRC Industrial Injuries and Burns Unit, Birmingham Accident Hospital.)

It is recognised that data concerning skin contact with hot surfaces and burns are not complete in terms of all important factors. For this reason, three 'areas' are presented on curves of material surface temperature versus exposure time. These show an area where a burn is possible and within which the 'burn threshold' (for a superficial partial thickness burn) lies. The area above this is where a burn would be expected and the area below this is where a burn would not be expected. Curves showing the three areas are provided for metals, plastics, ceramics, glass/stone and wood. 'Correction' curves are also provided for coated metals. Curves showing the important area of exposure times up to 10 seconds for contact with bare uncoated metal are presented in Figure 7.2.

For long durations of contact, a skin temperature and hence material temperature of 43°C will eventually produce a burn. The data presented in BS EN 563 (1994) are intended for the determination of temperature limit values, for machines for example. However, it is interesting that the standard provides data for a minimum contact time of 1.0 second. It is debatable whether realistic contact times of less than 1.0 second occur, and also how the ranges of temperatures provided in the proposed standard should be used to establish temperature limit values.

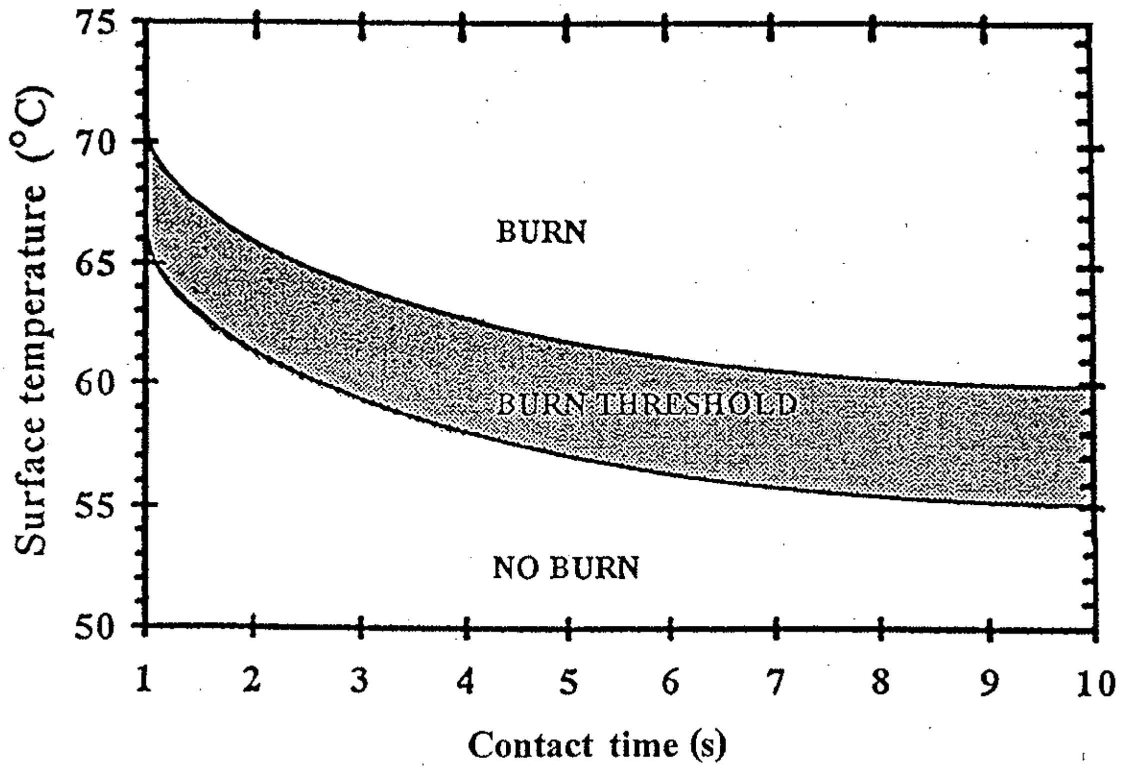


Figure 7.2: Burn thresholds for skin contact with bare uncoated metal
(from BS EN 563, 1994)

7.3 Practical Methodology for Assessing Workplaces

Practical methodologies for the assessment of workplaces can be derived from BS EN 563 (1994). However, some interpretation is needed to develop a risk assessment methodology. An example is provided of a case where there is a requirement to assess an existing machine. The following methodology is recommended.

1. Establish by task analysis and observation, worker behaviour under normal and extreme use of the machine. Hence, identify touchable surfaces.
2. Establish conditions that would produce maximum temperatures of touchable parts of the machine (not normally heated as an integral part of the functioning of the machine).
3. If possible, discuss with the operator the use of the machine and possible burning.
4. Operate machine as in 2. above and measure surface temperatures by an appropriate technique.
5. Estimate contact periods from 1. above
6. Assess each touchable surface temperature by comparing it with burn threshold data provided in the standard.
7. Interpret results in terms of context, application and what is achievable.

Protective measures

Protective measures can be used to reduce the risk of skin damage. Naturally an attempt should be made to redesign a machine or product to reduce temperatures to acceptable levels. If this is not possible then the principles of heat transfer and data on skin damage can be used to design for protection. For example, if a surface is to become hot and likely to be touched, the surface could be insulated with materials that would not produce skin damage at the temperature. 'Fins' can be used to reduce the thermal inertia of a surface so the amount of heat transferred will not cause a burn. Other measures include the use of warning signs. If, despite all other control measures, there is a risk of skin burns then advice and suitable treatment should be available; the facility for immediate immersion of the damaged skin in cold water is advised.

Measures are divided into three types in BS EN 563.

- Engineering measures - *eg* reduction of surface temperature, insulation, guards and surface structuring.
- Organisational methods - *eg* warning signs and signals, training and technical documentation.
- Personal protective measures - *eg* individual protection (wearing gloves *etc*).

Thermal Radiation

Thermal radiation effects on bare skin are beyond the scope of this chapter but clearly can be significant. Thermal radiation, however, can also influence contact burns where the outside surface of clothing is affected. In this case, heat is transferred between the outer surface of the clothing and the clothing next to the skin. Contact with skin will then occur and existing data regarding the effects of surface temperature, material type, contact duration and area will all be relevant and existing criteria can be used. In the case of a hot environment, for example, where high radiant load is experienced from explosions or fires, the outside surface temperature of the clothing will greatly increase. Heat will then be conducted through the clothing to the inner surfaces next to the skin. The surface temperatures and thermal properties and behaviour of the inner garments next to the skin will determine the extent of skin damage.

Hot water

The principles of skin damage caused by hot water are similar to those for solid surfaces with the additional issues of hot water vapour, steam and convective heat transfer. The Department of Health have published 'Health Guidance Note: "Safe" hot water and surface temperatures' (NHS, 1992), particularly relevant to health care buildings. For safe hot water the note suggests that 'nominal maximum temperature for hot water outlets accessible to patients, residents and visitors should not exceed 43°C'. If water is at temperatures above 43°C then staff should be especially vigilant. Table 7.1 provides physical precautions that should be taken for "safe" hot water. The guide also states that for some applications, such as bidets, safe temperatures of around 37 - 38°C are required. Guidance is also provided for devices for control and 'shutoff of water' based on maximum temperatures.

This gives rise to a conflict in relation to recommended water temperatures for the control of legionella (the genus of bacteria found in hot water systems which can cause Legionnaires' disease); these recommended temperatures are generally 60°C or higher for production and storage, down to 50°C for circulation in pipes (HSE, 1991). Thus appropriate mixing systems at or close to the point of use must be employed with suitable 'fail-safe' appliances to avoid scalding if failure of mixing occurs.

Table 7.1
Physical precautions for "safe" hot water (NHS,1992)

Area	Recommended as a minimum	Options
Staff	None	1. Mechanical mixers 2. Thermostatic mixers 3. Thermostatic mixers with fail safe devices
Patient, resident and visitor area		
-Hand basins	Single lever or control mechanical mixers starting from cold with a tamperproof stop to limit full hot water flow	1. Thermostatic mixers 2. Thermostatic mixers with fail safe devices
-Whole body immersion and lower maximum "safe" water temperature	Thermostatic mixers with fail safe devices	None

7.4 Cold Surfaces

For skin reaction on contact with cold surfaces, both ISO and CEN have draft documents in preparation and in particular CEN have a requirement for a standard. However, it is acknowledged that there are insufficient knowledge and ergonomics data to produce a standard at this stage and that research is urgently required.

Although it is desirable to have data and an understanding of the effects of contact with cold surfaces, surveys of cold stores have shown little evidence that it has caused major problems at the work place. It is likely that possible problems will relate to skin damage due to freezing skin and also possible sticking to surfaces. The mechanisms for these are not fully understood however. Longer term effects may exist, for example, in the regular handling of cold food or other products. The nature and extent of such problems is not clear. For contact in the cold, the ACGIH provide guidance notes for practical procedures, ACGIH (1995). Local cold injury is also referred to in Chapter 11.

7.5 Mathematical Models

It is possible to predict a contact temperature between the skin surface and a material using the principles of heat transfer. A simple model assuming perfect contact between semi-infinite slabs of material will provide such a prediction based upon the thermal penetration coefficients (square root of the product of thermal conductivity, density and specific heat) of the two materials. It would be of great benefit if such a model were accurate as likely skin reaction could then be predicted from contact temperature. However, the assumptions in such models are often restrictive and although useful in the determination of the relative effects of different material types, no models exist that could be used to predict likely skin damage. Models are discussed by Parsons (1993), who also makes practical suggestions for model development (see also Chapter 10).

8 ACCIDENT RATES AND PERFORMANCE

8.1 Accident Rates

Investigation of accident rates, especially in the munitions and mining industries during and after the first world war by Vernon, Bedford and others, has shown a relationship between accident rates and temperature in those industries (Chrenko, 1974).

Figures 8.1 and 8.2 illustrate some data from these investigations. In munitions factories the lowest accident rates occurred between 18 and 21°C. Results from the mining industry are more complicated. At temperatures over 17°C there was a marked increase in accident rates involving less than 10 days absence, but little increase in more serious reported accidents. Bedford suggested that this may be due to considerations other than the accident itself, implying that if working conditions were unpleasant due to high temperature then a worker would be more likely to use a minor accident as an excuse to stay off work than if working conditions were acceptable, but that this would not apply in the case of more serious accidents.

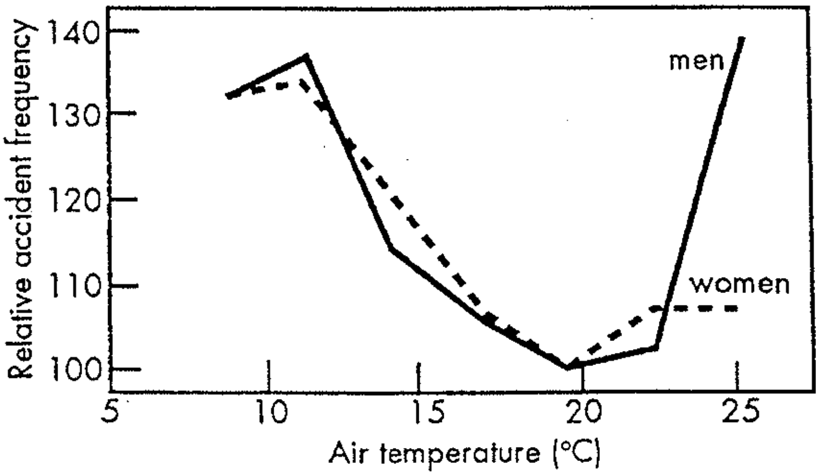


Figure 8.1: Accident frequency related to workplace temperature (munitions workers)
(adapted from Chrenko, 1974)

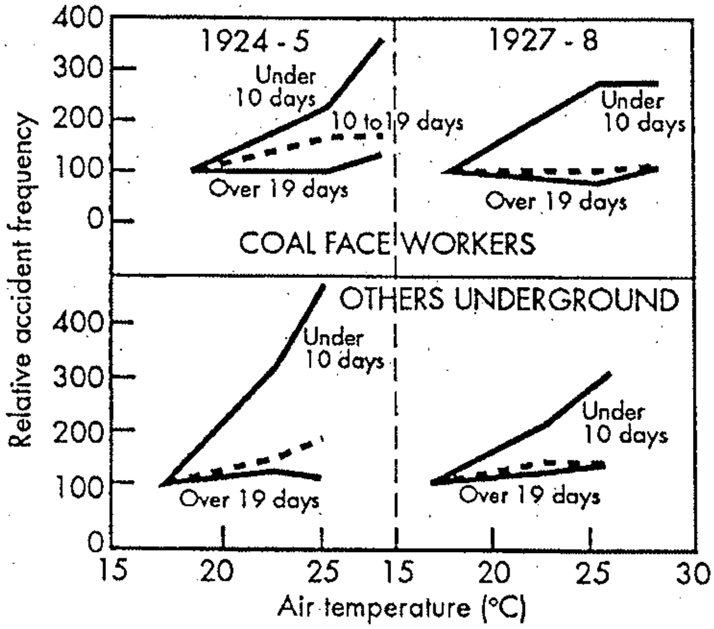


Figure 8.2: Accident frequency related to workplace temperature (mining)
(adapted from Chrenko, 1974)

The investigation of accident frequencies amongst coal miners also showed that these were, to some extent, age related. At temperatures of 21°C or less, accident rates were relatively constant for men of all ages. At higher temperatures, the accident rates varied considerably with age. The lowest frequency was noted in the 30-40 year old age group, the highest in the 50-60 year old group.

Little recent information is available and, whilst it may be reasonable to expect some increase in accident frequency at high and low temperatures, the pattern noted in munitions and mining industries will not necessarily be relevant to other, unrelated industries.

8.2 Performance and Productivity

Individual performance can be affected by environmental stresses, including heat. A number of investigators have found that subjects performed better in laboratory tests when uncomfortably hot than when comfortable suggesting that heat has an arousing effect. Comfortably warm conditions are soporific, inducing drowsiness but this wears off as temperature rises to be replaced by greater awareness, irritability and improved concentration. At very high temperatures, concentration again becomes difficult (Astrand and Rodahl, 1986).

The relationship found in laboratory-scale tests of relatively short duration does not hold true in industrial situations where the subject works for long periods in heat. The worker is likely to become fatigued, particularly at higher temperatures where there is also a risk of heat stress. Increased or decreased temperature may also lead to dissatisfaction, increased absenteeism, reduced productivity and increased accident rate (Ramsey *et al*, 1983). Tests on office workers have shown little effect on performance of varying temperatures within acceptable comfort values.

A number of studies have been undertaken to look at manual performance in the cold. The critical skin temperature at which the onset of numbness occurred appears to be typically 6°C, but the figure varies considerably between individuals. Manual dexterity decreases with decreasing temperature due to a combination of factors, including numbness and stiffening of finger joints. The critical hand skin temperature at which dexterity worsens is typically 13 to 16°C.

It would appear for work places in general that if conditions can be kept in the accepted range of comfort for given tasks and clothing attire then it is best to do so in relation to performance, productivity and general well-being of occupants. Conversely, if conditions are outside the accepted comfort range, advantages are to be gained in bringing conditions within the range.

The overall topic is reviewed in McIntyre (1980).

8.3 Performance in the Heat

Human performance is influenced by numerous psychological and physiological factors and by differences in individual's response to specific environment and task combinations. Many factors have been shown to affect performance but tend to disguise the underlying thermal influences, rather than to explain them. There are, however, some basic relationships as discussed below.

1. Acclimatisation

Task performance related to degree of acclimatisation is an area which is not well defined. Much of the reported literature does not specify whether subjects are acclimatised or unacclimatised. In general, the acclimatised individual should be more tolerant and physiologically more able to work in a hot environment, and should show more resistance to performance losses if the tasks involve motor responses; for simple and mental tasks this difference is less likely to be observed.

2. Arousal

Studies have suggested that there is an optimum arousal (or central stimulation) level for any task being performed in the heat, and it is typically lower for complex tasks than for simple tasks. Arousal can not only retard performance, but has also been shown to improve performance in many instances. Since temperature spans the continuum from cool, to comfortable, to hot, the idea of an inverted U to describe performance is attractive. It is difficult to generalise, however, due to the problems of determining the level of arousal at any given point of exposure to the heat, as well as the interaction of arousal with the task differences and other variables.

3. Skill / training

Performance in the heat has also been studied as a function of skill or training level and the skill requirements of the task. In general, persons with high skill will have higher resistance to performance loss unless they are already operating at a high psychological load which, with the addition of temperature, becomes an overload condition, and negatively affects performance.

4. Clothing

Increases in the amount of clothing affect insulative and permeability characteristics and can interfere with a person's heat dissipation abilities. Tables have been developed for estimating the equivalent thermal load based on different levels of clothing (Ramsey 1993). Studies of perceptual motor performance in protective clothing, during and after physical work, have shown no significant decrements for cognitive or vigilance tasks at the temperature and workloads involved, but fine motor skills were impaired and also partially ameliorated by cyclic cooling in a protective clothing garment.

5. Physical work

Studies involving physical work effects on the performance of perceptual motor tasks have been reported. Exposure to work and heat which will generate localised or general fatigue will normally have a negative effect on muscular based perceptual motor performance, but will have less direct effect on tasks which are primarily cognitive.

6. Elevated core temperature

Work and thermal environments which elevate the body temperature have also been shown to have adverse effects on task performance. In some studies body temperature was not reported, only inferred. A zone of tolerance of deep body temperature for unimpaired cognitive and neuromuscular performance has been proposed. This relationship between body temperature and task performance appears to be a dominant factor for some types of task.

7. Combined stressors

The combined environmental stressors of heat and noise have been studied. Some instances show the combined effects of the two stressors to be smaller and some report them to be additive; further, these differences are seen in some tasks and not in other tasks. High altitude and heat are commonly investigated areas and other combined stressors have also been reported. Performance results with combined stressors are highly variable and appear to be a direct function of the stressor levels and the specificity of the conditions used in the study.

8. Comfort

Comfort level is a function of numerous variables but for the sedentary, normally clothed worker (0.5-0.7 clo) with low air movement (less than 0.25 ms^{-1}) the comfort range is approximately 22±2°C (see Section 3.3). Comfort for a person doing work slightly above the sedentary level would likely be 1-2°C lower. Numerous studies of task performance near the range of comfort have been conducted and performance decrements have sometimes been noted; if so, the lower temperatures are most often associated with best performance.

A review of all of these issues is given in Ramsey (1995).

8.4 Performance in the Cold

There have been numerous studies into the effects of cold on performance and there are clear repeatable findings that performance decreases in the long term, although during the first 6 hours of exposure to moderately low temperatures (*ca* 12°C) decision and movement reactions may be increased. In the cold, vasoconstriction and lowering of tissue temperatures causes numbness, a decrease in manual dexterity and strength. In an extensive study where subjects were exposed to cold for fourteen days, dexterity of fingers and hand strength were markedly diminished even after short exposures. Fox (1967) in an extensive review, concluded that there is a clear relationship between hand skin temperatures and manual performance. The critical hand skin temperatures '... below which there is a serious decline' are 8°C for tactile sensitivity and 12-16°C for manual dexterity.

More recent studies have shown significant effects in more moderate cold. The American Conference of Governmental Industrial Hygienists (ACGIH, 1995) suggest special protection for the hands to maintain manual dexterity and prevent accidents, if fine work is performed for more than 10-20 minutes and air temperatures are less than 16°C. Rapid cooling of the hands can be caused by windchill when driving a motor cycle, for example (high relative air velocity and low air temperature) causing difficulty in operating controls. Finger strength and speed and manual dexterity have been shown to decrease as the temperature falls from 24°C through 18, 12 to 6°C.

A number of studies have investigated the effects of cold on manual dexterity and compared them with the effects of gloves. Different glove designs ranging in number of digit compartments from the standard five-finger glove to the mitten have been investigated, with attempts to determine the relative importance of cold and glove design to the overall effects on manual performance.

Reviews are given in Parsons (1993) and Ramsey (1983).

9 UK STATUTORY REQUIREMENTS

9.1 Health and Safety Legislation

The Health and Safety at Work etc Act 1974 places a duty on employers to ensure, so far as is reasonably practicable, the health, safety and welfare at work of all their employees, in particular, the provision of a working environment that is, so far as is reasonably practicable, safe without risks to health, and adequate as regards facilities and arrangements for their welfare at work.

The Workplace (Health, Safety and Welfare) Regulations 1992 require during working hours the temperature in all workplaces inside buildings to be 'reasonable'. Also sufficient numbers of thermometers should be provided to enable workers to determine the workroom temperature. The regulations do not specify maximum or minimum temperatures. The Approved Code of Practice accompanying these regulations advises on measures to achieve compliance including minimum temperatures in work places. The Approved Code of Practice recommends reasonable temperatures in workrooms to be at least 16°C unless much of the work involves severe physical effort, in which case the temperature should be at least 13°C.

The Workplace (Health, Safety and Welfare) Regulations 1992 replaced a large number of regulations and orders which dealt with very specific workplaces. These regulations also repealed parts of the Factories Act 1961 and the Offices Shops and Railway Premises Act 1963.

The Control of Substances Hazardous to Health (COSHH) Regulations 1994 do not involve the thermal environment directly. However, if thermal conditions influence the extent of a chemical hazard *eg* by increasing evaporation rates of a toxic substance then they should be included within an assessment under COSHH and have implications on the control measures employed.

The Management of Health and Safety at Work Regulations 1992 require employers to make a suitable and sufficient assessment of the risks to the health and safety of their employees, to which they are exposed whilst they are at work. This assessment would identify the risk from the thermal environment, both hot and cold environments, and also the measures to be taken to protect workers from those risks (see Section 9.3)

9.2 Building and Related Regulations

The relevant section of the Building Regulations 1991 relating to thermal aspects of building design is Part L, "Conservation of fuel and power". Part F of the Regulations, "Ventilation", also relates indirectly to the thermal environment.

Part L of these regulations is concerned primarily with the thermal performance of the building fabric and glazing. They define maximum conduction values, *ie* "U" values, of external walls, roofs and floors of buildings and also maximum allowable areas of glazing. Different standards apply to different building types (*eg* offices, factories and dwellings).

Part L is also concerned with methods of control of heating systems in relation to fuel use. Part F is concerned with means of ventilation and control of condensation and Part J concerns heat producing appliances (principally health and safety aspects).

Advice on means and standards which will achieve compliance with the Building Regulations is given in Approved Documents F and L (Dept. of Environment, 1995).

The Fuel and Electricity (Heating) (Control) Order 1974 and as amended by the Fuel and Electricity (Heating) (Control) (Amendment) Order 1980 prohibits the use of fuel and electricity to heat premises above 19° C. This does not mean that the temperature inside buildings should be kept below 19°C; but that the heating system should not be used to raise it above 19°C. The temperature within a workplace may be raised by sources other than the heating system, *eg* lighting, workplace equipment and machinery and also solar radiation (sunlight). These regulations are still in force.

Food Hygiene Regulations (Food Safety (Temperature Control) Regulations 1995) set maximum product and space temperatures for certain foodstuffs, for instance 12°C air temperature in cutting rooms for meat products. This could cause concern and conflict between food hygiene requirements and what might be considered as 'reasonable' temperatures for employees. The HSE have addressed this issue and provide appropriate guidance (HSE,1994).

9.3 Risk Assessment

There is now a legal requirement (under the Management of Health and Safety at Work Regulations 1992) to identify the hazards of the working environment, including those which are related to the thermal conditions, and to evaluate any risks there might be to operatives. The thermal environment is not only complex but, in many cases, also dynamic in that it is changing as work proceeds; thus an assessment often requires an appropriately skilled person.

The first step in the risk assessment is to develop a detailed picture of the system and the importance of its various components and hazards. This is normally done by considering initially the four environmental factors, the work rate and any protective clothing being worn. The task must be examined in relation to the influence of heat stress on it and the ability of the operative to do it safely, together with physical constraints *eg* enclosed or restricted spaces or any changes in height, as these may pose additional hazards such as increasing the work rate of the operative when climbing or descending, and hence their vulnerability to heat stress.

It can be argued that, as the main risk from environmental extremes is either hypothermia or hyperthermia, the risk can be adequately controlled by operatives wearing body temperature sensors which tell them when exposure to the conditions should cease. This approach may eventually become the norm. Its drawback is that the approach accepts that operatives should work with deep body temperatures elevated or depressed to the adopted value. Furthermore the discipline of the risk assessment is avoided and with it any improvements in safe working conditions and productivity that might have been identified. One situation where personal monitors can be justified is when personnel are wearing protective clothing, particularly impermeable garments or gas-tight suits. But despite the security of a personal monitor it is important to undertake a full risk assessment to see if the work can be done without such personal protection and, if it has to be used, the best and most comfortable way of using it.

In the risk analysis the hazards associated with the following have to be identified and quantified.

- the thermal environment, its daily and seasonal fluctuations
- the work load and its variation with the tasks being done
- the influence of clothing on heat loss from the body
- how clothing may influence the stress by increasing the metabolic heat load of the wearer
- the magnitude of the thermal stress.

Although the main issue of concern in many risk assessments is the influence of clothing on the thermoregulatory capability of the wearer, clothing also influences the work load and hence the amount of metabolic heat produced. Whether this is good or bad is determined by whether there is a need to lose or conserve heat. The dressing procedures may involve hard work, mobility may be impaired and movement and work tasks made difficult. Loss of hearing and visual field may indirectly increase the energy cost of work and movement.

The critical inter-relationships between clothing insulation, the workrate and environmental temperature have been known for many years (Section 5.2.2, Figure 5.1) but the significance of the change in the slopes of the lines with changes in workrate have not always been appreciated by industry. When the slope is shallow due to a high work rate the wearer is very sensitive to even small changes in clothing insulation value and in the temperate to cool and cold conditions insensitive to temperature changes. With a steep slope due to low work rate the reverse is the case; large amounts of insulation have to be added or removed to deal with changes in ambient temperature as the wearer is sensitive to temperature changes.

When the wearer is sweating another feature of clothing becomes important - its ability to restrict sweat evaporation from the skin. When doing physical work, even in the state of thermal comfort, sweat is produced which wets a certain area of skin in order to be evaporated, normally expressed as a percentage wetted skin surface area. This percentage is of course influenced by atmospheric humidity and wind speeds as well as by the metabolic heat production or work rate.

If, for example, two tasks require that 50% of the skin surface area is wetted in order to evaporate sufficient sweat (E_{req} - Section 4.2.2) then the addition of a protective garment may impose restriction on evaporation so that 75% of the skin has to be wetted in order to achieve the required evaporation rate. A 50% safety margin has been reduced to 25%. The garment itself may increase the cooling required as the wearer has to work against it when active;

typically a further 10% skin wettedness may be required. Finally, an increase in ambient humidity conditions (*eg* due to weather changes or build up of moisture in the work place) could add a further need of 15% to skin wettedness. Thus, what was a 50% skin wettedness requirement has risen to 100% (75+10+15) with thus no margin of safety and the risk of a rising core temperature.

A flow chart illustrating the risk assessment procedure is given in Figure 9.1, to be used in conjunction with the hazards list (Table 9.1) and potential consequences list (Table 9.2).

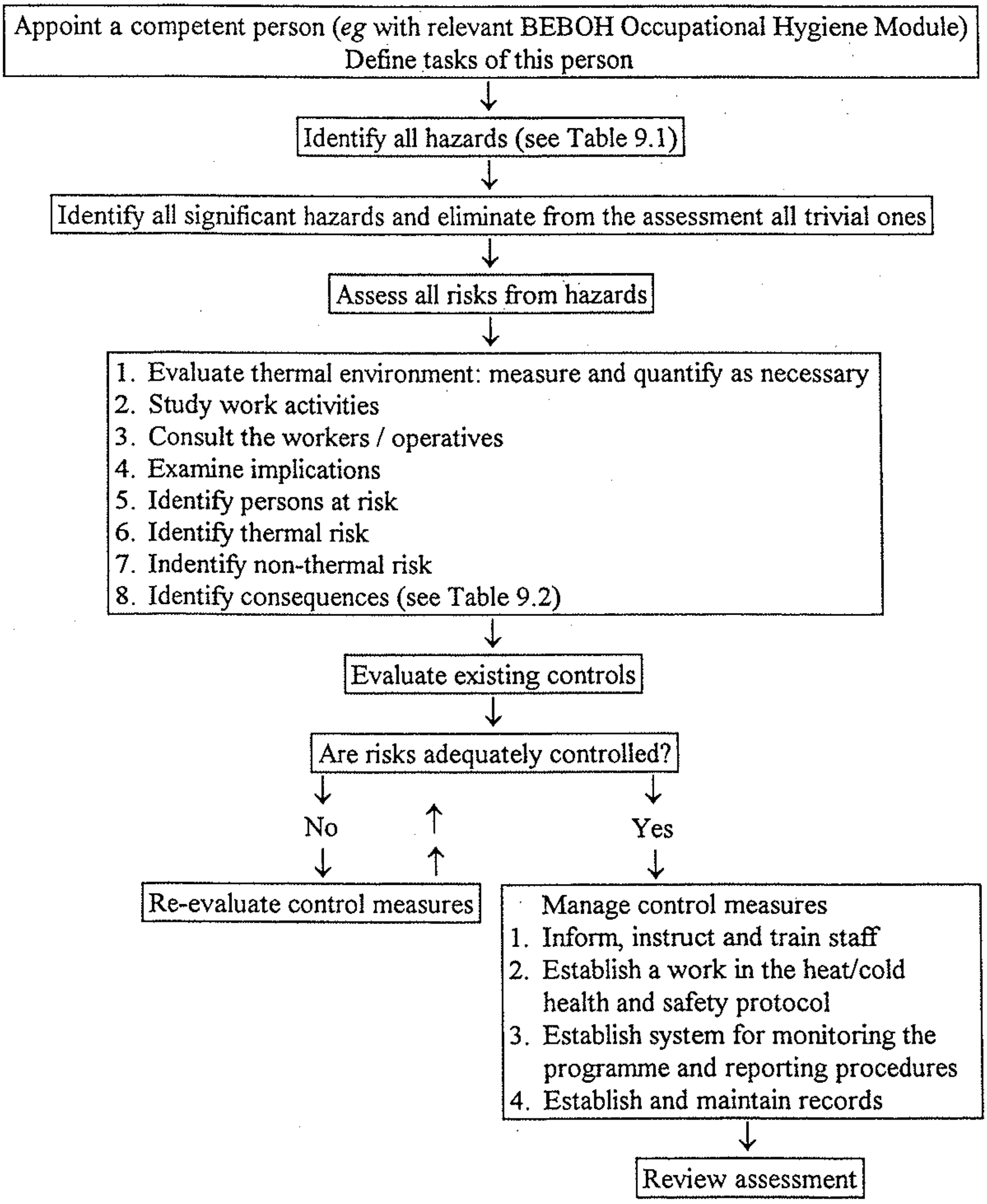


Fig 9.1: Thermal environment risk assessment flow chart

Table 9.1 Thermal environment hazards list (examples)

General

- dry bulb (air) temperature
- humidity
- radiation temperature - localised or general
- air movement / wind speed
- restricted air exchange to skin
- hot / cold surfaces
- work rates, high or low
- work period-exposure time
- enclosed, confined space
- restricted air movement
- tasks and accident hazards
- climbing - ascending - descending; change in work rate
- operatives state of health
  - acute infections
  - acclimatised or not
  - obesity
  - receiving medication (see Section 11.3)
  - age, fitness
  - eye sight, hearing
- the dynamics of the environment *eg* changing relative humidity/temperature
- relevant physical and chemical agents
  - vibration
  - altitude
  - carbon monoxide
  - dust
  - dust from low humidities
  - gases, vapours and dusts soluble in sweat

Clothing & PPE related hazards and factors

- restricted visual field
- hearing affected
- work load increased
- mobility restricted
- some movements blocked
- dressing and undressing time and energy costs
- stand-by time and its affect on body temperature
- decontamination time and effect on body temperature

Table 9.2: Potential consequences of thermal hazards (examples)

General

- increase in human error/accidents
- discomfort
- reduced productivity, quality
- reduced work period, increased rest periods
- hypothermia, hyperthermia
- increased / decreased response time

Heat (see also Section 11.1)

- fainting (heat syncope)
- injury / death from falling after fainting
- heat hyperventilation; heat tetany
- heat stroke
- injury / death from heat stroke
- skin disorders, prickly heat, dermatitis
- low humidity dermatitis, dust dermatitis
- water depletion dehydration
- cramps, salt and electrolyte depletion
- heat oedema
- heat exhaustion
- possible other medical effects (see Section 11)
- local heat injury / burn (see Section 7)
- loss of sleep
- contamination of sweat and skin by chemicals

Cold (see also Section 11.2)

- discomfort
- loss of dexterity
- loss of grip / strength
- increase in blood pressure
- respiratory infection
- local cold injury

10 THERMAL MODELLING

10.1 Introduction

The increase in knowledge and understanding of human thermoregulation and of the processes of heat exchange between a clothed worker and his thermal environment has led to the production of mathematical models of worker response to hot, moderate and cold environments. The development of the digital computer has provided the opportunity for these relatively complex models to be conveniently used in practical applications.

Use of the models has great potential. For example they could be used for determining safe exposure times for people working in extreme heat or cold, for designing work/rest regimes, for investigating the effectiveness of different forms of environmental control, for identifying clothing insulation required in cold environments, for providing advice concerning the design of offices or new workplaces, *etc*. The models have limitations, however, and it is important to identify their correct role in contributing to the solution of practical problems. Some of the more influential models and examples of their potential use in practical application are described below.

10.1.1 What is a thermal model?

Models used for assessing human response to thermal environments range from the very simple to the extremely complex. For example, the formula for the WBGT index, given in Section 4.2.1, could be regarded as a simple model where calculations can be carried out 'by hand'. Heat balance equations, upon which rational thermal indices are based, could be regarded as models which require more sophisticated calculation. The term 'thermal model', however, usually refers to a dynamic representation of the human response to thermal environments such that the model can provide predictions of the changes in the human response with exposure time.

Types of thermal model range from empirical models, where equations have been derived by fitting curves to the responses of human subjects, to rationally derived models, which involve dynamic representations of the human body and its thermoregulatory system. It is usually necessary to represent thermal models on digital computers. These can range from simple PCs for the relatively simple models to large main-frame computers where sophisticated simulations of the human body are used (*eg* where finite element techniques are employed).

10.2 Existing Thermal Models

10.2.1 Givoni/Goldman model

Givoni and Goldman (1972) developed an empirical model based on the responses of US soldiers to hot environments. They provided a series of equations which predict the rectal temperature response with time. The model assumes that for any combination of metabolic rate, environment and clothing, there must be an internal body temperature and corresponding skin temperature at which the human body will reach equilibrium. This state of final equilibrium may be beyond the limits of human endurance.

The final equilibrium rectal temperature is calculated as:

$$T_{ref} = F1(M_{net}) + F2(H_{r+c}) + F3(E_{req} - E_{max})$$

where: T_{ref} = final equilibrium rectal temperature (°C)

M_{net} = metabolic heat load (W)

H_{r+c} = sensible environmental heat load (W)

E_{req} = required evaporative cooling
= $M_{net} + H_{r+c}$ (W)

E_{max} = maximum evaporative capacity of environment (W)

F1, F2 and F3 are experimentally derived functions that are applied to each component of the equation.

The Givoni and Goldman method then fits an equation to the curve that the human rectal temperature would follow, from an initial rectal temperature to the final equilibrium temperature, as a function of time, given an exposure to a particular set of environmental conditions. From this equation it is possible to predict the rectal temperature at any moment during an environmental exposure. Givoni and Goldman provide three different sets of equations for rest, work and recovery from work. This is necessary because of the different rectal temperature response profile of each type of activity.

The Givoni/Goldman model was developed during the 1970s at the US Army Research Institute of Environmental Medicine (USARIEM) and the model has been used by the US Army.

10.2.2 J B Pierce Laboratory (2-Node) model

The JB Pierce Laboratory (2-node) model of human thermoregulation (Nishi and Gagge, 1977) makes a conceptual distinction between the passive (controlled) and active (controlling) systems of human thermoregulation. The model represents the passive system, the human body, as two compartments: a body core surrounded by a skin shell (Figure 10.1). The relative masses of the two compartments are adjusted according to the blood flow. For example, if the blood flow is high the body is taken to be mostly core and the relative mass of the core to the skin shell is increased. Heat is transferred between the two compartments by conduction and by convective transfer from the blood. Metabolic heat production occurs in the body core. The skin shell exchanges heat with the environment by means of convection, radiation and the evaporation of sweat.

The controlling system assumes a fixed 'set-point' theory of human thermoregulation, where controlling signals result from a deviation of the body's actual temperatures from reference temperatures. These signals are integrated by the controller, which then produces appropriate effector commands. Effector action takes the form of shivering, vasoconstriction, vasodilatation and sweating.

The JB Pierce Lab (2-node) model is an integral component of the American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE) method for assessing thermal comfort (ASHRAE, 1989).

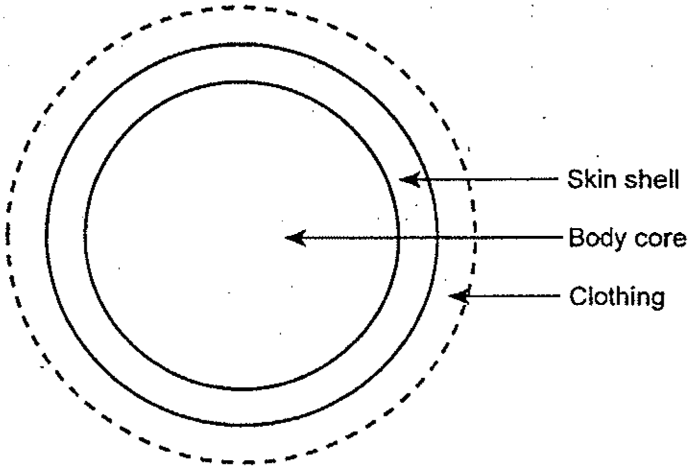


Figure 10.1: J B Pierce Lab (2-node) model representation of the human thermoregulatory controlled (passive) system.

10.2.3 Stolwijk and Hardy 25-node model

The Stolwijk and Hardy (1977) (25-node) model is a model of human thermoregulation that represents the human body as 25 compartments (6 body segments x 4 layers + 1 blood = 25 compartments) as shown in Figure 10.2.

The model represents the head as a sphere, and the trunk, arms, hands, legs and feet as cylinders. Each of these segments is divided into four layers: core, muscle, fat and skin compartments. The model assumes that the body is symmetrical in order to reduce the number of calculations required. The blood is represented as a 25th compartment. Each compartment is assigned a mass, volume and specific heat. These values were obtained in part from experimentation and in part from the literature and relate to an average sized male with a body weight of 74.4 kg and a surface area of 1.89 m^2.

Heat flows by conduction from a compartment to the adjacent compartment and from segment to segment by convective transfer to and from the blood. Metabolic heat production is divided between the various segments and their layers. External body compartments exchange heat with the environment by means of convection, radiation and by the evaporation of sweat.

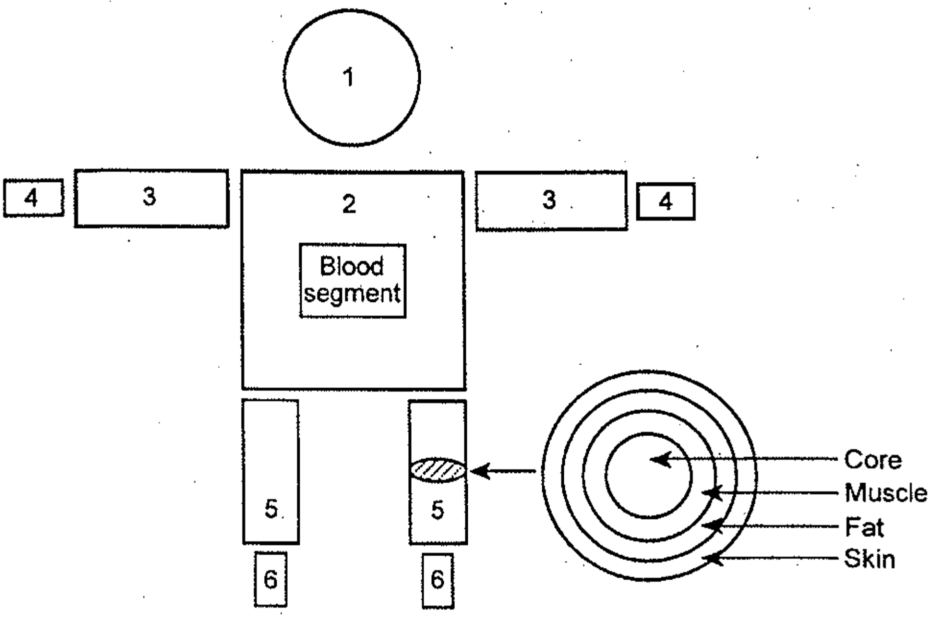


Figure 10.2: The Stolwijk and Hardy (1977) (25-node) model representation of the human thermoregulatory controlled (passive) system.
(6 body segments x 4 layers +1 blood = 25 compartments)

A schematic representation of the Stolwijk and Hardy controlling system is given in Figure 10.3. The controlling system is based on a 'set-point' theory of human thermoregulatory control. Signals controlling vasodilatation, vasoconstriction, sweating and shivering are calculated as a function of the difference of the actual temperatures of the compartments. The local signals are modified according to the density of thermoreceptors for a compartment. These signals are then integrated to produce core, core and skin, and skin signals. The effector regulator interprets the integrated signals and produces effector commands. The effector commands are implemented as effector action: shivering, vasodilatation, vasoconstriction and sweating, after being modified according to compartmental conditions.

The Stolwijk and Hardy (25-node) model has formed the basis of many other specialised models and has been used by the National Aeronautics and Space Agency (NASA). Recent developments (Haslam and Parsons, 1988) have added clothing to the model and made it more useful for practical applications.

10.3 Other Models

There have been a number of modifications and enhancements to the models described above. Haslam and Parsons (1988) modified each of the models so that they could be used in changing climates and for changing work-rates and clothing. They also included vapour permeation characteristics of clothing. The 'model' based on ISO 7933 (see Section 4.2.2) was also included and the modified versions were called the lutre, lut2, lut25 and lutiso versions. The 25-node model described above was adapted by other investigators so that it could be used for cold water immersion environments and the number of compartments greatly increased together with the sophistication of the modelling of the thermoregulatory system.

Wissler (1988) describes a sophisticated model which has been used in practical applications. The model, which runs on a main-frame computer, computes 225 temperatures in 15 elements. It also considers O_2, CO_2 and lactate concentrations. It allows for various clothing types including liquid cooled or heated garments, and has been validated over a number of years. There are practical problems with implementation of the model for routine use and this must be regarded as a model to be used for specialist investigation. Another model described computes several hundred thousand temperatures in a three-dimensional simulation which requires a supercomputer to run. There is clearly a trade-off to be made between practicality, sophistication and accuracy.

For further discussion and descriptions of the models and their applications the reader is referred to the review by Wissler (1988), to Haslam and Parsons (1989, 1994) and to Parsons (1993, 1995).

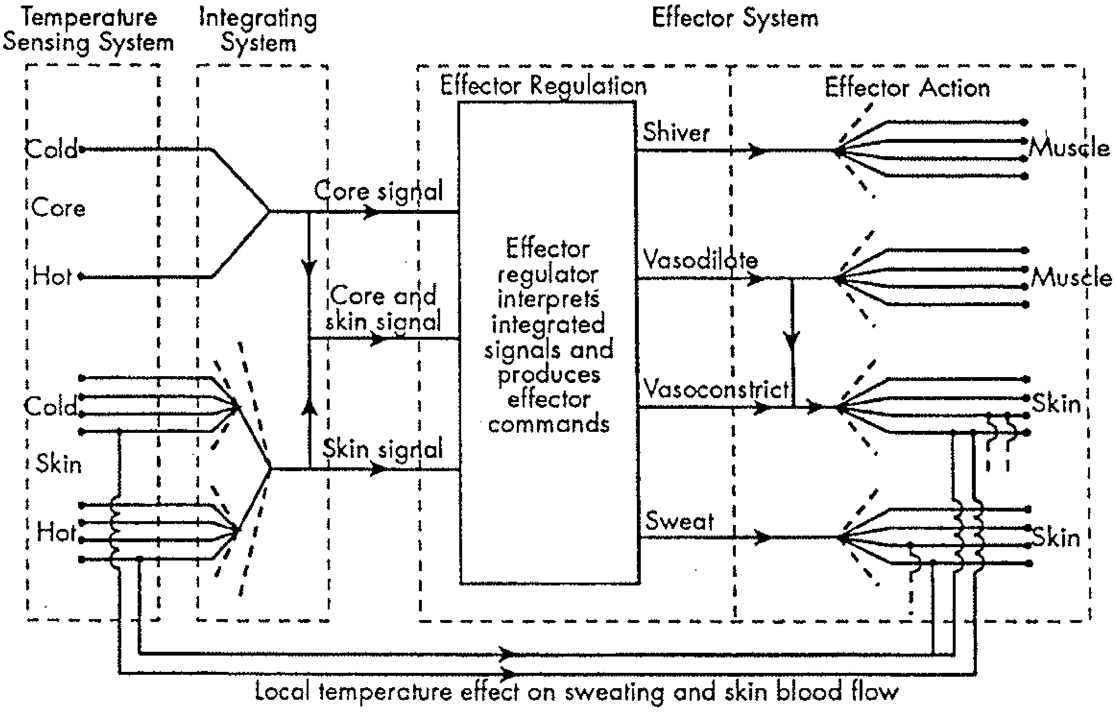


Figure 10.3: The Stolwijk and Hardy (25-node) model representation of the human thermoregulatory controlling (active) system.

10.4 Examples of Potential Use of Models in Practical Applications

If a sufficiently versatile and accurate thermal model can be achieved, and it is claimed that this is already the case, then the model will be able to perform many functions in the assessment of the human response to thermal environments. This will lead to the use of computer-aided design in this area. Examples of the outcome of the use of a thermal model in practical applications are provided below. Hypothetical practical problems are posed and the J B Pierce 2-Node model is used to help provide a solution.

Example 1: Safe exposure time for a hot environment

Workers are to be exposed to a hot environment in which there is molten metal contributing to the mean radiant temperature. They must wear protective clothing and work moderately hard. The air temperature is 35°C and the mean radiant temperature is 50°C. Air movement is at 0.2 ms^{-1} and relative humidity is at 80% due to spraying of water to keep down dust. What would be a safe exposure time?

Conclusions from model run:

One of the criteria which can be used as a practical limit for exposure of workers to hot environments is that the internal body (core) temperature should not exceed 38°C. The response of the model shows that this could occur after 35 minutes of exposure. The model can be used again to determine the change in this value caused by working practices or environmental controls, changing environmental conditions, clothing or work rates. Other practical considerations can be combined with the information from the model to provide a possible answer to the question.

Example 2: Clothing insulation required for a cold environment

A group of workers must work outside for four hours at night in an air temperature of 2°C with a wind speed of 1 ms^{-1}. Is the clothing of 1.5 clo adequate to keep them comfortable doing light work? If not, what should the clothing insulation be?

Conclusions from model run:

Criteria that clothing is acceptable could be that the internal body (core) temperature does not fall and that mean skin temperature can be maintained above 30°C. The run of the model with a clo value of 1.5 clo predicts that the mean skin temperature falls to 26.7°C. If the clothing insulation is increased to 1.9 clo then the mean skin temperature is maintained above 30°C. A possible solution therefore is to raise the clothing insulation to 1.9 clo. Tables of clo values are available to provide suggestions. Other solutions can also be investigated with the model.

Overall Conclusions:

The above examples demonstrate how thermal models can contribute to the design and assessment of thermal environments. It should be clear that the models which can run conveniently and quickly provide powerful potential tools in this area. At present, however, although it is generally accepted that the models have great potential, there has been relatively little evaluation of the accuracy of prediction and the role of the models when used in practical application has yet to be determined.

11 MEDICAL EFFECTS - SUPPLEMENTARY INFORMATION

11.1 Heat

11.1.1 Introduction

Disorders due to heat occur most frequently with sudden increases in heat stress when there are marked changes in ambient temperature or when newcomers are first exposed to physical work in the heat. Severely hot conditions, particularly of high humidity or radiant heat, and lack of acclimatisation in personnel are the factors that most commonly lead to heat disorders. Those most at risk often have a history of heat intolerance or are physically unfit. Differences in thermal tolerance between the sexes arise mainly from different habitual levels of exercise. In general, men have a higher sweating capacity and greater thermal tolerance than women, but both sexes do acclimatise to heat. Existing illness such as heart disease, skin disorders and viral or bacterial infections add to the risks of heat exposure by compromising the normal functioning of the thermoregulatory system. Those suffering from hereditary sickle cell blood disease, mostly originating from Africa, are at risk from sickle cell 'crises' precipitated by dehydration in hot conditions. Due caution should also be taken with any individual receiving medication, for many drugs are known to affect adversely thermoregulation (see Section 11.3).

11.1.2 Range of illnesses

Heat illnesses may take many different forms varying from trivial disorders such as skin rashes and heat syncope (fainting) to serious life-threatening events such as heat-stroke (*eg* Leithead and Lind, 1964; WHO, 1969). The initial physiological adjustments to heat involving cutaneous vasodilation and fluid balance changes may, in some individuals, cause swelling of the ankles or feet (**heat oedema**).

Heat syncope may result from a drop in blood pressure during prolonged standing in the heat or be due to a sudden change from sitting to standing. The victim quickly recovers if allowed to lie down. In some industrial situations, however, the resultant faint may itself be dangerous if the victim is held upright in a confined space and the fall in blood pressure sustained.

Prickly heat, a form of skin rash accompanied by a pricking sensation in the skin during sweating, occurs in some susceptible individuals when parts of the skin are continuously wetted by sweat in humid environments or on areas where sweat cannot evaporate. Immediate relief from the discomfort can be provided by moving into cool surroundings, or by cool showers followed by drying the skin and lightly applying calamine lotion or zinc oxide powder.

Hyperventilation in hot conditions can arise especially when respiratory protective equipment is being worn. It is the consequence of overbreathing often due to anxiety and may lead to distressing symptoms such as tetany (muscle spasms) and paraesthesiae (tingling sensations) in the extremities. It is readily treated by removing the individual from the hot climate and asking them to rebreathe into a small bag held over the nose and mouth until the symptoms improve, usually within a few minutes.

11.1.3 Water and salt intake effects

More serious heat-induced disorders may arise from an imbalance of water and salt intake. The loss of large amounts of water and salt during copious sweating may lead to dehydration, exhaustion and collapse in the heat.

(a) Water-deficiency heat exhaustion.
Dangerous levels of dehydration (>10% of body weight) can result within 24 hours from strenuous work in hot conditions. Even when drinking water is available in this situation, an individual almost never completely replaces his sweat losses from moment to moment so that he is usually in a mild negative balance. Voluntary dehydration of this type is best countered by providing readily available supplies of palatable fluids.

A moderate degree of dehydration, *eg* 5% reduction in body weight, is usually accompanied by a sensation of thirst with which the subject becomes more and more obsessed as dehydration progresses. The subject complains of irritability and fatigue and eventually exhaustion and clinical signs of dehydration become apparent. The conscious patient should be encouraged to re-hydrate by regular water replacement and to avoid further fluid losses by rest in a cool space.

A fluid balance chart can be helpful to ensure a net gain over the following few days. Clinical recovery quickly follows the establishment of a good urine output.

(b) Salt-deficiency heat exhaustion.
A negative salt balance in hot conditions usually arises in one of two ways: firstly in the unacclimatised person with a naturally high salt content in sweat when sweat salt losses are not replaced by dietary salt supplementation during the first few days of work in the heat; secondly in those who drink water freely in the absence of salt replacement.

Supplementation of salt over and above the normal (temperate) intake of about 10 g of salt per day is usually unnecessary in heat-acclimatised individuals since physiological adaptations have occurred to restore salt balance. Muscle cramps are common and, combined with symptoms of fatigue, loss of appetite and vomiting, make the diagnosis fairly obvious.

A high intake of salted drinks under supervision is required in the treatment of mild cases, with the added safeguard of bed-rest in a cool space. Salt tablets have disadvantages: in some people they cause nausea and vomiting which simply intensifies the existing negative salt balance.

11.1.4 Heat stroke

This is the least common but most serious of heat disorders. It carries a high mortality rate, particularly if effective treatment is not given immediately. Characteristically, deep body temperature reaches very high levels of 41°C or above, there are profound central nervous disturbances involving convulsions, mania or coma, and often a hot, dry skin. The attack may be sudden or there may be warning symptoms such as irritability, dizziness or mental confusion. The immediate task is the crucial one of measuring rectal temperature and this is often difficult in a struggling patient.

Heat-stroke is an emergency situation calling for effective cooling to reduce rectal temperature to below 39°C within an hour. After this, active cooling should be discontinued to allow body temperature to stabilise. The most efficient methods to achieve cooling combine evaporative and convective cooling by spraying the body surface with water droplets at a skin temperature of about 32°C in the presence of high air movement. Following the reduction in temperature, attention may then be paid to combating shock and treating intercurrent disease if present.

11.1.5 Supervision

An important factor in the prevention of heat illnesses is the supervision of individuals moving into hot regions or working in hot environments in industry. This broadly involves the control of human activities in outdoor heat and reduction of indoor heat loads to within recognised safety limits. Successful prevention often results from careful selection and medical screening of personnel, combined with a deliberate attempt to heat acclimatise before heat exposure. Guidance will be available in an ISO standard in preparation (see ISO/DIS 12894 in Appendix A).

11.1.6 Medical screening

Susceptibility to heat varies from person to person and it is important that those who are more at risk from heat effects should not be exposed to unduly hot conditions. Factors which should be taken into account when assessing suitability for work in hot environments include:

(a) ***Weight and physical fitness***: those who are overweight or unfit are more likely to experience ill-effects.

(b) ***Age***: the older a person is the more likely they are to suffer from the effects of heat; particular consideration should be given to individuals over 45 years of age.

(c) ***Medical disorders***: many disorders affect a person's ability to work in hot conditions. These include disorders such as diarrhoea, vomiting, colds and influenza, and major disorders such as lung, heart and circulatory illnesses. Chronic skin diseases may be made worse by working in a hot environment and often predispose to heat illness. Low or high thyroid gland activity produce marked intolerance to cold and heat respectively.

(d) ***Some medications*** have an adverse affect on individuals exposed to heat (Table 11.2). Habitual alcohol abuse has directly or indirectly contributed to the deaths of workers exposed to hot working conditions.

(e) ***Previous heat intolerance***: workers who have shown themselves susceptible to the effects of heat in the past, even if for no clear reason, are likely to be at greater risk with further exposure.

11.1.7 Acclimatisation

After a sufficient period of exposure the body is able to adapt to heat and tolerate higher ambient temperatures. The effects are therefore less severe on acclimatised than unacclimatised persons. Acclimatisation can either be achieved artifically by controlled exposure in a climatic chamber, or naturally by working at high temperatures for short periods each day.

Acclimatisation should take place gradually over a period of 7 to 10 days. Fit persons can become acclimatised more readily than unfit personnel. When exposure to heat ceases, acclimatisation continues for about a week, then it declines and is lost completely after about a month.

The improvement in heat tolerance is due to an increased ability to sweat and a reduced pulse rate; sweating commences at lower core and skin temperatures and the salt content of the sweat is reduced.

11.2 Cold

11.2.1 Hypothermia

Hypothermia is a condition of low core temperature and is clinically defined as a deep body temperature below 35°C. It is potentially life-threatening and usually develops insidiously without the subject being aware of the threat. As the body temperature falls below 35°C there are increasing disturbances of brain and cardiac function. There is listlessness, confusion and disorientation with amnesia for the events at the time of hypothermia. Consciousness is lost at a body temperature between 33 and 26°C, with considerable variability between individuals (Collins, 1983).

Cardiac output and blood pressure rise initially in the cold associated with intense vasoconstriction and shivering, but as cardiac output subsequently falls, heart rate slows due to the direct effect of a cold core temperature on cardiac muscle.

During hypothermia, cold tissues require much less oxygen on which to survive, but at body temperatures below 26°C the cardiac output is insufficient to supply even minimal oxygen requirements and death ensues unless the hypothermic subject is rewarmed.

Another important hazard of hypothermia is disturbance of the heart rhythm due to the effects of cold. Atrial fibrillation commonly occurs at deep body temperatures between 35 and 28°C while at core temperatures below 28°C the more dangerous condition of ventricular fibrillation can occur leading to cardiac arrest.

Loss of fluid from the circulation to the extra-vascular space contributes to a loss in blood volume, hypotension, and the accumulation of oedema fluid in the tissues. Loss of fluid by cold diuresis at the beginning of cold exposure helps to create dehydration which is made worse in profound hypothermia when the kidneys fail to reabsorb water and salt.

11.2.2 Management

Management of hypothermia depends largely on the condition of the victim, the prevailing conditions and available help. When an unconscious hypothermic subject is found, special care and hospital treatment are usually urgently required. Much can be done, however, to prevent the situation from becoming worse in exposed outdoor situations.

(a) In those showing signs of hypothermia, further exhaustion and heat loss can be prevented by insisting on rest on a non-conducting surface and erecting some form of shelter against wind and rain.

(b) An impermeable garment put on over clothing wetted by sweat or rain will reduce evaporative heat loss, and any additional clothing even if wet will reduce convective heat loss. Ideally if good shelter is available it is better to remove wet garments and reclothe in several layers of warm, dry clothes.

(c) Body temperature has usually fallen slowly and is relatively stable in air exposure. Core temperature should be measured by rectal temperature using a low-reading thermometer. Provided that there is no serious injury or extensive frostbite, recovery is invariable if a moderately hypothermic victim is placed recumbent in a well-insulated sleeping-bag.

(d) Covering the head, mouth and nose loosely with a scarf can help to reduce heat loss significantly.

(e) A person who is not exhausted or severely hypothermic can be encouraged to stimulate internal heat production by some body movements.

(f) Active surface warming is initially counter-productive and may cause an ‘after-drop’ in core temperature. In the mildly hypothermic state (34 to 35°C core temperature) it may be better to risk a slight temperature after-drop if in the long run body temperature can be raised by surface warming.

(g) Hot, sugared liquids can be fed slowly to the conscious hypothermic subject but no attempt should be made to give fluids to the unconscious.

(h) Alcohol, which can cause a dangerous fall in blood sugar level and lead to further rapid body cooling in an exhausted victim, should be avoided.

(i) Encouragement is an important component assisting recovery and a conscious hypothermic subject should not be left alone unless unavoidable.

A more dangerous cause of hypothermia than exposure to cold air occurs as the result of water immersion. Many people develop profound hypothermia after several hours immersion in water at 15 to 20°C and survival time may be quite short in water below 10°C (Figure 11.1).

Body cooling during immersion can be reduced by wearing thick conventional clothes including gloves and footwear if wet suits or waterproof garments are not available. Hard exercise in water including vigorous swimming with use of arms and legs may increase heat loss substantially more than internal heat production. There is some evidence that leg exercises alone may help to maintain body temperature for a while.

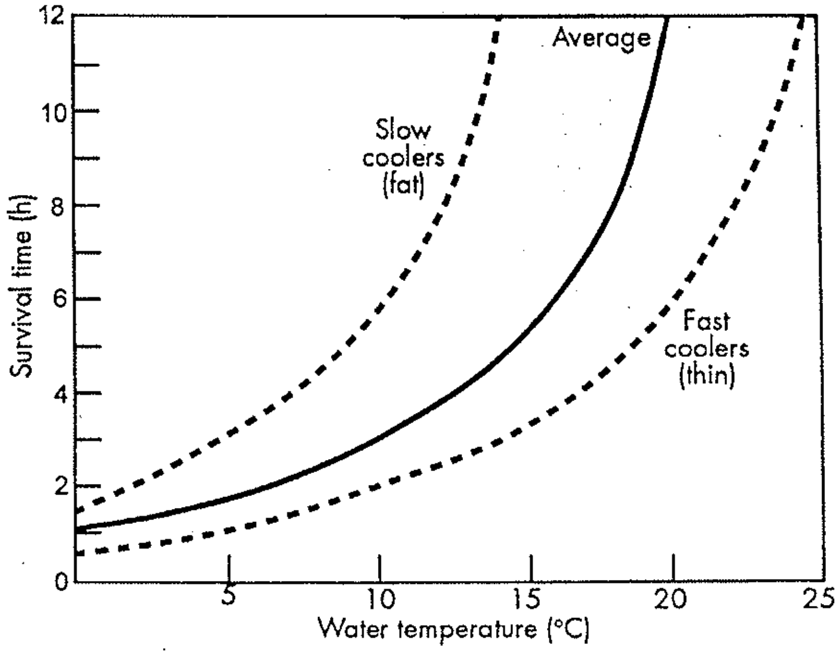


Figure 11.1: Predicted survival time of lightly clothed humans in cold water based on time to cool to 30°C core temperature.

The zone of survival includes a large individual variability from body size and fatness. Survival time would be shifted upwards slightly by thermally protective and heavier clothing, and downwards by significant physical activity. (After Hayward *et al*, 1975)

Those who have a body temperature below 31°C at the time of rescue from water are at great risk for about the first 30 min because of the possibility of circulatory collapse and body temperature after-drop. One method of treatment for previously fit young people is fast rewarming by immersion of the trunk (but not the arms and legs) in a water-bath at 41 to 43°C, or 44 to 46°C if clothed. The water temperature of a domestic bath falls rapidly by about 7°C in the first 30 seconds as the result of immersing a hypothermic subject and the water should be quickly rewarmed. When body temperature has risen to 33°C, the subject should be removed from the warm bath, dried, and placed recumbent in warm air or under blankets to continue rewarming more slowly.

11.2.3 Local cold injury

Local cooling of the limbs can induce non-freezing cold injury or freezing injury (frostbite) with or without the presence of hypothermia. Cooling for many minutes below 12°C without freezing may cause sensory and motor paralysis of the local nerves.

Trench foot (immersion foot) is due to prolonged cooling of the feet in mud or water causing crippling non-freezing cold injury with local damage to nerves and tissues, and muscle weakness. After several hours at low temperature, nerve and muscle undergo lasting damage and there is subsequent degeneration of function when normal body temperature and blood flow is restored.

Local cooling below -0.5°C can freeze human tissues, though they often supercool initially and only freeze when rather lower temperatures are reached. Necrosis of tissues caused by damage to the cells of the blood vessels is responsible for most of the local damage in frostbite. With ensuing gangrene there may be loss of fingers or toes or even the greater part of a limb.

Special attention should be paid to personnel sustaining any form of traumatic injury whilst in freezing conditions because there is then a predisposition to secondary cold injury. Provision must be made to prevent total body hypothermia resulting from immobilisation in these circumstances and to avoid secondary freezing of damaged tissues.

11.2.4 Other medical effects of cold

People who suffer from heart disease, especially in the older age group, are at greater risk of a coronary heart attack in cold conditions. The increased incidence of anginal attacks and coronary and cerebral thrombosis in cold winters is closely related to the effects of low environmental temperatures and is probably due to increased blood pressure, cardiac strain and increased blood viscosity.

Respiratory disease is also enhanced in cold weather particularly when there are atmospheric pollutants with freezing fog or smog. Cold may cause bronchospasm and adversely affect physical work performance and in some may lead to exercise-induced asthma.

Cold allergy occasionally develops on removal from the cold with widespread vasodilatation over the whole body, headache and hypotension. Those with circulatory problems require special protection against cold. Individuals who suffer from Raynaud's phenomenon (constriction of blood supply to the extremities causing white finger or toe) are particularly sensitive to local cold, which causes intense vasospasm and numbness in the unprotected extremities. Raynaud's phenomenon in the hands is known to result from vibration ('vibration white finger') caused by the use of pneumatic tools so that this may be a particular hazard in cold conditions.

A cold air-stream directed onto the side of the face can sometimes induce an acute paralysis of the facial nerve. This arises from swelling entrapment of the nerve in the bony facial canal and it results in a Bell's palsy on one side of the face which may take some weeks to resolve.

Employees should be excluded from work in cold at −1°C or below if they suffer from disease of the thermoregulatory or cardiovascular systems or if they are taking any medication that may reduce their tolerance to work in cold environments. Proper medical screening of potential workers in cold conditions is therefore important.

11.2.5 Warning signs

Pain in the hands or feet due to intense vasoconstriction may be the first sign of danger in cold stress. Maximum shivering develops when the body temperature has fallen to hypothermic levels (35°C) and this is an indication that the exposure should be terminated. Useful physical or mental work is limited when severe shivering occurs and at low body temperatures there may be unusual and unexpected behavioural changes in the cold.

11.3 Drugs and Thermoregulation

It is common experience that fevers, rigors and disturbances in body temperature regulation can result from infections by micro-organisms and exogenous pyrogens. A number of drugs and chemicals also have direct effects on the nervous control of body temperature or on metabolism and heat production of the body. These substances may have indirect effects on body temperature through induced toxicity reactions or through the interaction of different drugs or chemicals used simultaneously.

Some drugs may affect body temperature in neutral ambient temperature conditions, *eg* salicylates (aspirin) and other compounds that reduce a raised body temperature, while others may seriously affect thermoregulatory processes in the presence of thermal stress, *eg* atropine-like substances that reduce sweating.

The better known examples of body temperature - drug responses in humans associated with hypo- and hyperthermia are listed in Tables 11.1 and 11.2 respectively. Reactions to various groups of drugs, or even individual compounds within a group, can be variable depending on age, environmental conditions, stress and other factors.

It is obvious that many of these drugs exhibit a dual action and are capable of producing either hypothermia or hyperthermia depending on the dose used and on the prevailing environmental conditions. Most drugs will have some indirect effect on responses to heat and cold through their action on different systems of the body; those listed are known to have specific effects on the thermoregulatory system.

Table 11.1
Some substances associated with hypothermia (*ie* cooling of the body)

Drug	**Action on thermoregulation**
Alcohol	Central nervous inhibition. Hypoglycaemia. Peripheral vasodilatation. Impairment of behavioural thermo-regulation and judgement in low temperatures. May alter 'set-point'.
Antidepressants	Rapid depression of body temperature. Reduced awareness of cold. Potentiate hypothermic effect of barbiturates and alcohol.
Tranquillisers *eg* benzodiazepines	Can induce hypothermia, especially in high doses.
Hypnotics	Lower body temperature in cold environments. Peripheral vasodilatation. Augmented by alcohol. Hypothermia may occur with non-barbiturate hypnotics (*eg* nitrazepam) especially in the elderly.
Psychotropics *eg* phenothiazanes	Powerful hypothermic action in cold with long-term central action on body temperature. May also have peripheral action.
Cannabis	Fall in body temperature in ambient temperatures within or below thermoneutral. Hypothermia with overdosage of cannabinoids.
Morphine	Hypothermia with high dosage and during withdrawal of drugs
Anaesthetics	Central nervous depression. Hypothermia may develop in ambient temperatures below 24°C.
Hypoglycaemics *eg* biguanides	Reduced metabolic heat production during treatment of diabetes mellitus.
Antithyroids *eg* carbimazole	Reduced metabolic heat production.
Sympathetic and ganglion-blocking agents *eg* reserpine	Reduced vasoconstriction in cold causing fall in body temperature.
Organophosphates *eg* pesticides	Anticholinesterase action on autonomic nervous system resulting in reduced body temperature. May alter 'set-point'. Can also lead to heat stroke (Table 11.2).

Table 11.2
Some substances associated with hyperthermia (*ie* heating of the body)

Drug	**Action on thermoregulation**
Alcohol	Inhibition of central nervous function. Dehydration. Impairment of behavioural thermoregulation and judgement.
Antidepressants *eg* tricyclics	Hyperthermia with high doses especially in combination with other agents *eg* amphetamines. Counteract reserpine-induced hypothermia.
Hypnotics *eg* barbiturates	Central nervous depressant. Body temperature increases in hot environments. Effects augmented by alcohol.
Psychotropics *eg* phenothiazines	Hyperthermia in high ambient temperature. Central effect on thermoregulation with possible peripheral actions.
Cannabis	Hyperthermia in hot environments.
Morphine	Hyperthermia usually with low doses.
Amphetamines	Central nervous stimulant. Vasoconstriction. Increased peripheral heat production.
Anaesthetics	Central nervous depression of thermoregulatory centres. Hyperthermia in hot environments. 'Malignant hyperthermia' a rare complication of *eg* halothane anaesthesia involving muscle contracture in susceptible subjects.
Cocaine	Overdose may result in heat-stroke.
Anticholinergics *eg* atropine	'Atropine fever'. Effects on thermoregulatory centres. Inhibition of sweating.
Organophosphates *eg* pesticides	Potential heat-stroke *via* alteration of 'set-point' (see Table 11.1).

APPENDIX A:

RELEVANT BS/EN/ISO STANDARDS

Overall

BS EN ISO 11399: 1995 - New standard
Ergonomics of the thermal environment : Principles and application of relevant International Standards

This standard summarises the principles and application of the other relevant thermal standards.

Assessment of Comfort

BS EN ISO 7730: 1995 (Originally ISO 7730: 1984; rev. 1995)
Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort.

Assessment of Heat Stress

BS EN 27243 : 1994 (*ie* ISO 7243: 1989)
Hot environments - Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature).

ISO 7933: 1989
Hot environments - Analytical determination and interpretation of thermal stress using calculation of required sweat rate.

Assessment of Cold Stress

ISO under development (TR (Technical Report) 11079: 1993)
Evaluation of cold environments - Determination of required clothing insulation, IREQ.

Measuring Equipment

BS EN 27726: 1994 (*ie* ISO 7726: 1985 under revision for 1996)
Thermal environments - Instruments and methods for measuring physical quantities.

Measurement of Other Parameters

BS EN 28996: 1994 (*ie* ISO 8996: 1990)
Ergonomics - Determination of metabolic heat production.

ISO 9886: 1992
Evaluation of thermal strain by physiological measurements.

Clothing

BS ISO 9920: 1995 (*ie* ISO 9920:1995)
Ergonomics of the thermal environment - Estimation of thermal insulation and evaporative resistance of a clothing ensemble.

Other topics and those under development

(Note: DIS = Draft international standard
NP = New project)

Subjective

BS ISO 10551: 1995 (*ie* ISO 10551:1995)
Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales.

Surfaces

BS EN 563: 1994
Safety of machinery - Temperatures of touchable surfaces - Ergonomics data to establish temperature limit values for hot surfaces
(...and similar for cold surfaces under development).

Others

BS 7643: Part 1: 1993
ISO 6242-1: 1992
Building construction - Expression of users' requirements - Part 1: Thermal requirements.

ISO (under development) (13731)
Ergonomics of the thermal environment: Definitions, symbols and units.

ISO/DIS 12894 (In preparation)
Medical supervision of individuals exposed to extreme hot or cold environments.

ISO/NP 14505
Ergonomics of the thermal environment in vehicles.

ISO/NP 14415
Ergonomics of the thermal environment: Application of International Standards to the disabled, aged and handicapped persons.

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