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Working in hot conditions in mining: a literature review

Graveling RA, Morris LA, Graves RJ



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WORKING IN HOT CONDITIONS
IN MINING: A LITERATURE
REVIEW

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LA Morris
RJ Graves

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SUMMARY

This review of the literature on working in hot conditions in mining was originally written for the Health and Safety Executive's Mines and Quarries Inspectorate to provide them with a collated source of information in formulating possible legislative policy for UK mines. Most of the hot mines in the UK are coal mines. The one potash mine also has hot conditions although neither that nor the coal mines appear to have thermal conditions as severe as those encountered on the European mainland.

The review includes a brief overview of thermal physiology: environmental and metabolic heat loads and the physiological and behavioural responses to such loads. It also encompasses methods for the assessment of hot conditions either directly, through the measurement of physiological strain, or indirectly via thermal indices.

These elements are then examined in the context of UK mining conditions with sections on the thermal and metabolic heat loads reported in coal and potash mines and an assessment of those thermal indices which suitably reflect the potential effects of such loadings. The Basic Effective Temperature (BET) index is currently used in both the coal and potash mining industries. Although this index has its limitations the review concluded that, as a 'first order' monitoring index, the BET scale would appear to predict heat strain with an acceptable degree of accuracy within the range of climates currently encountered in hot UK mines.

Fluctuations in environmental heat load are reported, both over time and between adjacent locations. The review draws attention to the need to take both these fluctuations and those of metabolic heat load into account in formulating a method for determining and evaluating the likely degree of thermal stress. The calculated thermal stress will usually be evaluated against some form of Standard or criterion. The review examines those Standards etc. already in use and concludes that, depending upon work rate and pattern, an action limit of between 27 and 31°C BET can be applied.

Finally the review examines various control measures such as refrigeration and personal cooling for their potential impact on the workforce. It concludes that many of those currently employed have some merit although many can have undesirable 'side-effects'. For example, local cooling can create problems elsewhere underground where the extracted heat is discharged.

WORKING IN HOT CONDITIONS IN MINING: A LITERATURE REVIEW

by

R.A. Graveling, L.A. Morris and R.J. Graves

1. INTRODUCTION

1.1 Background and Terms of Reference

The Health and Safety Executive's Mine and Quarries Inspectorate required information to enable them to decide whether there may be a problem in relation to hot conditions developing in mining which would require legislative action. Accordingly, they wished for a review which took account of the potential trends towards deeper and hotter mines which were likely to occur in the next ten to fifteen years.

The intention of the review was to provide definitive information on the problems of working in hot conditions which would be relevant to mining. This would include relevant information from other industries. The scope of the review was to include standards, control, protection, measurement techniques, regulations, procedures and experience in other countries. The review should include the Institute of Occupational Medicine's opinions of the usefulness and relevance of the work described though the Inspectorate would have to decide what action, if any, would be required.

1.2 Hot Conditions in Mining

It is widely recognised that hot workplace climates can lead to reduced work performance and, if sufficiently severe, to acute and chronic disturbances to health (LEITHEAD and LIND, 1964). In mining there has traditionally been an awareness of the effects of climate on health and productive efficiency, and as a consequence, there have been considerable developments in methods of assessment and control (WEINER, 1972).

In modern coal mines, hot-humid climates may be encountered in deep, highly mechanised workings where coal output is high (VOSS, 1976). Under these conditions, mine air is heated primarily by the strata with smaller contributions from adiabatic compression and the oxidation of carbonaceous matter. In addition mine air is heated intermittently by operating machinery and cut coal. High ambient humidities may occur in the vicinity of the coalface largely as a result of moisture picked up from the strata and dust suppression water sprayed during cutting operations (PEARCE, 1985). Although such conditions have been a significant problem in the deep coal mines of Belgium and West Germany this has not been the case in

comparable depth (BROWNING, 1979). However, it has been predicted (BROWNING, 1979; PEARCE, 1985) that problems of heat and humidity will become more prevalent with the current trend towards deeper and more highly mechanised workings.

Hot conditions are also encountered in underground potash mines of which there is one operating in the United Kingdom. Potash mine climates are drier than those encountered in coal mines, but a similar combination of strata temperatures and mechanisation results in comparable conditions. Like coal mines, as the age of the mine increases the greater distances of the actual workings from the shafts are likely to result in an increase of ambient temperatures. In tackling such conditions, mine managers will clearly require reliable methods of assessing the potential effects of climate on the workforce together with effective, practical methods for ameliorating any adverse influences. This document provides a detailed review of the effects of working in hot conditions on the workforce. It describes the underlying physiological changes which occur on exposure to heat and looks at the health implications of such changes. Hot conditions may also influence behaviour with concomitant effects on safety and the review also examines the scientific literature on these topics.

Physiological changes form the basis of any monitoring procedures either through direct monitoring of the physiological status of the workforce or indirectly by using predictive equations or indices. A wide variety of these indices are described and compared within the context of the thermal conditions encountered in hot deep mining in the United Kingdom.

Finally, the use of various control measures is examined from the viewpoint of their likely effect on the workforce. These measures are viewed against a background of the various legislative measures which have been adopted in some countries to minimise the risk to health and safety of individuals working in hot conditions.

2. HEAT BALANCE AND HEAT EXCHANGE

In this report, the terms stress and strain have been used in the engineering sense of load and response.

2.1 Heat Stress Factors

Man, as with other mammals, is 'homeothermal' - that is, he maintains his body temperature at a reasonably constant level in spite of wide variations in environmental temperature. The normal deep body temperature (core temperature) at rest is 36-37.5°C although diurnal variations of some 1-1.5°C may occur in any normal person, even at rest, and temperatures as high as 40-41°C have been recorded in athletes (KEELE and NEIL, 1971). These latter values serve as an extreme illustration of the effects on core temperature of 'working' in hot conditions. They also illustrate the wide individual variation in heat tolerance. Some individuals cannot tolerate core temperatures of 38-39°C whereas others, as illustrated above, continue to perform well at much higher temperatures.

Body temperature is maintained by achieving heat balance - an equilibrium between the various modes of heat gain/production and heat loss from the body. There are two major sources of heat load, environmental; which may constitute a positive (heat gain) or negative load (heat loss); and metabolic, primarily attributed to the heat production associated with muscular work although also influenced by dietary factors.

The processes of heat production and exchange are normally represented in the form of a heat balance equation shown in Figure 1.

2.1.1 Environmental heat load

The major modes of heat exchange between man and the environment are convection, radiation and evaporation. Other than for brief periods of body contact with hot tools, equipment, floors, etc. which may cause burns, conduction plays a minor role in industrial heat stress.

(a) Convection (C).

The rate of convective heat exchange between the skin of a person and the ambient air immediately surrounding the skin is a function of the difference in temperature between the air and the skin temperature together with the rate of air movement over the skin.

Thus it can be seen that, where air temperature is greater than skin temperature, there will be a gain in body heat from the ambient air by convection and, when the reverse applies, heat will be lost from the body to the ambient air

$$M \pm C \pm R - E = \pm S \quad (+ = \text{heat flow to body} \\ - = \text{heat flow from body})$$

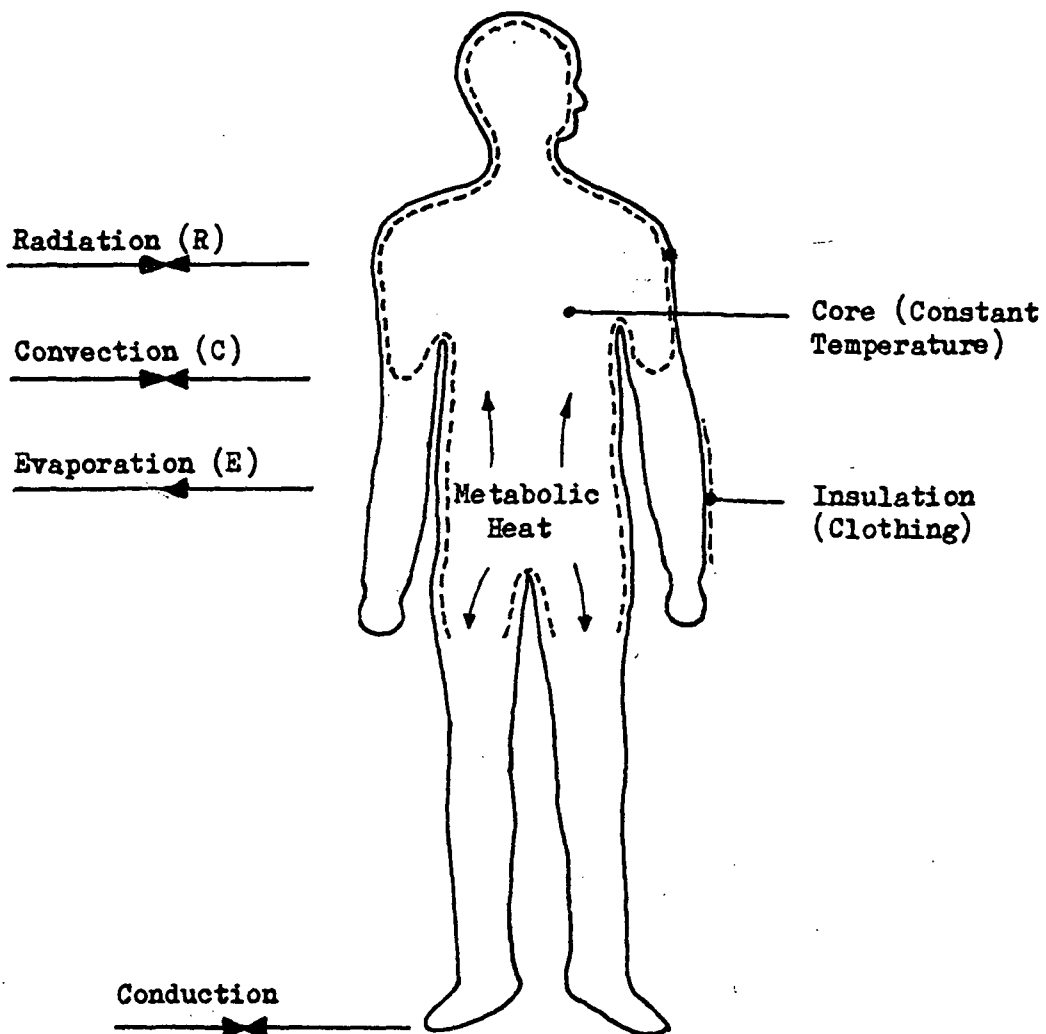


FIGURE 11 - Heat Exchange Between Man and His Thermal Environment

by this route. Skin temperature is usually regarded as the 'mean weighted skin temperature' a function which takes into account fluctuations in skin temperature over the body surface.

(b) Radiation (R).

The rate of radiative heat exchange between the skin of a person and the ambient air is a function of the difference between the absolute temperature of the solid surroundings, and the skin temperature. In addition to its contribution to the heat balance equation, radiant heat can have adverse 'local' effects causing skin burns and other disorders as described, for example, by ORDINANZ (1970). These are regarded as outside the terms of reference of this review as they are unlikely to be encountered in mining (GRAVES et al., 1981).

(c) Evaporation (E).

The evaporation of water (sweat) from the skin surface results in a heat loss from the body. The maximum evaporative capacity (and heat loss) is a function of air motion and the water vapour pressure difference between the ambient air and the wetted skin at skin temperature. In humid climates, this difference is likely to be reduced, therefore this mode of heat loss is considerably impaired. This is particularly the case where low air movement allows the air immediately surrounding the skin to become relatively more humid, reducing the skin-air gradient.

2.1.2 Metabolic heat load

In addition to heat exchange between the body and the environment, the other major source of heat load is that produced by internal metabolic processes. Of these, although digestion and other activities do make a slight contribution, the major influence is that associated with external work. MORRIS et al. (1983) listed four work components as contributing to the metabolic heat load: work rate, work nature, work pattern and posture.

(a) Work rate.

Muscular work is an inefficient process. At best, the major muscles of the body such as the large leg muscles, can only achieve 20-25% efficiency. As with all machines, a substantial proportion of the remainder is produced as heat. There is therefore a direct relationship between work rate and metabolic heat production.

(b) Work nature.

As stated above, muscle work is, at best, only some 20%

efficient. Much modern work both in mining (e.g. GRAVELING et al., 1980) and elsewhere (e.g. KILBOM, 1976) comprises a mixture of dynamic and static work. As the proportion of static work increases, i.e. there is less external movement, the muscles become increasingly inefficient, with an increasing proportion of the energy consumed produced as heat. The nature of the work can clearly therefore influence the overall metabolic heat load.

(c) Work pattern.

The intermittent nature of modern industrial work has long been recognised. This intermittency is perceived as having a beneficial effect on work tolerance (SIMONSON, 1971) but it has been suggested that it may adversely affect thermoregulatory efficiency (EKBLOM et al., 1971). However, it has also been suggested that 'spontaneous intermittency' in the form of self-pacing may allow workers to operate safely in adverse climates (MAIRIAUX and MALCHAIRE, 1985). The importance of the work pattern in influencing total thermal stress is reflected both in the use of time-weighted averaging in assessing metabolic heat load and in the adoption of work-rest scheduling as an avenue for amelioration. The implications of intermittent work patterns for metabolic heat load assessment are discussed in more detail in section 5.2.2. Its use is also referred to in section 7 where it forms an integral part of some standards. Work-rest scheduling as a remedial/preventative measure is discussed in section 8.1.4 (work reorganisation).

(d) Posture.

Posture can affect heat balance either by inducing additional muscle loading or by directly influencing heat exchange by restricting heat transfer from the body surface (WAKIN, 1964).

2.1.3 The influence of clothing

Heat exchange is reasonably easy to analyse in the basic model incorporating exchange between a nude man's skin and the micro-climate created by a layer of ambient air. However, when a layer or layers of clothing are provided, heat exchange analysis is more complicated. The space between the skin and the outermost layer of clothing becomes a complex micro-environment consisting of air and fabric layers changing in depth with body movement (BIRNBAUM and CROCKFORD, 1978). The insulative characteristics of this micro-environment are a function of air trapped between the skin and clothing, the amount of air trapped between the material fibres and the amount of still air above the material. Consequently, any factor that increases the thickness of the air layers and hence its insulative potential will lead to decreased heat loss. The 'picture' is even more complicated by potential variability in

air exchange between the clothing layers and the environment. The number, size, shape and position of openings in the garment will all influence air exchange. This process is further affected by the "pumping effect" caused by movements of the wearer.

In most hot industrial climates, the clothing worn can be regarded as a compromise between that required to retain a minimum level of decency (not always applicable in mining!) and that required to minimise interference with heat exchange. However, where protective clothing of some sort becomes necessary for non-climatic reasons, such as when handling corrosive or irritant materials, then this may well be an important element in the heat balance equation. Thus, briefs and a vest or tee-shirt have an insulative value of 0.1 to 0.15 clo (the unit of clothing insulation) whereas a coverall on top of these raises the total to 0.6 to 0.7 clo depending upon the fabric. As a guide to the significance of this, ELLIS et al. (1972) refer to a correction factor of 1°C added to the measured wet bulb temperature to allow for overalls being worn rather than shorts. Similarly, using the normal scale for Effective Temperature (light industrial clothing) rather than the basic scale (stripped to the waist) results in an increase in Effective Temperature of about 0.5°C.

3. HEAT STRAIN: PHYSIOLOGICAL AND BEHAVIOURAL RESPONSES TO IMPOSED HEAT STRESS

3.1 Physiological Responses

There are many physiological responses to an increase in heat load. These can constitute: reactive (acute) responses, relating to the body's coping mechanisms in 'immediate' response to exposure; or adaptive, reflecting an adjustment of physiological systems to continued (chronic) heat exposure and forming the basis of the process of adaptation or acclimatisation. A third category of response can be described, that of a generalised or non-specific response to 'stress' in accordance with the model proposed by SELYE (1950). However, these general responses are frequently difficult if not impossible to separate from the specific responses to the stimulus (GRAVELING, 1978) and will not be discussed here.

The main compensatory reactions to increased heat load are an increase in the blood flow through the blood vessels of the skin as a result of their enlargement (cutaneous vasodilatation) and sweating (KEELE and NEIL, 1971). Vasodilatation is brought about by a number of processes including direct effects of external heat on the superficial blood vessels, local nerve paths (reflexes) from 'warm endings' (temperature sensors in the skin), and central neural control from the hypothalamus. Initially, central neural control is mediated via the autonomic nervous system. Continued control is achieved by changes in hormonal levels in the blood. Adrenaline and thyroxine secretion into the blood is inhibited and adrenal corticoid secretion is increased. Sweating is similarly stimulated either by local reflex pathways or under central nervous control.

These compensatory responses evoke further responses, particularly in the cardiovascular system. Vasodilatation produces an increase in the active capacity of the circulatory system, reducing venous return. Heart rate increases to maintain or even increase cardiac output. Despite this increase in cardiac output, there is a decrease in diastolic blood pressure because of the decrease in peripheral resistance produced by vasodilatation. Systolic blood pressure varies according to the balance between increased cardiac output and decreased resistance.

Where muscular work contributes to the heat load, then the physiological demands of the work also influence the cardiovascular system, sometimes with conflicting results. Thus, during exercise, vasodilatation occurs in the muscles, increasing the demands on the cardiovascular system still further and occasioning greater changes in heart rate and blood pressure. These are exacerbated by continuing sweat loss which results in a gradual reduction in the circulatory volume. Paradoxically, one of the responses to heat exposure, despite

the decrease in thyroxine secretion, is an increase in general metabolic activity. This increased activity inevitably leads to greater metabolic heat production increasing heat load still further.

Although it does contain other constituents, the major components of sweat are water and sodium chloride (salt). Large losses of water by sweat pose a potential threat to successful thermoregulation, because a progressive depletion of body water content occurs if the water lost is not replaced; hypohydration by itself affects thermoregulation and results in a rise of core temperature (NIOSH, 1986). The salt concentration in sweat can vary from 0.1-0.4%. As sweat production rates of one litre per hour have frequently been recorded, salt losses of 4 gh^{-1} are clearly readily achievable (NIOSH, 1986). Part of the process of heat acclimatisation involves a progression over some 2-3 days towards the production of more dilute sweat. However, in acute exposure of unacclimatised workers, continued loss of salt and water, with subsequent dilution of the remaining salt by replacement only of water loss, can lead to clinical syndromes such as muscle cramps. NIOSH (1986) concluded that the salt content of the average US diet was probably sufficient to provide for adequate replacement. Other 'Western' diets such as the UK have frequently been criticised for their high salt content and it is likely that a similar situation therefore exists in this country. However, individuals on treatment with diuretics and low salt diet for the control of hypertension, might require more careful observation.

Two hormones are important in thermoregulation, the antidiuretic hormone (ADH) and aldosterone. A variety of stimuli encourages the synthesis and release of these hormones, such as changes in plasma volume, plasma concentration of sodium chloride, etc. ADH is released by the pituitary gland, which has direct neural connections with the hypothalamus but may receive neural input from other sources. Its function is to reduce water loss by the kidney, but it has no effect on the water loss through sweat glands. Aldosterone is released from the adrenal glands and reduces salt lost both in the kidney and in the sweat glands. However, aldosterone functions partly by replacing sodium in the urine with potassium.

As potassium is also lost in sweat, there can be a serious depletion of potassium when workers who are unacclimatized suddenly have to work hard in hot climates. Marked depletion of potassium can lead to the development of heat stroke (LEITHEAD and LIND, 1964). However, potassium loss is usually not a problem, except for individuals taking diuretics, because potassium is present in most foods, particularly meats and fruits. Since diuretics cause potassium loss, workers taking such medication while working in a hot environment may require special medical supervision.

These responses to heat load are not necessarily mediated via

changes in core temperature. As indicated above, the peripheral receptors will 'drive' the appropriate responses and this, coupled with the heat capacity of the body, can mean that little or no change in core temperature occurs (LIPPOLD and WINTON, 1968). During work in moderate climates, core temperature will be determined by metabolic heat production. NIELSEN (1938) demonstrated that when a man worked continuously at the same rate in a comfortable climate, his core temperature increased to a new equilibrium level within 60 minutes. The level of this equilibrium and the time taken to reach it depended on the rate of exercise, i.e. the harder the work rate, the higher the body temperature and the longer this took to reach equilibrium. In climates which had air temperatures in the range 5°-30°C, the equilibrium level was independent of the environment. Although other research (e.g. LIND, 1963a) has shown that the upper limit to which core temperature remains independent of environmental temperature varies inversely with work rate, the principle still holds true. Above this upper 'critical level', core temperature will start to rise comparatively rapidly as the body enters a state of disequilibrium. This phenomenon has served to provide the basic criteria for limiting work in the heat (LIND, 1963a) via heat stress standards. It is discussed further in section 5.2.3 and in the standards section (section 7).

The competition between the physiological demands placed on the body due to environmental heat load and those attributable to muscular work can lead to an impairment of the oxygen supply to the working muscles. As a result, the muscles increasingly utilise anaerobic processes resulting in an increased concentration of lactic acid in the muscle tissues and the blood. The release of lactic acid into the bloodstream elicits further responses such as increased respiration.

Finally, the NIOSH revised criteria document (NIOSH, 1986) contains a comprehensive tabulation of acute heat disorders including fainting (postural heat syncope), heat exhaustion and heat stroke. These all result from the physiological responses detailed above. Thus, fainting results from insufficient blood supply to the brain due to pooling of blood in the skin and lower parts of the body. Heat exhaustion results from excessive fluid loss in sweating without adequate replacement and heat stroke stems from a failure of the sweating response leading to an increase in core body temperature.

The NIOSH document also suggests the possibility of chronic heat disorders due to long term heat exposure. However, the current level of information on these disorders did not provide any usable information for the heat stress standard although it was considered by NIOSH to be a topic warranting further investigation. The symptoms of the major heat disorders are briefly outlined in section 3.4 (Acute Health Effects of Heat). Summary details of their treatment and prevention can be found in NIOSH (1986), pages 41-43.

3.2

Factors Which Modify the Physiological Responses to Heat Stress

As was briefly referred to in the previous section, acclimatisation can alter some physiological responses to heat stress, acting to increase sweating efficiency by initiating its onset at a lower temperature, increasing the volume of sweat production and reducing the salt content. These changes occur with repeated exposure. However, some other human characteristics can modify the thermal response. These include: fitness and physical work capacity, diet and obesity, age and sex. Each of these will be discussed below. In addition there are inherent individual differences in, for example, circulatory system capacity, efficiency of sweat production and regulation of electrolyte (salt) balance. These latter factors can be considered to be intrinsic variables contributing to the population variability in response to heat which must also be taken into account.

(a) Fitness and physical work capacity.

There is an interaction between physical work capacity and heat such that heat reduces physical work capacity and increases in physical work capacity generally improve heat tolerance. A NIOSH working group examining the influence of various external variables on heat stress, concluded that physical fitness was the most important factor and that some form of screening test should be considered (DUKES-DOBOS and HENSCHER, 1980). SHVARTZ (1980) reported data from studies of groups of physically trained and untrained men working in hot conditions (40°C dry bulb, 30°C wet bulb). After working for 180 minutes there was a mean difference in rectal temperature of 0.4°C. No details of the levels of physical training were given.

SIMONSON (1971) reviewed the effects on physical work capacity of heat. Comparisons between studies, and determination of precise relationships were difficult because of the different climates examined, differences in the means of expressing these climates, and because of the variation in assessment criteria. Many of the studies related to tolerance times in heat rather than a direct evaluation of changes in physical working capacity. A number of studies have reported reductions in efficiency or of 'load moved', etc. varying from 10-80% reduction with increasing environmental heat load. However, data from a number of studies, e.g. that of MAIRIAUX and MALCHAIRE (1974) on psychophysical limits to manual handling loads, have shown reductions in the voluntary work rate. Consequently, it is frequently not possible to differentiate between genuine reductions in work capacity and reductions in work tolerance. ASTRAND and RODAHL (1977) reported the response of an individual to a standard work task in a cool (undefined) and hot (40-50°C air temperature and radiation) conditions. There was no

difference in maximal oxygen uptake with temperature change. However, although oxygen uptake and therefore the absolute working capacity would appear from this to be unaffected, the disproportionate increases in other physiological parameters such as heart rate and core temperature, together with psychological influences, reduce the effective working capacity with increasing temperature.

(b) Diet and obesity.

The intake of food makes a major contribution to the diurnal variation of core temperature (IAMPINETRO et al., 1957) promoting a considerable increase in core temperature, presumably related to the catabolic activity associated with digestion although competition for blood flow between the skin and the digestive organs may also play a part. However, the precise characteristics of the diet are relatively unimportant. In most circumstances, the normal, mixed diet will not place any particular load on an individual working in the heat or have any influence on his responses. However, as stated above, electrolyte imbalance could occur if an individual was on a very low salt diet. NIOSH (1986) drew attention to the possibility that a high protein diet, because of the high protein content, may increase water intake requirements. It has also been suggested that vitamin C deficient diets could usefully be supplemented to aid thermoregulatory function (STRYDOM et al., 1976) although again it is unlikely that an individual on a normal mixed Western diet would derive any benefit from this.

Probably the main effect of diet is its long-term effect on obesity. It is well established that obesity predisposes individuals to heat disorders (LEITHEAD and LIND, 1964). The acquisition of fat means that additional weight must be carried, thereby calling for a greater expenditure of energy to perform a given task and use of a greater proportion of the work capacity. In addition, the body surface to body weight ratio (m^2 to kg) becomes less favourable for heat dissipation. Probably more important is the lower physical fitness and decreased maximum work capacity and cardiovascular capacity frequently associated with obesity. The increased layer of subcutaneous fat provides an insulative barrier between the skin and the deep-lying tissues which theoretically reduces the direct transfer of heat from the muscles to the skin (NIOSH, 1986).

(c) Age.

BARTNICKI et al. (1969a) suggested that the optimum age for heat tolerance was 31-35 years while, above 40 years, thermal tolerance was impaired. HENSCHER (1976) reviewed some of the literature and, while the papers reviewed did not examine the age range in such detail, the general observation of a decrease in heat tolerance with age above

40 years was supported. NIOSH (1986) attributed this to a 'more sluggish response of the sweat glands'. WAGNER et al. (1972) reported that younger males (20-29 years) sweated more freely, maintained lower core temperatures and had greater 'circulatory stability' than older males (46-67 years). However, as HENSCHER (1976) pointed out, it is difficult to differentiate age from other factors such as physical work capacity, etc. which also deteriorate with age. Thus, the groups examined by BARTNICKI et al. (1969a) had variations in weight and body surface area which may also have contributed to the observed 'age' effects. It would appear therefore that heat tolerance may be reduced over the age of about 40 years although this may not be directly attributable to the aging process.

(d) Sex (gender).

NIOSH (1986) stated that, purely on the basis of a lower aerobic capacity, the average woman is at a disadvantage when she has to perform the same job as an averaged-sized man. However, the document concluded that, when they worked at similar proportions of their physical work capacity, women performed either similarly or only slightly less well and that this performance was relatively unaffected by the menstrual cycle. This would appear to be contrary to earlier NIOSH publications such as that written by HENSCHER (1976) who suggested that there was a difference and commented that this was despite a greater number of sweat glands per unit area in females. BARTNICKI et al. (1969b) provided apparently confusing data. Women showed a lower sweat rate and smaller increases of core temperature and heart rate in response to a standard hot environment; which could be regarded as indicative of less heat stress. However, when calculated as sweat rate per 1°C core temperature increase, the data were interpreted as indicating better tolerance by the men. This interpretation was supported by the observation that more women than men displayed signs of distress and fainting during the climate chamber studies. HENSCHER (1976) cited several cases where, despite comparable or smaller physiological responses, women were less tolerant of heat than men either voluntarily (willingness to remain) or involuntarily (fainting, etc.).

The contention of the NIOSH document (NIOSH, 1986) that women perform either similarly or only slightly less well would appear to be at odds with at least one of the references they cite. AVELLINI et al. (1980) reported that unacclimatised women demonstrated longer tolerance times and lower core temperatures than men pre-ovulation but were more comparable to men post-ovulation although they still maintained lower physiological responses. These subjects were comparable for fitness (aerobic capacity), body surface area and area to mass ratio. However, FRYE and KAMON (1981), in a study of men and women matched

solely for fitness, found no effect of menstrual phase in the women and lower core temperatures in unacclimatised men. Both papers were in agreement that most differences were reduced by acclimatisation.

The literature on this topic is therefore rather confused as to whether, in absolute terms, women are better, worse or no different to men. However, the influence of other factors such as fitness, size and weight, which do differ between the sexes, is such that, in an 'average' mixed industrial population, the women are likely to be less tolerant of heat stress.

3.3 Performance and Behavioural Responses

Apart from the effects of heat stress on physical work capacity (and consequently physical performance) referred to earlier (section 3.2), there is an immense body of literature on the effects on psychomotor and cognitive tasks. It is also widely recognised that, possibly through these effects, heat may have a detrimental effect on safety and accidents (BELDING, 1976). This section is concerned with how hot conditions affect peoples' ability to do work and the way they behave.

The NIOSH recommended standard for occupational exposure to hot environments (NIOSH, 1972) laid down maximum temperatures for sedentary jobs requiring unimpaired mental performance ranging from temperatures over 40°C for brief exposures to 30°C for 4 hours. However, JENSEN (1980) reported that this provision was subsequently deleted by the Occupational Safety and Health Administration (OSHA) Standards Advisory Committee and the updated recommendations (NIOSH, 1986) do not contain any such provisions. The current American Congress of Government Industrial Hygienists (ACGIH) threshold limit value document (ACGIH, 1984) makes no reference to impairment of performance in heat. However, the more recent NIOSH document does identify work on accidents and heat stress as a 'research need'. JENSEN (1980) reported on a working group established to examine the question of whether accident prevention aspects should be included in the heat stress standard. The group concluded that there was 'significant evidence' of decreased mental performance in hot conditions. However, much of the data were from laboratory tasks which bore little resemblance to industrial applications. A further consideration was the lack of detailed evidence establishing an accurate correlation between thermal stress and accidents.

BELL (1967) reviewed the effects of hot environments and performance. The interaction was shown to be highly complex, depending upon many factors including exposure time, task characteristics, skill requirements and capabilities, and the motivation of those involved. The author concluded that previous attempts to produce limiting values were premature and that a much greater database was required covering all the potential contributory variables.

The review did however encompass reports from the Industrial Fatigue Research Board which suggested adverse environmental influences upon working efficiency - covering tinsplate factories, coal mines, and the weaving industries. However, BELL (1967) questioned the relevance of such reports due to their age, and that was 20 years ago!

Studies of the detrimental effects of heat on basic processes such as vigilance (FRASER, 1956) and peripheral vision (BURSILL, 1958), could be regarded as having some relevance to accident potential. More recently, RAMSEY *et al.* (1983) reported an examination of 'safety-related behaviour' and thermal environment. The authors identified an apparent inverted U curve relationship between the incidence of observed unsafe behaviour and the ambient temperature (WBGT). This was based on extensive observations at a metal products manufacturing plant, and at a foundry, over a 14 month period. Section 3.2 also discussed reported effects of heat on performance such as SNOOK and CIRIELLO (1974) reporting a decrease in voluntary handling capacity and MAIRIAUX and MALCHAIRE (1985) reporting a self-imposed decrease in work rate where working conditions permitted.

There seems little doubt that heat stress can reduce mental and psychomotor performance. The AUSTRALIAN COUNCIL of TRADES UNIONS, in an advisory document on heat stress, stated categorically that heat stress promotes accidents and reduces concentration (ACTU, 1983). JENSEN (1980) suggested that although such effects were apparent they were not sufficiently researched or clear-cut to be incorporated into a standard. The problem was considered to be one of identifying an appropriate limiting level from what was regarded as a relatively smooth curve of performance decrement against temperature, there being no such inflection point as can be identified for physical work (LIND, 1963a).

However, GRETHER (1973) reported a comprehensive review of a wide variety of tasks, concluding that there was a generally consistent decrement in performance above approximately 29°C Effective Temperature. Previously, WING (1965) had developed a proposed thermal tolerance limit relating exposure time against temperature for 'unimpaired mental performance' adopting a criterion of statistically reliable decrements in performance. The author placed caveats on the curve as relating to military personnel during 'highly stress-sensitive mental tasks' suggesting that, as such, it should be regarded as a lower limit. Perhaps not surprisingly, as it encompasses much of the same data (plus others) the figure of 85°F BET proposed by GRETHER (1973) coincides with the limiting curve for the longer exposure durations (4 hours) of WING (1965).

In conclusion, although it is accepted that elevated temperatures have an adverse effect on performance and behaviour, it would appear that no generalisable criterion level can be identified. Any such level which does emerge is likely

to be at least 29-30°C ET and, for less 'sensitive' tasks, could well be higher.

3.4 Acute Health Effects of Heat

The physiological effects of heat, if uncorrected, can lead to a number of deleterious health effects of varying severity. Although these have been extensively documented, it was considered worthwhile to outline briefly the main symptoms of these disorders and to try to give an indication of the potential importance of heat stress as a health hazard. However, although the factors which predispose an individual to some form of heat-induced disorder are known, they have not been sufficiently documented in Caucasian populations to establish heat exposure criteria on the basis of any predicted risk assessment.

(a) Heat exhaustion.

The symptoms of heat exhaustion are headache, nausea, vertigo, weakness, thirst and giddiness. It should be noted however that these symptoms are common to both heat exhaustion and the more serious heat stroke. As heat exhaustion can be expected to occur approximately ten times more frequently than heat stroke, such symptoms are clearly more likely to indicate heat exhaustion. In heat exhaustion, core temperature usually increases by 1-2°C although, because of the wide variation in tolerance of elevated core temperature between individuals, heat exhaustion may occur with virtually no increase in core temperature.

(b) Heat stroke.

As stated above, the symptoms of heat exhaustion (giddiness, weakness, etc.) are also early indications of heat stroke. Untreated, heat stroke results in unconsciousness, convulsions, delirium or other indications of a 'major disruption of central nervous function' (NIOSH, 1986). It is usually (but not always) associated with cessation of sweating, resulting in hot, dry skin. Clinically, 'hyperpyrexia' is defined as a core (rectal) temperature in excess of 41°C. NIOSH (1986) described heat stroke as a 'MEDICAL EMERGENCY' which can prove to be fatal or at least to cause serious permanent damage to physiological systems. As metabolic rate is increased by an increase in body temperature, such increases can initiate a self-perpetuating vicious circle unless external cooling is provided.

(c) Fainting (heat syncope).

Insufficient blood supply to the brain as a result of mechanisms intended to dissipate heat can result in a brief loss of consciousness (fainting). This is to a large

extent a self-limiting process as collapsing effectively improves the blood supply to the brain.

(d) Heat cramps.

Muscle cramps occur in response to an electrolyte imbalance in the working muscles. In the heat, salt loss in sweating plays a major role in this although other electrolytes such as magnesium and potassium ions are probably involved (NIOSH, 1986). LIPPOLD and WINTON (1969) also describe Miners' or Stokers' cramp which occurs when salt concentrations are rapidly diluted by ingesting large volumes of water without replenishing the salt loss.

(e) Prickly heat.

NIOSH (1986) describe a number of heat rashes of which prickly heat is the most common. Unevaporated sweat may cause the outer layers of the skin to swell resulting in a blockage of the sweat ducts. This may be exacerbated by mechanical damage due to restrictive clothing. This results in the formation of small red papules or blisters and a characteristic prickling sensation with sweating.

4. ASSESSMENT OF HOT CONDITIONS

4.1 Measurement of Heat Strain

In theory, any of the direct or indirect physiological responses to heat load can be used to measure the degree of thermal strain. However, in practice only a limited selection of these measures are used. The ISO draft standard on the evaluation of thermal strain (ISO, 1986) lists four principle parameters: body core temperature, heart rate, skin temperature and weight loss through sweating.

Thermoregulatory mechanisms begin to break down when core temperature reaches 38°C (LÖFSTED, 1966) and this level has often been used as a criterion for heat strain. However, because of the operation of other thermoregulatory mechanisms, core temperature does not always reflect the total physiological load. It is important, therefore, to assess several physiological parameters if the true heat load imposed on man is to be evaluated.

Dissipation of a given heat load involves cardiovascular transfer of heat from the core to the peripheral tissues, where it is transferred to the environment by both nonevaporative and evaporative means. Vasodilatation of skin blood vessels places additional demands on the heart and its output must be augmented or redistributed to maintain heat transfer. This circulatory load can be assessed in terms of heart rate changes but the usefulness of this parameter is limited in that it is influenced by non-thermal factors, i.e. workload, noise, emotion, digestion, etc.. These factors must be carefully controlled if heart rate is to be used as a measure of heat strain (VOGT et al., 1973).

The skin temperature reflects the increased blood supply to the skin and determines the rate of heat transfer to the environment. The core-skin temperature gradient can also be used to estimate the efficiency of the thermoregulatory mechanisms. It has been found that as skin temperature approaches core temperature, additional strain is imposed on the circulation (LEITHEAD and LIND, 1964).

Sweat secretion is dependent on both core and skin temperature levels and is considered to be the ideal heat strain parameter (HATCH, 1963).

4.1.1 Core temperature

Measurements of core temperature are usually taken from easily accessible sites such as the auditory canal (tympanic temperature and auditory canal temperature), mouth (oral or sublingual) and rectum (rectal). Other measures include oesophageal and intra-abdominal temperatures. Differences have been found between temperatures recorded at these sites but

they behave in similar ways when heat load is imposed, although the time relation and magnitude of changes may vary from site to site (PIIRONEN, 1970). For example, in a study of changes in temperature at four core temperature measuring sites (oesophageal, auditory canal, sublingual and rectal), EDWARDS et al. (1978) showed rectal temperature to have a slower increase during heat gain, reach lower peak levels and show a lower recovery rate. Core temperature is an important measurement in interpreting the inter-relationship between work and climate.

In addition to physiological accuracy, social acceptability is an important consideration in core temperature measurement in an industrial population. GRAVES et al. (1981) compared four measurements of core temperature including rectal temperature and insulated and uninsulated auditory canal temperatures. The fourth measure utilised a non-invasive transcutaneous Deep Body Thermometer which appeared attractive for industrial use (FOX and SOLMAN, 1971). The results from the transcutaneous Deep Body Thermometer were found to be unreliable in active subjects and, despite the advantage to be gained from a non-invasive measure, its use was not considered further. It was further concluded that, of the remaining transducers, the insulated aural transducers provided the most reliable recordings. The results from this closely reflected those of the rectal probe but had the additional benefit of greater stability and greater social acceptability. Social acceptability would be a major issue in obtaining measurements of core temperature from industrial workers and the oesophageal probe, requiring the ingestion of a probe with a trailing wire would undoubtedly meet with strong resistance. Similar problems may be encountered with intra-abdominal temperature measurements although use of the intra-abdominal pressure radio pill (e.g. DAVIS, 1981) have shown that this may not be insurmountable.

Correct insertion of a temperature probe for tympanic temperature measurement requires contact with the tympanic membrane 'easily identified by the painful sensation felt by the subject' (ISO, 1986) and such measurements may also encounter some resistance amongst any workforce!

Insulated auditory canal temperature has been widely used with industrial subjects by the Institute of Occupational Medicine and would appear to be the most practicable monitoring site although sublingual may be appropriate for 'spot' sampling (GRAVES et al., 1981; NICHOLL et al., 1983; MORRIS and GRAVELING, 1986). Measurement of urine temperature has been suggested (ISO, 1986) although it would appear to be particularly prone to external influences during measurement.

4.1.2 Heart rate

During work in hot conditions two demands are made on the cardiovascular system:

- (a) transfer of oxygen from the lungs to the active muscles;
- (b) transfer of heat from the core to the peripheral tissues.

Both of these demands are reflected in the heart rate response to work (VOGT et al., 1973). Consequently, it is possible to assess the work and heat load imposed on man from his heart rate response. Several techniques of this type are described below.

BROUHA (1960) devised a number of simple heart rate indices to measure work and heat load. The simplest of these was the heart rate increment defined as work heart rate minus resting heart rate with the subject seated. Cardiac cost, which is the total number of extra heart beats above the resting level, and the recovery pulse rate were also used to assess circulatory strain during work. Deliberate rest periods must be introduced into the normal pattern of work if these measures are to be used with any accuracy.

Another approach is that of VOGT et al. (1973) who developed a method of partitioning heart rate into components related to thermal and physical load. The method uses man as a measuring instrument to integrate the effects of work and thermal load over time. The heart rate response is used as an index of cardiac output, which is believed to indicate the relative effects of workload and climatic stress. Partitioning gives two components: a motor component related to physical workload and a thermal component dependent upon the core temperature and the core-skin temperature difference. The application of this method is based upon a preliminary calibration session. This involves measurement of heart rate at specified workloads and climatic conditions. Other workloads and climatic conditions can be related to this in order to determine equivalent motor and thermal stress levels for each work period. However, this method requires the deliberate introduction of rest periods during work to obtain accurate partitioning. Although subject to many errors in field use, this technique is useful in laboratory studies where conditions are controlled.

4.1.3 Skin temperature

The skin surface is the interface between man and the environment and consequently skin temperature has a considerable influence on heat exchange. Skin temperature can influence heat transfer in two ways:

- (a) transfer of heat from the core to periphery is dependent on the core-skin temperature gradient;
- (b) heat transfer (to the environment) is directly related to the skin temperature.

At moderately warm temperatures, skin temperature equilibrates at a level which allows effective dissipation of heat, but as

the temperature increases the core-skin temperature gradient is considerably reduced (LEITHEAD and LIND, 1964). At this point, core temperature increases and hence becomes directly dependent on the level of thermal stress.

The traditional method of skin temperature measurement involves determination of a weighted average of temperatures recorded from representative skin sites (LEITHEAD and LIND, 1964). The authors reported this technique to be subject to practical limitations in field conditions particularly in the humid climates encountered in coal mining (GRAVES et al., 1981) and, although used in some European industries, is generally restricted to more controlled laboratory evaluation of heat stress.

4.1.4 Sweat loss

Sweat loss has been considered to be a good integrative measure of heat strain (DUNHAM et al., 1946; HATCH, 1963). The importance of this parameter is reflected by the number of heat stress indices which have been developed to predict it, e.g. P4SR, ITS (see MORRIS, 1984 for discussion).

Accurate sweat loss measurements require a high degree of technical sophistication and control. Weighing accuracies of ± 4 g are common (HALL and POLTE, 1960; ROBINSON et al., 1965; MAIRIAUX et al., 1986). Other precautions include minimising air movement around subjects during weighings (ROBINSON et al., 1965) and have extended to collecting dripping sweat in an oil bath to determine evaporative sweat loss (MAIRIAUX et al., 1986). Thus, although its successful use in some mining studies has been reported (VOGT et al., 1981), as with skin temperature measurement it has mainly been restricted to laboratory studies.

4.2 Thermal Indices - Measurement of Heat Stress

4.2.1 Introduction

A number of measures that provide information on man's response to thermal stress were identified in the previous section. A drawback with these is that they may interfere with man's work patterns. Another is that they may frequently require complex and expensive measuring devices coupled with skilled operation and interpretation. These facilities and requirements are not normally available in industrial situations, so a simpler method of determining likely responses to heat load is needed. In consequence, there has been considerable interest in the development of thermal indices or integrative measures of heat stress which could be used to compare different sets of thermal conditions. Although a considerable research effort has been directed towards producing a universally applicable thermal index, this goal has not yet been achieved and all indices currently available are subject to operational limitations (JENSEN and HEINS, 1977). In fact serious errors may be

introduced into the estimation of heat load if indices are used in conditions for which they are not valid (CROCKFORD, 1973).

The origins of thermal indices have been traced back to the 18th century (BRUNER, 1959) and three major trends were apparent in their subsequent development (FOX, 1965):

- (a) The use of instruments to simulate human heat exchange.
- (b) The development of empirical scales relating physiological and subjective responses to climatic variables.
- (c) The development of indices based on mathematical analysis of heat exchange.

The first of these three approaches in the development of thermal indices is based on simple physical representation of heat exchange between man and the environment using instruments. The specific instrument represents heat gain/loss and the reading obtained is the measure of the effects of the environment on man.

The second approach depends upon empirical relationships between climatic changes and physiological and subjective responses. These responses provide a basis upon which scales can be constructed to integrate the effects of the relevant climatic variables.

The third approach is based upon mathematically describing the heat exchange between man and his environment. This analysis shows whether heat balance is possible or not and consequently defines the limits on those climatic variables that contribute to this situation.

4.2.2 Summary of thermal indices

Many thermal indices have been proposed at one time or another. They can be classified according to their lines of development as described above. Details on them are contained in Appendix 1. This section summarises the main indices discussed in subsequent sections on comparative validity, etc.

4.2.2.1 Instruments designed to simulate human heat exchange: Many direct measurement instruments have been used as simple 'indices'. Instruments used include: dry bulb thermometer, wet bulb thermometer, Kata thermometer, globe thermometer and the wet globe thermometer (bottle).

4.2.2.2 Empirical indices, based on human responses:

Effective Temperature

- Basic scale (BET or ET(A)).

- Normal scale (NET)
both calculated from dry bulb temperature, wet bulb temperature and air velocity using nomograms.
- Corrected scale (CET)
replaces dry bulb with globe temperature.
- Effective Temperature including Radiation (ETR)
alternative to CET.
- Modified scale (MET)
incorporates work rate nomograms.

Effective Temperature was developed, in conjunction with the US Bureau of Mines, on the basis of subjective comparisons between climates by sedentary subjects. Despite this lack of any physiological basis, it has become widely used and is applied in mining industries in a number of countries including Britain, Germany, Belgium and France. It is frequently regarded as mainly applicable to warm-humid climates.

Température Effective Limite (TEL) or Belgian Effective Temperature

Calculated from dry bulb temperature and psychrometric wet bulb temperature. The Belgian Effective Temperature or Température Effective Limite was developed for the hot humid conditions of the Belgian coal mining industry and is incorporated into Belgian mining thermal limits. It does not appear to have been widely used elsewhere although it has been reported to be applicable to some other forms of mining (SCHWARZ, 1977).

Predicted Four Hour Sweat Rate (P4SR)

Calculated from dry bulb temperature, wet bulb temperature, air velocity, work rate and clothing using a nomogram. The P4SR scale was derived from physiological research for the Royal Navy for tropical application and is applicable over a wide range of conditions, although is not necessarily the best in comparison with indices specifically developed for the climates under consideration.

Wet Bulb Globe Temperature (WBGT)

Outdoor - calculated from natural wet bulb temperature, globe temperature and dry bulb temperature.

Indoor - calculated from natural wet bulb temperature and globe temperature.

WBGT was developed for the US military, especially for conditions of high radiant heat load. It is widely used in American standards although a NIOSH workshop (DUKES-DOBOS and HENSCHEL, 1980) recommended the Wet Globe Temperature with either WBGT or ET as alternative second choices.

Swedish Wet Bulb Globe Temperature (SWBGT)

Calculated from psychrometric wet bulb temperature instead of natural wet bulb temperature, it is otherwise very similar to WBGT and gives broadly comparable results.

Wet-Dry Index (or Oxford Index) (WD)

Calculated from dry bulb temperature and psychrometric wet bulb temperature. Developed by Lind in calculating tolerance times for mines rescue personnel wearing breathing apparatus, this index has been little used elsewhere.

Resultant Temperature (Température Résultante Minière) (t_r)

Calculated from psychrometric wet bulb temperature, dry bulb temperature and air velocity. This index is the official index of the French mining industry. It gives similar values to the Effective Temperature scale from which it was developed conceptually and is seldom used elsewhere.

4.2.2.3 Indices based on mathematical analyses of heat exchange:

Operative Temperature (T_o)

Calculated from dry bulb temperature and mean radiant temperature. Operative Temperature does not take humidity into account and is seldom used, although it has served as the basis for a number of derivative indices.

Standard Operative Temperature (T_{so})

Derivative of T_o incorporating mean skin temperature as a measure of air movement, but still not incorporating any allowance for humidity and therefore of limited utility.

Humid Operative Temperature (T_{oh})

Calculated from mean skin temperature and wettedness using a graph. Derived from calculations based upon a saturated reference environment, Humid Operative Temperature gives similar values to Effective Temperature and has not been widely used.

New Effective Temperature Scale (ET^*)

Derived from T_{oh} not ET. Similar calculation to T_{oh} but referenced to a standard relative humidity of 50%. ET^* has been described as 'scientifically excellent' although the NIOSH working party regarded it as too complex for routine industrial heat stress monitoring (BANKS, 1980). A comparatively new index, its use has not yet been widely reported although it is considered to be applicable over a wide range of climates.

Heat Stress Index (HSI)

Derived from a nomogram on the basis of the ratio of the required rate of sweat evaporation to the maximum evaporative capacity of the environment. Despite being influential in the development of a number of other indices, the Heat Stress Index is generally less good as an index of physiological strain than its derivatives.

Relative Heat Strain (RHS)

Based on HSI but incorporates clothing factors. Derived from a nomogram on basis of dry bulb temperature and the partial pressure of water vapour in the air. The value used for the dry bulb temperature is 'corrected' for clothing, activity, air velocity and radiant heat. Derived from HSI, it has been described as an accurate predictor of physiological strain in hot-humid conditions although it is not widely used in industry.

Index of Thermal Stress (ITS)

Similar to HSI but includes an allowance for sweating efficiency. ITS is applicable over a wide range of conditions although its originator has described it as only being valid in conditions where heat balance is possible.

Required Sweat Rate (S_r)

Uses sweating efficiency and also incorporates the latent heat of vapourisation of water. Another comparatively new index, the Required Sweat Rate was originally devised as an industrial index. Although the original nomogram has been replaced by a computer program, it is still a relatively complex index. It is applicable across a wide range of climates and recent unpublished industrial evaluations have suggested that it compares favourably with other indices (METZ, personal communication).

Specific Cooling Power (SCP) and Air Cooling Power (ACP)

Again based on radiant, convective and evaporative heat flows, the maximum cooling power can be calculated.

Specific Cooling Power is a simplified version of this assuming a constant skin temperature (35°C). It can be calculated from a nomogram using psychrometric wet bulb temperature and air velocity.

WELLER (1981) derived a nomogram for use in a potash mine based on the maximum cooling power which he called the Air Cooling Power. This also involves using psychrometric wet bulb temperature and air velocity in conjunction with a nomogram. The Specific Cooling Power and its various derivations were developed for use in humid conditions of South African gold mines. Criteria for their use have generally been derived

for South African (Bantu) populations and should not be applied to European populations. They do not appear to have been widely used outside South Africa.

Q_S Index

Based on metabolic, convective and radiant heat loads, this index can be measured using a specially developed instrument which reads dry bulb temperature, humidity, radiant heat flux and air velocity. The user enters metabolic heat production, clothing insulation and skin temperature. This index and its forerunner (Q_{TR}) have been tested across a wide range of climates including hot-humid mines but have not been widely used in industry.

4.2.3 Comparative validity of indices

In discussing the relationships between several thermal indices, JENSEN and HEINS (1977) claimed that "the ultimate test of validity of an index is its ability to provide us with a number which can be used to accurately predict how people will respond to the environmental conditions being measured". In many practical applications, the ability of an index to predict physiological strain has been a major consideration, especially where climatic conditions present a risk to health.

Several studies have been undertaken to compare the predictive abilities of thermal indices. These studies, although limited in scale, have influenced the selection of indices and have guided their subsequent development.

LIND and HELLON (1957) compared the P4SR and BET scales in severe hot environments (BET = 34 to 39°C) where the metabolic conditions approximated those used in the original construction of the BET scale. Resting, nude, acclimatized men were subjected to two series of climates: hot-dry (relative humidity = 45%) and hot-humid climates (relative humidity = 85%). The results showed that different climates with the same BET level produced different levels of physiological strain (tolerance time, rectal temperature, skin temperature, heart rate, sweat loss, forearm blood flow). For the same BET the humid climates produced greater levels of strain. P4SR, however, accurately ranked the environments according to their physiological severity and it was concluded that this index could be used with confidence in severe hot environments (P4SR > 2 litres, BET > 34°C). In reviewing the results of earlier studies, MacPHERSON (1960) also concluded that P4SR was a more accurate predictor of physiological strain (sweat loss, final rectal temperature and pulse rate) than ET (basic and normal) in acclimatized men working in hot conditions.

LÖFSTEDT (1966) compared P4SR with HSI, using unacclimatized male and female subjects in a wide range of workload and climate conditions. P4SR gave better correlations with sweat rate ($r = 0.89$), rectal temperature ($r = 0.81$) and mean body

temperature ($r = 0.77$) than HSI ($R = 0.35, 0.35$ and 0.43 respectively). It was concluded that P4SR was a superior index of thermal stress in both hot-dry and hot-humid conditions (air temperature = $29-60^{\circ}\text{C}$, vapour pressure = $0.7-8.0$ kPa) for exposures not exceeding four hours in duration.

KLEMM and HALL (1972) compared three empirical indices, CET, WBGT and WD in simulated "aerospace" conditions (air temperature = $31-60^{\circ}\text{C}$, relative humidity = $10-70\%$, velocity = 1.1 ms^{-1}). Under these conditions, it was found that all three indices could be used with caution to predict heat strain (heart rate, rectal temperature, skin temperature, sweat loss and body heat storage) in lightly clothed, male subjects resting in these conditions. WBGT was stated to be the most reliable index in that smaller differences in physiological strain were observed between different climates with the same WBGT value.

WYNDHAM and HEYNS (1973) compared five indices (MET, SCP, PEST, P4SR and Wet-Kata CP) within the resting climatic envelope found in South African gold mines (air temperature = $29-36^{\circ}\text{C}$, relative humidity = 100% , velocity = $0.5-2\text{ ms}^{-1}$). Taking as a criterion the ability to predict fourth hour rectal temperature (a determinant of heat stroke), MET was found to be the most accurate index. The wet-kata CP was, however, found to be more accurate at low work rates (metabolic cost = 209 W).

KUHLEMEIER et al. (1976) compared the predictive abilities of P4SR and HSI using North American industrial subjects undertaking one hour's treadmill exercise (metabolic cost = $295-492\text{ W}$) in a wide range of climates ($\text{CET} = 13.5-36^{\circ}\text{C}$). No significant difference was found between the correlations of P4SR and HSI with heart rate and rectal temperature. The reported correlation coefficients for P4SR ($r \sim 0.7$) were considerably lower than those reported in other studies (MacPHERSON, 1960; LÖFSTEDT, 1966).

LJÜNBERG et al. (1979) examined five indices; CET, SWBGT, HSI, P4SR and ET^* in a hot-humid and a hot-dry climate (equivalent in terms of SWBGT = 32°C) using sedentary, unacclimatized male and female subjects. Heart rate, mean skin temperature and sweat rate reached higher levels in the hot-dry conditions (air temperature = 40°C , relative humidity = 40%) but the empirical indices did not distinguish between the two climates. The results suggested that the more complex indices, HSI, P4SR and ET^* , would have greater predictive accuracy for sedentary work in severe hot conditions.

PULKET et al. (1980) reported a comparative study of eleven thermal indices in hot-humid conditions (air temperature = $34-38^{\circ}\text{C}$, vapour pressure = $3.3-4.4$ kPa, velocity = $0.2-1.5\text{ ms}^{-1}$). The indices examined included eight from this review; RHS, P4SR, HSI, ET, CET, WGT, WBGT and T_{O} . The ability of each index to predict four heat strain parameters (heart rate, rectal temperature increment, mean skin temperature and sweat

loss) was compared taking, as a criterion level, a correlation coefficient (linear regression) of $r = 0.7$ (no rationale was reported for this criterion). Only one index, RHS, satisfied this criterion for all four physiological parameters. P4SR predicted only heart rate and sweat loss whereas HSI predicted only the latter strain, with "acceptable" accuracy.

The remaining indices in the group (ET, CET, WGT, WBGT and T_{O}) satisfied the criterion in predicting only one strain; mean skin temperature.

GRAVES *et al.* (1981) studied four indices which had been selected for their suitability for use in UK coal mines. The selection criteria included the relevance to UK mining climates and the practicability of the index for possible use by mining personnel. The indices examined were: BET, WBGT, P4SR and ITS. In a climate chamber study (climates in the range 18.4–33.6°C BET) ITS was found to give the best prediction of heat strain as measured by aural temperature (P4SR, $r = 0.577$; ITS, $r = 0.614$; BET, $r = 0.558$; WBGT, $r = 0.560$) although there was little to choose between them. Subsequently, the four indices were examined for their predictive ability in actual mining conditions (BET, 22.1–27.1°C) as part of a study of the physiological responses to thermal load in a development heading. The four indices all indicated the acceptability of the working climate, an indication which was borne out by the heart rate recordings obtained.

RUBLACK *et al.* (1981) compared the Q_{S} index with P4SR, ITS, HSI, Globe Temperature, WBGT, ET and T_{Oh} using 37 subjects in a wide range of climates, work rates and clothing assemblies (air temperature = 18–50°C, velocity = 0.05 to 0.5 ms^{-1} , 'low' to 'high' relative humidity, external workload 100 W and clothing insulation 0–1 clo). Q_{S} was found to be the most accurate predictor of sweat rate ($r = 0.93$) followed by P4SR ($r = 0.86$) and ITS ($r = 0.80$). A similar result was found when the indices were correlated with heart rate and oesophageal temperature increment, although the coefficients were lower. Two of the more complex indices assessed, HSI and T_{Oh} gave poor predictions of sweat rate ($r < 0.6$).

VOGT *et al.* (1981) compared three indices (Resultant temperature (mining), P4SR and S_{r}) in respect of their ability to predict sweat loss by men working in a hot-dry potash mine (air temperature = 24–46°C, mean radiant temperature = 26–48°C, psychrometric wet bulb = 19–31°C, velocity = 0.1–4.2 ms^{-1}). P4SR and S_{r} gave good correlations with observed sweat loss ($r = 0.921$ and 0.892 respectively). A poor correlation ($r = 0.689$) was found, however, between resultant temperature and sweat loss.

GOEDECKE and PUHLFURST (1983) compared three indices $Q_{\text{TR}}(Q_{\text{S}})$, P4SR and ITS in simulated hot-dry mining conditions (air temperature = 40–55°C, relative humidity = 19–25%, velocity = 0.3 ms^{-1}). Men worked with an external load of 112 W (24

minutes work - 6 minutes rest) for up to three hours, and heart rate, rectal temperature and sweat loss were measured. All three indices correlated highly ($r > 0.7$) with the three physiological parameters but Q_{TR} gave the most accurate predictions of the observed sweat losses.

MORRIS and GRAVELING (1986) examined the relationship between five heat stress indices and a variety of physiological responses to an intermittent work regime. The responses measured were: core (aural) temperature, several cardiac measures, sweat loss and mean skin temperature. The indices examined were BET, WBGT, ITS, P4SR and W_{req} . The latter index, Required Skin Wettedness, is a component of the Required Sweat Rate. The relationships were examined across three climates with wet and dry bulb temperatures of 23/26, 27/31 and 31/35°C, all at an airflow of 0.15 ms^{-1} . These represented BET values of 24, 28 and 32°C respectively.

Of the five indices compared, the literature (e.g. KERSLAKE, 1972; VOGT *et al.*, 1981) suggested that the more comprehensive indices P4SR, ITS and W_{req} , would have greater predictive accuracy than BET or WBGT. However, the results (summarised in Table 1) showed that the latter indices predicted strain with at least equivalent accuracy to the others in the group. BET gave the most consistent indication of thermal strain within the range of conditions examined.

While these findings appear anomalous in the context of earlier work, there is some evidence to suggest that, within a restricted envelope of thermal conditions, an empirical index may have superior predictive ability to a more complex one. WYNDHAM and HEYNS (1973), for example, have shown that within the narrow envelope of saturated climates found in gold mines, wet kata cooling power can give a better indication of thermal strain than P4SR. Furthermore, it has been shown (GRAVES *et al.*, 1981; MORRIS, 1985) than in warm-humid conditions with limited air movement, BET is capable of predicting strain with equivalent accuracy to more complex indices.

TABLE 1.

Linear Correlation Coefficients :
Heat Stress Indices and Physiological Strains

Index	Cardiac Cost	Final HR (work)	Final HR (rest)	Aural Temperature	Mean Skin Temperature	Sweat Loss
Wreq	0.557	0.691	0.680	0.678	0.784	0.440*
P4SR	0.551	0.676	0.705	0.712	0.777	0.382*
ITS	0.524	0.643	0.643	0.645	0.692	0.394*
BET	0.598	0.718	0.692	0.709	0.834	0.468**
WBGT	0.562	0.698	0.696	0.653	0.889	0.492**

df = 1,26 (n = 30) except for final HR (rest) where df = 1,14 (n = 18)

All significant at $p < 0.005$ except:

* significant $p < 0.05$

** significant $p < 0.01$

It is apparent that the experimental conditions and assessment criteria have differed considerably in the above studies. Caution must therefore be exercised in drawing general conclusions from them. However, the major part of the experimental evidence points to the superior predictive ability of P4SR over a wide range of environmental, workload and clothing conditions. P4SR is closely followed in this respect by some of the heat balance indices; ITS and S_r . HSI, although based on similar principles would appear to have limited predictive ability in many conditions.

Within a restricted climatic envelope however, P4SR may not be the most accurate predictor of strain. The studies of WYNDHAM and HEYNS (1973a), PULKET *et al.* (1980) and GOEDECKE and PÜHLFURST (1983) show MET, RHS and Q_{TR} to have superior predictive ability in saturated, hot-humid and hot-dry climates, respectively, whereas MORRIS and GRAVELING (1986) suggested that BET was equally effective in hot-humid climates representative of UK coal mining conditions.

Several studies showed the poor predictive ability of indices which were based solely on climatic factors (ET, WBGT, WGT, T_{O_0} , WD, Resultant Temperature). The study of PULKET *et al.* (1980) showed, however, that some of these indices can predict

mean skin temperature, a determinant of thermal comfort (FANGER, 1970) with acceptable accuracy in hot-humid conditions. This observation was borne out by the relatively high correlations obtained by MORRIS and GRAVELING (1986) between mean skin temperature and BET and WBGT as shown in Table 1.

There would appear to be contradictions in the findings of some of the studies, P4SR having greater predictive accuracy than HSI in some studies (LÖFSTEDT, 1966; PULKET et al., 1980; RUBBLACK et al., 1981) and equal predictive accuracy in others (KUHLEMEIER et al., 1976). These differences may be attributable to differences in the protocols and subjects used by the investigators.

It would seem therefore that although the more complex indices may be more widely applicable, particularly towards the extremes of temperature and, more especially, humidity, simpler indices such as BET may provide an acceptable level of predictive ability over a narrower climatic range. In such circumstances, the operational advantages of BET or similar indices may outweigh their reduced sensitivity. Where direct physiological monitoring is not possible and there is concern over the validity of limit values, the more complex indices may be used to establish a reference procedure so that comparability of exposure limits may be derived for different climatic envelopes (METZ, personal communication).

The selection of an index for use in mining is discussed in section 6 following the description of the conditions in which any such index will be required which is described in section 5.

5. HOT CLIMATES IN UK MINES

5.1 Introduction

Reference was found in the literature to heat problems in coal and potash mines in the United Kingdom. Although other forms of mining are known to be associated with heat problems in other countries, no reference was found to such problems in this country. Indeed, there was little reference to other forms of underground mining at all. Letters were sent to the management of other companies involved in underground mining, identified through the British Geological Survey: Directory of Mines and Quarries (HARRIS, et al., 1984). The companies covered fluorspar, gypsum, ironstone and salt. The fluorspar workings also encompassed lead, barytes and calcite. None of these reported climatic temperatures at present anywhere near those likely to create hot working environments. Although some companies did report the expectation of increased temperatures in future workings, temperatures would have to increase dramatically to give any cause for concern. Brief enquiries were also made of all clay, fire clay, silica sand, slate and tin mining operations none of which indicated any problems with excessive heat. Being shallow workings, the general picture was 'warm in winter, cool in summer'. HARRIS et al. (1984) did not include any current underground mineworkings for galena, calcspar, whetstone, fullers earth, lead or any other metalliferous mines which have, on occasion, been worked in the UK. This section is therefore limited to climates in UK coal and potash mines. Both industries currently utilise the Basic Effective Temperature thermal index and this index is therefore used in this section. As a guide to those unfamiliar with its use, Figure 2 gives the nomogram from which it is obtained by entering in values of wet-bulb temperature, dry-bulb (or globe) temperature and air velocity.

5.2 Coal Mines

5.2.1 Environmental heat load

A national survey of climatic conditions in all longwall districts and headings was carried out in the National Coal Board (ALLAN, 1976). 241 collieries containing 739 longwall districts and 710 headings were surveyed. The data were categorised into three ranges: those with effective temperatures (BET) below 24°C, between 24 and 27°C, and above 27°C. Table 2 shows a summary of the districts and headings with BETs above 24°C. The maximum temperature reported was 31.9°C BET.

All the measurements were taken at statutory ventilation measuring points within the main ventilating circuit and so climates at workplaces such as stable holes, ripping lips, packholes, etc. were not included. ALLAN (1976) adopted a criterion of temperatures in excess of 27°C BET being

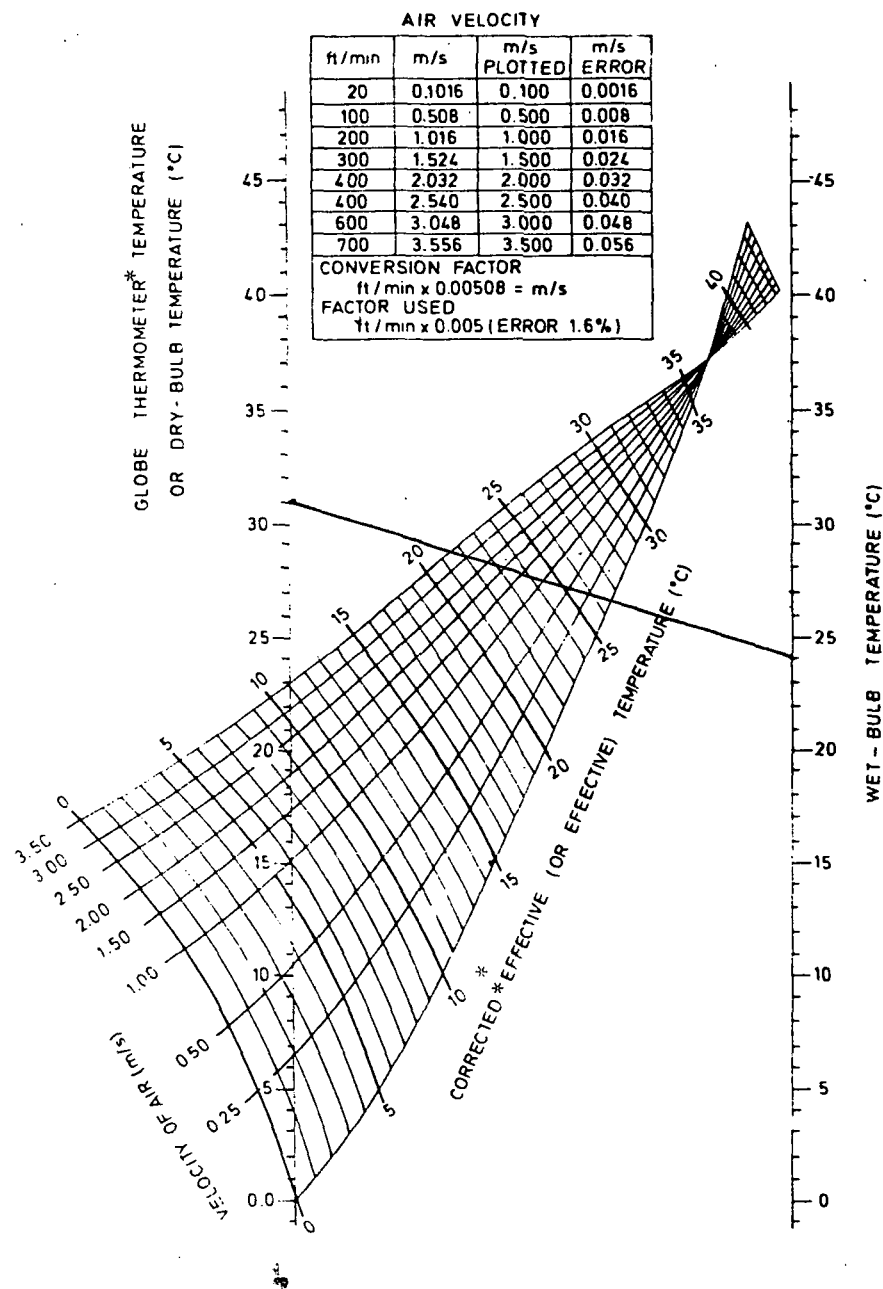


FIGURE 2. Chart Showing Basic Scale of Corrected Effective (or effective) Temperature
 (From ELLIS et al., 1972, British Journal of Industrial Medicine; 29: 361-377)

*Corrected Effective Temperature uses globe thermometer temperature where a radiant heat component exists.

"sufficiently high to initiate complaints from workmen and to justify action for improvement". From the table above, it can be seen that 2.7% of headings and 3.7% of longwall districts had climatic conditions above this level. Subsequent authors (e.g. VERMA, 1979; ALDRED *et al.*, 1984(a) and (b)) have regarded a temperature of 28°C BET as constituting some form of upper limit for normal working.

TABLE 2.

Percentage of Headings and Longwall Districts with BET above 24°C

BET ($^{\circ}\text{C}$)	Percentage of Longwall Districts	Percentage of Headings
24-27	10.2	13.1
27-27.9	1.8	1.1
28 +	1.9	1.6

Estimates of the number of men actually exposed to such conditions, based on these percentages, may well be conservative. GRAVES *et al.* (1981) showed that climatic measurements taken at such points (e.g. at defined points on the face and 10 m back from the face line) were often lower than those obtained where the men were actually working. This was mainly attributable to the reduction in air speed in locations such as packholes, etc. (NICHOLL, 1978). Even in the roadway, airflows at specific locations at face-ends can vary by a factor of 10 (unpublished data). More recent climatic survey data was reported by NICHOLL *et al.* (1983). This limited survey reported a peak temperature of 32.3°C BET recorded at a gate-end. Recent, unpublished data suggests that slightly higher temperatures may now be encountered in more recent developments.

Data from VERMA (1981) showed variations in wet bulb temperature over time in a heading in excess of 5°C . Approximations from graphical data (assuming the median air speed for headings of 0.35 ms^{-1} reported by GRAVES *et al.* (1981)) give a BET range of $26.5\text{--}30^{\circ}\text{C}$. Precise timing and location of measurements clearly therefore play a critical role in determining the values recorded and careful consideration should be given to this in evaluating the thermal load in any location. Recent research (MAIRIAUX *et al.*, 1986) has shown time-weighted averaging of climatic conditions to give reliable indications of thermal load, particularly in

warm-humid conditions.

The sources of heat in underground mining are well known and have been amply documented elsewhere (e.g. WHITTAKER, 1981; VERMA, 1981). It is also widely recognised that the trends in many of these parameters are likely to result in an increase in heat from these sources (VERMA, 1984). VINCENT (1975) estimated that the number of 'problem' faces (BET greater than 28°C) would at least double by 1985 and if predicted increases in face performance materialised then the increase was likely to be four-fold. However, the predictive model assumed that no special counter-measures were installed. Although no evidence has been found to confirm or deny predictions of this magnitude, it is still believed (e.g. ANDERSON and LONGSON, 1986) that the climatic trend is upwards.

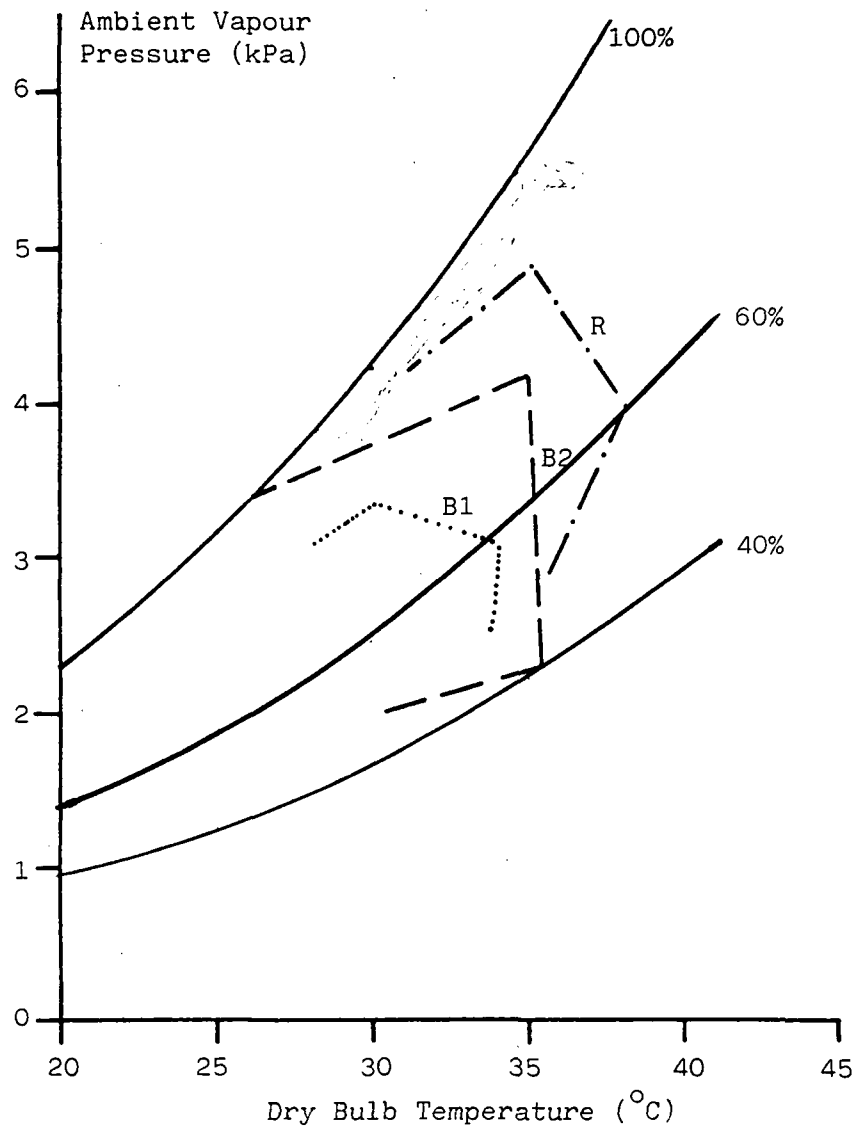
As an illustration of one source of heat, WHITTAKER (1981) discussed the trends (at that time) towards increasingly powerful coalface machinery. Although he rightly predicted the change in policy towards making better use of existing machinery (e.g. TREGELLES and WORTHINGTON, 1982), he also indicated that increasing the percentage use of current equipment would still make a significant contribution to the total environmental heat load.

GRAVES *et al.* (1981) considered the climatic conditions which could be said to typify hot climates in UK coal mines. They concluded that the hot mining 'thermal envelope' could be described by moderately high dry bulb temperatures, humidities above 60% (80% of humidities recorded exceeded this value, NICHOLL, 1978) and air velocities below 1 ms⁻¹. These could be regarded as producing BET values of 25°C and above.

MORRIS (1984) plotted the upper limits of this envelope in terms of dry bulb temperature and vapour pressure for comparison with those from other mining industries. This figure, reproduced with modifications as Figure 3, shows an increasing trend from earlier UK data (LEITHEAD and LIND, 1964), through the data of GRAVES *et al.* (1981) to West German deep coal mine data from a similar period (VOSS, 1981). The more comprehensive UK data of ALLAN (1976) would fall between B2 and R, i.e. the UK mining envelope is closer to that of the German coal mining industry than is suggested by this figure. The three lines indicate the upward trend in the UK data and possibly, through the German data, indicate the potential for further upward growth if the UK mining industry continues to 'follow' mainland European coal mining in this respect.

5.2.2 Metabolic heat load

Coal mining has traditionally been regarded as hard physical work (ASTRAND and RODAHL, 1977). SIEBER (1963) and LIND (1964) reported typical shift average work rate levels of 290-315 watts for miners working in mechanised or partially mechanised



Key:-

- R = Coalfaces, Ruhr coalfield
- B1 = Upper limits, British colliery climates, 1960's
- B2 = Envelope of hot-humid mine climates

FIGURE 3 Mine Climate Envelopes

faces and headings. However, MÜCKE and VOSS (1971) claimed that, since the early 1960s, the increased level of mechanisation had reduced the physical workload of mining. GRAVELING *et al.* (1980) reported the results of a survey of physical stress in UK coal miners. They concluded that, as a result of increased mechanisation, prolonged dynamic work was only very rarely observed as a potential stress problem. Such dynamic physical work as was observed tended to occur in short, comparatively heavy bursts. In many of the mining tasks studied, there was a high incidence of heavy static and postural muscle loading which also tended to occur in brief periods of heavy demand.

These characteristics of intermittent, static and dynamic work were studied in detail by MORRIS and GRAVELING (1986). The authors based the level and pattern of the workloads studied on those encountered in modern coal mining. They examined the effects in a range of climates (BET values ranging from 24-32°C) which covered the range of the mining hot thermal envelope. Briefly, the results showed that intermittency had no disproportionate effect on overall thermal strain. This was seen as confirming the validity of applying time-weighted averaging procedures to metabolic heat loads as has previously been shown to be the case for environmental heat loads (MAIRIAUX *et al.*, 1986). The studies also indicated that intermittent static load components did not have a disproportionate effect on thermal strain as had previously been suggested. MORRIS and GRAVELING (1986) concluded that heat stress criteria and assessment techniques, derived originally for continuous dynamic workloads, were likely to be equally valid for the intermittent, combined static and dynamic workloads typical of modern coal mining tasks. This is an important consideration because of the relevance of intermittency to both the determination of metabolic heat load (e.g. time-weighted averaging for standards) and to formal or informal work-rest scheduling as a means of reducing heat strain. However, they did sound a cautionary note over the use of time-weighted averaging. It was recognised that such procedures would mask peaks of physiological strain which could present a risk to individuals susceptible to heat.

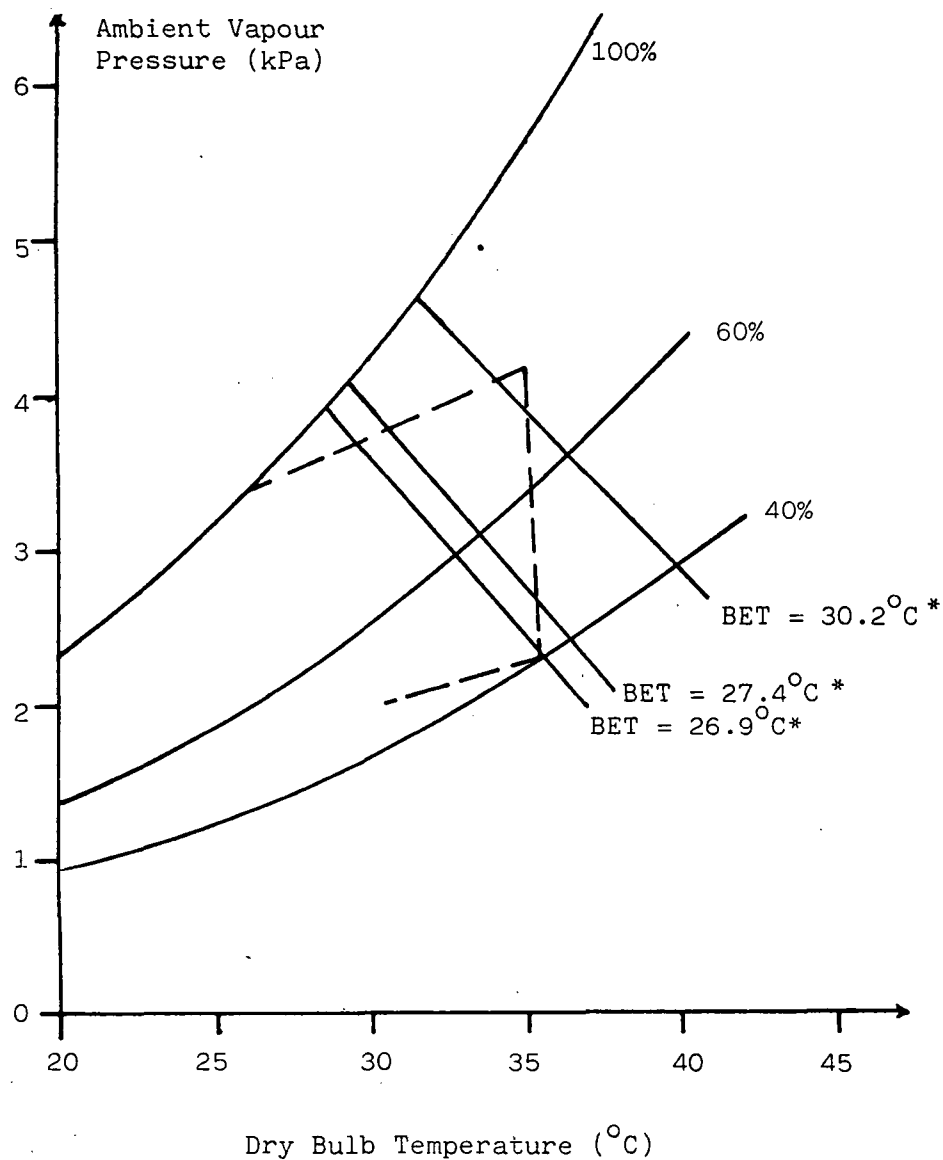
Applying shift averaging procedures, MORRIS (1984) reported shift mean workloads in a development team. The loads could be characterised as moderate or moderately heavy (ASTRAND and RODAHL, 1977; CHRISTENSEN, 1964), ratings which are in agreement with those reported by GRAVELING *et al.* (1980) for rock drilling and arch-setting. Although accurate determination of the metabolic heat load associated with these workloads is not possible, calculations based on estimated oxygen consumption and respiratory quotient (KEELE and NEIL, 1971) suggest that the values reported previously as 'typical' ($\approx$ 300 watts) should perhaps be regarded as representing an upper limit to the metabolic load associated with modern coal mining tasks (MORRIS, 1984).

5.2.3 Significance of environmental and metabolic heat loads

As stated earlier (2.1.1), evaporative heat loss is considerably impaired in conditions of high humidity and low air movement, conditions which are typical of coal mining. It can therefore be seen that, even if dry bulb temperatures are not particularly high, these other factors can cause problems for what is normally a major avenue for heat loss. Under these conditions, convective heat loss is of greater importance. GRAVES *et al.* (1981) showed that, in climates representative of hot UK coal mining (25–32°C BET) skin temperatures were typically 35–36°C. As dry bulb temperatures approach these values then the skin-air temperature difference will not permit much sensible heat loss (radiation and convection).

As stated earlier (3.1), in moderate climates core temperature is determined by metabolic heat load and is independent of climate. LIND (1963a) illustrated this pattern for three levels of work across a wide range of temperatures including values spanning the hot mining thermal envelope (25–32°C BET). The data indicated that, at some critical temperature (which depended upon workload), core temperature would become dependent on the climate and increase markedly beyond the equilibrium level. Figure 4 shows the three temperatures at which this occurs for different work levels superimposed upon the mining hot thermal envelope. Thus the upper limit of the 'prescriptive zone' (LIND, 1963a) can be seen for heavy work (271 Wm⁻²), moderate work (194 Wm⁻²) and light work (116 Wm⁻²) to be 26.9°, 27.4° and 30.2° BET respectively. Despite their widespread adoption, too great a precision should not be attached to these values. It should be remembered that the moderate limit is derived from repeated experiments on three subjects and the light and heavy limits from two of these (LIND, 1963a). Although other experiments (e.g. KUHLEMEIER *et al.*, 1977) have indicated similar values, other reports, including LIND himself (LIND, 1977; KUHLEMEIER *et al.*, 1977) have suggested that the limit for a given work rate may vary by up to 4.5°C BET due to differences in acclimatisation status, clothing and heat tolerance capabilities. MORRIS and GRAVELING (1986) reported data from one of a series of experiments which indicated that, for average workloads ranging from 215–250 Wm⁻², the upper limit was probably slightly over 28°C BET although a wide range of individual susceptibility was observed.

Whatever the exact values of these limits, it can be seen that workload (metabolic heat load) will play an important role in determining the acceptability or otherwise of a coal mining climate. This factor, and its implications for limiting standards, is discussed in more detail in section 7. Discussions with the British Coal, Director of Medical Services have indicated that there is no evidence over the last few years (BURNS, personal communication) of heat related illnesses. Although there have been isolated unconfirmed reports, the



* High (26.9°C), Medium (27.4°C) and Low (30.2°C) workloads. (See text).

BET values calculated for 1.0 ms⁻¹

FIGURE 4 Prescriptive Zone Criteria and the Envelope of Hot-Humid Mine Climates

engineering and administrative solutions adopted (see section 7) appear to have been generally effective in preventing their occurrence.

5.3 Potash Mining

5.3.1 Environmental heat load

The climatic conditions at what is reported to be the only working potash mine in the UK have been extensively examined (WELLER, 1981; ROBINSON, 1983). WELLER (1981) obtained climatic measures (including wet bulb, dry bulb, globe temperature and air velocity) from headings described as 'representing average conditions'. As with coal mining, the dry bulb/globe temperature readings indicated an absence of radiant heat. Temperatures were reported for two headings, one with forced and one with exhausting ventilation. Mean wet and dry bulb temperatures were 22.1/38.7°C (forced) and 23.5/36.0°C (exhaust). These may be compared with the values reported by CHILTON and LAIRD (1982) of 26.3/38.4°C for a working face at the same mine. These temperatures represent relative humidities of approximately 25-38% which are substantially lower than the 60+% reported for coal mining. For comparison with coal mining, the Effective Temperatures are 26.6-27°C BET (WELLER, 1981) and 29.4°C (CHILTON and LAIRD, 1982).

ROBINSON (1983) reported air temperatures as part of a study of ice jackets. Temperatures were recorded at two locations presumably chosen, at least in part, for the relative severity of the climates although this is not specified in the report. As would be expected, temperatures fluctuated over the shift, apparently reflecting a combination of periods of machine operation and the movement of the subject around his working area. In one location, the wet and dry bulb temperatures ranged from 27.2-32.9°C (wet bulb) and 39.6-43.8°C (dry bulb) yielding an Effective Temperature range of 29.4-35.0°C BET and indicating relative humidities as high as 45%. Slightly lower temperatures yielding an Effective Temperature range of 26.6-35.0°C BET were recorded at a second location. Mean values from the half-hourly readings were 32.1°C and 29.9°C BET respectively. ROBINSON (1983) reported that these temperatures were comparable to those encountered in a French potash mine. They also fall within the potash mining hot thermal envelope described, for German mines, by WEUTHEN (1971).

Since then however, a series of events have reduced both the average Effective Temperatures and the incidence of exceptionally high (> 35°C BET) temperatures. These events included the replacement of the underground main fans with a surface installation. This permitted a reorganisation of the pit bottom area, reducing the extent of air recirculation and consequently reducing intake temperatures. The second event was the enforced closure of the South side of the mine due to

flooding. This area had been the site of the high Effective Temperatures reported by ROBINSON (1983), due in part to the concentration of a high proportion of working faces in a relatively small area. The third factor was the adoption of new mining procedures in which major roadways were driven in the underlying salt seam. The roadways in the salt 'stand' better, maintaining improved ventilation flows to the working districts. In addition, salt has a lower thermal conductivity than potash (WELLER, 1981) and the combination of higher flow rates and lower thermal conductivities result in less heat uptake by the intake air.

Peak summer temperatures (August, 1986) from the return side of three adjacent headings were 31.8, 31.5 and 33.0°C BET with relative humidities of 40-45% (unpublished data). The highest Effective Temperatures were encountered during Heliminer operations when dust suppression sprays increased the moisture content and thus the wet bulb temperature of the air in the immediate vicinity. It is reported (ROBINSON, personal communication) that further improvements to ventilation controls have generally restricted such temperatures to the headings themselves with lower temperatures a relatively short distance outbye on the intake side. ROBINSON (1983) described potash mine climatic conditions as hot and relatively dry, an observation which is clearly in accordance with the above figures. A brief visual inspection of summer temperature records over the last five years (unpublished data) did not reveal any noticeable upward trend in climatic conditions. Temperatures had, if anything, fallen slightly over the period.

As with coal mines, airflows out of the main ventilation flow and away from ventilation ducts are generally low. WELLER (1981) reported them as all below 0.6 ms⁻¹ and mostly below 0.2 ms⁻¹.

As with coal mines, the sources of environmental heat in potash mines have been studied in detail (WELLER, 1981; ROBINSON, 1983). ROBINSON (1983) estimated the heat sources with considerable thoroughness, including such sources as mine lighting and metabolic heat from the workforce as well as the obvious major sources of strata and machinery. At the depths of workings involved (> 1100 m), strata temperatures clearly make a significant contribution to the climatic load. It was estimated that this accounted for some 20-25% of the total heat input. All but a small amount of the remainder (< 2%) was attributable to machinery. ROBINSON (1984) reported the results of a ventilation planning exercise which was, in part, instrumental in the switch to major driveages in the salt seam. This predicted 1994 temperatures based on the assumption that major roadways would be in the salt, followed by extensive workings in the potash seam. Maximum summer temperatures at the predicted outer limits of workings were 43°C dry bulb and 27°C wet bulb giving an approximate Effective Temperature of 31°C at typical flow rates. Current values seem to suggest that difficulties may be encountered in achieving wet bulb

temperatures as low as 27°C although this may be partly countered by lower than expected dry bulb temperatures. However, it appears that the continuing programme of developing roadways in salt rather than potash may improve this situation. Current temperatures further outbye, where the roadway changes have already been implemented, are more or less in line with those predicted.

5.3.2 Metabolic heat load

WELLER (1981) estimated the metabolic heat load of UK potash mineworkers using data published for South African gold mines. Values assumed range from 275 watts to 470 watts depending upon the task. Assuming a body surface area of 1.8 m² would result in these loads being classified as 'light to moderate' and 'heavy' respectively (153 and 261 Wm⁻²). However, no indication is given regarding the duration of these tasks, which may modify the overall effect. The heavy task referred to was that of a transfer point attendant shovelling spilled material back onto a conveyor. Such a workload would be considered by many to be unacceptable for an entire shift (ignoring travelling time) regardless of the working temperature. Although occasional conveyor overloading may result in spillages, any transfer point which required constant shovelling to clean up round it would not be particularly acceptable from an engineering standpoint. The value of 470 watts should not therefore be regarded as a shift averaging workload but rather to be indicative of peak loading. The essential similarities between many coal and potash mining activities (excluding longwall face work) would suggest that the value of 300 watts estimated for coal mining would be reasonably representative of potash mining. This contention is supported by the work of ROBINSON (1983) who utilised a value of 275 watts in his estimates of heat production from the workforce. Tasks observed by one of the authors (RAG) during a visit to the potash mine add further support to this. Most of the main components of the heading operations are mechanised with the result that, during normal operations, heavy physical work is limited to relatively infrequent occasions such as when ventilation ducts are advanced. Other heavy work tends to occur further outbye where, as stated earlier, temperatures are somewhat lower.

A further estimate of workload may be derived from data reported by ROBINSON (1983) from a study of ice jackets. The pulse rates recorded, on two of the 'most exhausting jobs' fluctuated with the task being performed and, it is reported, with the temperature of the immediate location, although changes due to this would be minimal by comparison. The closest to operating in a 'temperate' climate occurred when the ice jackets were being worn. Heart rate ranges of 80-108 beats min⁻¹ (Heliminer operator) and 80-100 beats min⁻¹ (Eimco 915 operator) were reported. This included periods off their machines, cable handling, cleaning the panel conveyor, etc.. These rates can be compared directly with those reported by

GRAVES et al. (1981) for a variety of activities in a coal mine heading and represent a light to moderate workload. It would appear from this that, as suggested for coal mining, a value of approximately 300 watts would appear to constitute a reasonable upper limit for estimated average workload. However, as with coal mining, the workload is clearly intermittent and although this does not invalidate the average procedure such a process may mask potentially hazardous peak loading.

5.3.3. Significance of environmental and metabolic heat loads

Although the relative humidity in potash mines is lower than in coal mines, this is counteracted by the higher dry bulb temperatures. These changes yield broadly similar Effective Temperatures in the two forms of mining. WELLER (1981) questions the validity of this thermal index in potash mining. However, the criticism is levelled at the absence of a workload correction factor which is not relevant to this comparison (see section 6.2 for a further discussion of this criticism). The dry bulb temperatures reported mean that there will frequently be a heat gain from the environment by convection because of the negative skin/air temperature difference. However, in dry climates, heat loss is readily achieved through sweating although anything which reduces air exchange, e.g. clothing and low air velocities will impair its effectiveness. Body movement, as well as producing metabolic heat, will aid the loss of heat through sweating. Under these circumstances, fluid replacement and in the slightly longer term, salt replacement becomes important. ROBINSON (1983) records a shift intake for one individual of 6.8 litres. Although this may seem excessive, MacFARLANE (1963) reports values of 12-15 litres per day, reaching 20% of body weight in working adults. As with coal mining, the climates span the various prescriptive zone limits (LIND, 1963a) and workload will again be a crucial factor in determining an acceptable limit.

Discussions with potash mine personnel indicated that isolated instances of heat-related health problems did occur prior to the closure of the South side of the mine referred to above. No examples of such problems can be recalled since that time.

6. SELECTION OF THERMAL INDICES FOR MINING CLIMATES

6.1 Mining Industry Requirements

In mining industries, thermal indices have mainly been used in the routine assessment and control of climatic conditions in deep mines (MÜCKE and VOSS, 1971; SEELEMANN, 1973). They have also been used in the mathematic modelling of mine ventilation networks in order to assess the effects of control measures (WYNDHAM, 1974; VOSS, 1981). In mines rescue work, thermal indices have been used to limit the exposure of rescue personnel to potentially hazardous conditions (MAYNE and VANWONTERGHEM, 1980). In terms of the day-to-day operation of a mine, routine climatic assessment forms the major application.

Although a number of different indices have been routinely used in the mining industries of the world (see Table 3), the Basic or American Effective Temperature Scale would appear to be the most widely used index (VOSS, 1981). In recent years however, there has been considerable discussion about the physiological limitations of the Effective Temperature scale and it has been proposed that a more comprehensive index should be sought (WENZEL, 1977). Earlier studies (WENZEL, 1975) had suggested that an ideal thermal index would be one which defined physiologically equivalent conditions over a wide range of mine climates. However, WENZEL found that none of the major thermal indices fully satisfied this requirement.

While physiological accuracy has been considered to be an important requirement, it is clear that an index must satisfy the operational requirements of the mining industry if it is to be used effectively. MÜCKE and VOSS (1971) considered that the determination and interpretation of the index value should be straightforward, especially where the index formed the basis of climatic limits in mining. This was also considered to be an important requirement when selecting indices for a general industrial heat stress standard (RAMSEY and CHAI, 1983).

Within the context of the coal mining industry, this requirement has been satisfied by the Basic Effective Temperature Scale; the index value being derived from measurements routinely made by colliery ventilation staff (dry bulb temperature, wet bulb temperature and air velocity). Effective Temperature has also been used exclusively at the UK potash mine (WELLER, 1981) and, despite that author's recommendation of an alternative index, continues to be used (ROBINSON, personal communication).

A number of indices can be selected from the review in Appendix 1 which appear to be accurate predictors of physiological strain. However, in many cases, doubts have been expressed in

TABLE 3

Classification of Thermal Indices in Terms of Mining Criteria

Part I - Indices Based on Instruments

INDEX	MINING CRITERIA				
	Applicable in Industry	Includes All Major Factors	Straight- forward Operation	Predicts Physiol. Strain	Suitable for Climatic Limits
Dry Bulb Temperature (m)	□		■		□
Wet Bulb Temperature (m)	□		■	□	□
Wet Kata C.P. (m)-	□		■		□
Globe Temperature					
Equivalent Temperature					
Thermo-Integrator					
Wet Globe Temperature	■		■	□	□

Key:

(m) = index used in a mining industry

■ = satisfies criterion

□ = partially satisfies criterion

TABLE 3

Classification of Thermal Indices in Terms of Mining CriteriaPart II - Empirical Indices

INDEX	MINING CRITERIA				
	Applicable in Industry	Includes All Major Factors	Straight- forward Operation	Predicts Physiol. Strain	Suitable for Climatic Limits
Effective Temperature (m)	■	□	■	□	■
Modified Effective Temperature		■	□	■	
Température Effective Limite (m)	■	□	■		□
Resultant Temperature (ES)		□	■		
Predicted Four Hour Sweat Rate (m)	□	■		■	□
Index of Physiological Effect		□		□	
Wet Bulb Globe Temperature	■	□	■	□	■
Swedish WBGT	■	□	■	□	■
Wet-Dry Index (m)	■	□	■	□	□
Equatorial Comfort Index (m)	□	□	■		□
Température Résultante Minière (m)	■	□	■	□	■

TABLE 3

Classification of Thermal Indices in Terms of Mining CriteriaPart III - Heat Balance Indices

INDEX	MINING CRITERIA				
	Applicable in Industry	Includes All Major Factors	Straight- forward Operation	Predicts Physiol. Strain	Suitable for Climatic Limits
Operative Temperature					
Standard Operative Temp.					
Humid Operative Temp.		■		□	
Effective Temperature*		■		□	□
Thermal Acceptance Ratio		■		□	
Heat Stress Index	□	■		□	□
Relative Heat Strain		■		■	□
Index of Thermal Stress		■		■	□
Required Sweat Rate		■		■	□
Specific Cooling Power (m)	□	□	■		
Mine Cooling Power (m)	□	□	□		
Q_s (Q_{TR})		■		■	
Air Cooling Power	□	■	■		

respect of their operational suitability. This is particularly the case with the more complex indices, derived from a consideration of the components of the heat balance equation.

In order to select indices suitable for comparison with the Basic Effective Temperature, currently used in both forms of mining with hot climates within the UK, it is necessary to establish more detailed criteria. A NIOSH discussion document (NIOSH, 1972) proposed that the following criteria should be satisfied by any thermal index being considered for industrial use:

- "(a) Applicability should be proven in industrial use;
- (b) All important factors should be included;
- (c) The measurements and calculations required should be simple;
- (d) The included factors should have a valid weight in relation to total physiological strain;
- (e) Applicable and feasible for setting regulatory limits."

These criteria can be used, with some modification, to select an index potentially suitable for use in the mining industry. MORRIS (1984) proposed the following "mining" criteria:

- (a) Applicability should be proven in industrial use (preferably in mining operations).
- (b) All major factors contributing to heat load in mining conditions (air temperature, humidity, air movement, work rate) should be included.
- (c) The measurement procedures, calculations and interpretation should be straightforward.
- (d) The index value should predict physiological strain with acceptable accuracy.
- (e) Applicable for the purposes of mine climate guidelines or limits.

6.2 Assessment of Indices

Table 3 classifies the thermal indices reviewed against these criteria (MORRIS, 1984). Indices which are reported as having been in routine use in mining have also been identified in this table.

It can be seen from the table that no single index completely satisfied all five criteria. Five indices, all empirical, can be considered at least partially to fulfil all five criteria.

In addition to Effective Temperature, these were: Wet Bulb Globe Temperature, Swedish Wet Bulb Globe Temperature, Wet-Dry Index and the Température Résultante Minière.

The Température Résultante Minière while satisfying most of the "mining" criteria has been found to be similar to the Effective Temperature Scale in terms of predictive ability (LAVENNE, 1965) and has been restricted in its application to the French mining industry. There seems little purpose therefore in switching from Effective Temperature to this index.

Although LIND et al. (1956) reported the WD formula as providing a better prediction of physiological strain, it does not appear to have been used beyond its immediate purpose of determining mines rescue limits. LIND and HELLON (1957) suggested that it was only effective where men were working hard, in severe climatic conditions, a suggestion echoed by KLEMM and HALL (1972). The WD index was tested over a range of wet bulb temperatures (27-35°C) mainly at a dry bulb temperature of 49°C and at a single airflow (LIND et al., 1956). In the absence of further evaluative research therefore, there seems little in favour of adopting a relatively unproven index.

Unlike the WD formula, the WBGT index has been widely researched. There seems little doubt however, at least for coal mining climates, that there would be little benefit in switching to this index from BET. Extensive research by the Institute of Occupational Medicine (GRAVES et al., 1981; MORRIS and GRAVELING, 1986) has failed to show any improvement in predictive ability from using WBGT (or several of the more complex indices) rather than BET. These studies have encompassed extensive laboratory and field studies over more than six years. They have indicated that although some of the more complex indices may yield better correlations with physiological parameters, the Effective Temperature scale yields reasonably comparable values as a 'first order' index. (i.e. it can identify physiologically limiting conditions in coal mines. It is less adequate as a comparative measure of heat load (MORRIS, 1984)). This fact, together with its relative simplicity in use over the more complex indices, plus its wide acceptance within the industry (VERMA, 1979) make it the index of choice for the UK coal mining industry.

This research has been directed towards the current coal mining thermal envelope and has not been concerned with the predictive ability of Effective Temperature above 32°C, or in less humid environments - conditions which may well apply to potash mines. Both of these can however be examined in data reported by LIND and HELLON (1957). The investigation indicated that Effective Temperature was not effective in predicting the relative severity of severe climates of high or low humidity. The severe climates were Effective Temperatures from 34.4°C upwards in a humid (85% RH) and dry (45% RH) series. However,

examination of the reported means shows that, for the first two pairs of climates (ET values of 34.4°C and 35.6°C) the mean rectal temperatures were relatively close. After three hours exposure to the first climate, the mean rectal temperatures were identical in the two humidities. Rectal temperatures at the end of the second three hour climate session differed by 0.4°C. No variance measure was reported against which to assess this difference but this would not appear, from our own studies (e.g. MORRIS and GRAVELING, 1986) to be especially large in comparison with expected differences between individuals. In addition, this difference was less than that between the first two humid climates, representing a 1°C difference in wet bulb temperature. Two other measures, pulse rate and skin temperature, also showed a high level of agreement for the first pair of climates although the relationship broke down sooner. However, core temperature increase must be regarded as the critical physiological response to elevated environmental temperatures and greater weighting must therefore be given to the rectal temperature response than to any others. This acceptance of Effective Temperature at the lower temperatures studied was indicated by LIND in a later paper (LIND, 1960) in a further discussion of the results of his earlier work. LIND and HELLON (1957) criticised Effective Temperature as overestimating the heat stress of dry environments, but showing generally linear relationships between the humid series of environments and physiological responses.

WELLER, in a review of indices for use in a potash mine (WELLER, 1981), criticised the use of the Effective Temperature scale on several grounds. The first of these was its inaccuracy in severe heat stress. As can be seen from the discussion above, conditions generally regarded as severe are hotter than those currently encountered in UK coal or potash mines. Much of this criticism, including that on which Weller appears to have based his comments, stems from the South African gold mining industry where climates are worse (MORRIS, 1984). The second criticism appears to be based on a misunderstanding of the concept of thermal indices in general, and Effective Temperature in particular, in that the index is criticised because totally dissimilar environments have the same Effective Temperature. Finally, the index is criticised for not taking work rate into account. GRAVES *et al.* (1981) demonstrated that over a relatively narrow range of physical workloads this was not a disadvantage. Alternatively, consideration of workload can be incorporated in determining limiting criteria, and its omission from the index itself does not necessarily invalidate it.

Support for the continued use of Effective Temperature in potash mining can be derived from the limited physiological data reported by ROBINSON (1983). Linear regression analyses of the reported pulse rates and oral temperatures against Effective Temperatures yielded highly significant correlation coefficients. Pulse rate, despite the variations in workload

during the shift, yield the higher correlation coefficient ($r = .764$, $p < .0001$). Oral temperature yielded a lower but still significant correlation coefficient ($r = .591$, $p = .001$). Both correlations are based upon a total of 23 observations from two individuals. Oral temperature is particularly prone to fluctuations due to external influences such as drinking hot or cold liquids. Problems are also encountered in obtaining accurate readings from a clinical thermometer in dry bulb temperatures higher than body temperature as they were on occasions here. The lower correlation in this case is therefore understandable.

Indices such as Effective Temperature and, to a lesser extent, the more complex mathematical indices, inevitably involve a degree of approximation. As a screening measure rather than a substitute for direct monitoring of thermal strain, this level of difference is probably therefore acceptable. Care should be exercised if using Basic Effective Temperature in climates with very low relative humidity (less than 30%). In these conditions, dry bulb temperature may give a better indication of physiological strain. It should be noted that, as would be expected from other reports in the literature, the effects of the low humidity/high dry bulb climates are overestimated by Effective Temperature although not, it would appear, sufficient to justify discontinuation of its use in potash mines at current temperatures.

In conclusion therefore, Effective Temperature is currently used in the UK coal and potash mining industries. Of the indices currently available, no easily determined index appears to offer any meaningful improvement in predictive ability over the current range of climates. Should however conditions change in potash mining such as to lower the relative humidity at the upper end of the thermal envelope or to extend Effective Temperature above approximately 36°C , then further work may be necessary to ascertain the overestimation of physiological strain by Effective Temperature in such hot-dry conditions.

7. HEAT STRESS STANDARDS AND MINING

The objective of this section is to review the standards, legislation, working practices, etc. adopted by various countries to deal with hot conditions relevant to mining. This is dealt with in a number of parts. These cover the rationale behind the development of criteria, how the criteria have been incorporated into the various measures and the implications for mining conditions.

7.1 Development of Criteria

As was seen earlier, there are two main approaches to determining the effects of heat on the worker, the use of climatic descriptors and the measurement of physiological responses. Traditionally, the development of criteria has been based on the effects of heat on both physical and psychological performance, with the emphasis on specifying the levels at which deterioration of health occurs leading to heat stroke and collapse. It is only more recently that the behavioural component has been emphasised increasingly, and attention been focussed onto the effects of heat on safety.

In the main, research has concentrated on examining the relationship between the proportion of the population which will incur health risks as the hot conditions increase in severity. Typically, criteria in the form of predictive curves have been based on estimates of the percentage of the working population who will reach core temperatures likely to result in irreversible heat stroke. Such estimates have been derived from epidemiological data on heat stroke and experimental data. The National Institute for Occupational Safety and Health (NIOSH, 1986) quotes examples of the derivation of such estimates. For example, at an Effective Temperature (ET) of 34.6°C it has been estimated that there is a probability of 10^{-6} that a rectal temperature of 40°C would be exceeded. Similar estimates for other ETs were given; 35.3°C ($p = 10^{-4}$), 35.8°C ($p = 10^{-2}$), 36.6°C ($p = 10^{-0.05}$). These were BET correlates for acclimatised men at 100% humidity. The BET at which the probability of core temperature reaching 38-39°C can also be derived. However, these data are based upon South African research and a specific worker population.

Reservations have been expressed about the general applicability of the original data to less severe conditions and the derived criteria to general industrial situations (NIOSH, 1986). The outcomes of the research have been criterion values, either in the form of climatic indices or physiological responses, for example, in the form of Effective Temperature or core temperature values respectively.

The main points contributing to the development of many criteria are as follows:

- (a) The level of physiological strain increases with

increasing total heat stress, environmental and metabolic.

- (b) As a general observation, (a) holds for both heat acclimatised and non-acclimatised, men, women, all age groups, individuals with different levels of physiological performance.
- (c) Differences in strain response between individuals or between population groups relate to level of heat acclimatisation and physical work capacity.
- (d) Individual variability can be large, but as extreme levels of exposure are approached heat stress variability diminishes.
- (e) The derived relationships between heat stress and heat strain form the basis of predictive techniques (e.g. thermal indices).
- (f) Although the regression of heat strain on heat stress is useful to provide a prediction in relation to a population group, it does not provide an indication of individual susceptibility or when strain criteria will be exceeded.

The World Health Organisation (WHO, 1969) states that it is inadvisable to exceed a rectal temperature of 38°C in prolonged exposure to heavy work. However, 38-39°C is allowable under closely controlled conditions. The rationale is that once the 38°C rectal temperature is exceeded, the risk of heat casualties increases. Note that the interplay between the work component and the climatic conditions is recognised in that the criterion is related to "heavy work". A study by RAMSEY et al. (1983) indicated that there were a higher number of unsafe acts with increased heat stress. The latter was taken to be above an WBGT of approximately 20°C (23°C, Wet Bulb Globe Temperature - WBGT). However, as has been seen earlier (see Section 3.3), care must be taken in the interpretation of such statements.

As was seen earlier, the key to the development of criteria is to provide values which take account of the effects of work, climate and physiological response. In industrial settings, and particularly mining, it is difficult to take account of different work practices and varying conditions. By necessity, most researchers have adopted a simplified approach to protecting the workforce. This has involved selecting a physiological criterion value, for example, a rectal temperature of 38°C, and deriving climatic index values weighted by exposure and work practice.

Consequently, the criteria and standards that are derived in this way are not necessarily "absolute". They provide values at which more careful assessment of the specific conditions may be needed to determine whether the workforce may exceed

physiological criteria. Figure 5 illustrates this philosophy. This is taken from an International Standards Organisation (ISO) standard being drafted by one of the authors. This approach has been agreed by the working group of the Technical Committee (ISO/TC159/SC5/WG1) and is likely to be published as a Draft International Standard in the near future (GRAVES, 1987). This initiative by the UK was taken because up to the present the UK has voted against the ISO standards on the thermal environment which have been published. This stance was taken because there was concern that the ISO standards had been selected from amongst others which could also be used in thermal environments. Without such an "umbrella" document, the published standards may have been accepted by the member countries and applied without considering the limitations of an approach which apparently excluded other equally useful means of determining the effect of the thermal environment on the worker.

7.2 Summary of Criteria

Figure 6 shows criteria from various American sources plotted onto the ISO Standard (ISO, 1982). The sources are ACGIH (American Conference of Government Industrial Hygienists, 1984), AIHA (American Industrial Hygiene Association, 1975), and OSHA SACHS (Occupational Safety and Health Administration Standards Advisory Committee on Standards, RAMSEY, 1975). This has been simplified on the basis of the NIOSH (1986) interpretation of the various work-rest regimes and redrawn with BET values for convenience.

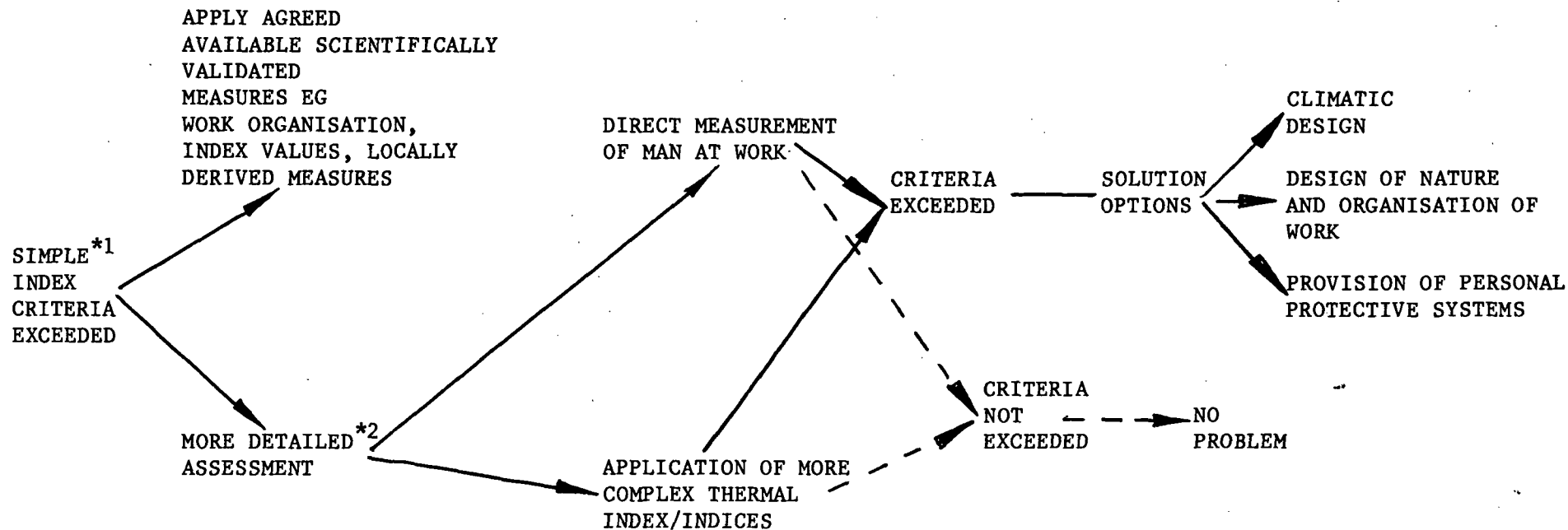
The ACGIH values are based on a rectal temperature of 38°C, with the assumptions that:

- (a) workers are acclimatised;
- (b) they are wearing normal work clothing;
- (c) they have adequate water and salt intake;
- (d) they should be capable of functioning effectively.

NIOSH concluded that a number of the index values from each of the sources (ISO, ACGIH, OSHA, and AIHA), once equated for most conditions, were broadly similar.

Figure 7 shows the NIOSH (1986) Heat Stress Exposure Limits for Heat-Acclimatised workers. The ISO (1982) WBGT ranges are also included for reference. It can be seen that the ISO values overlap the NIOSH curve for continuous work.

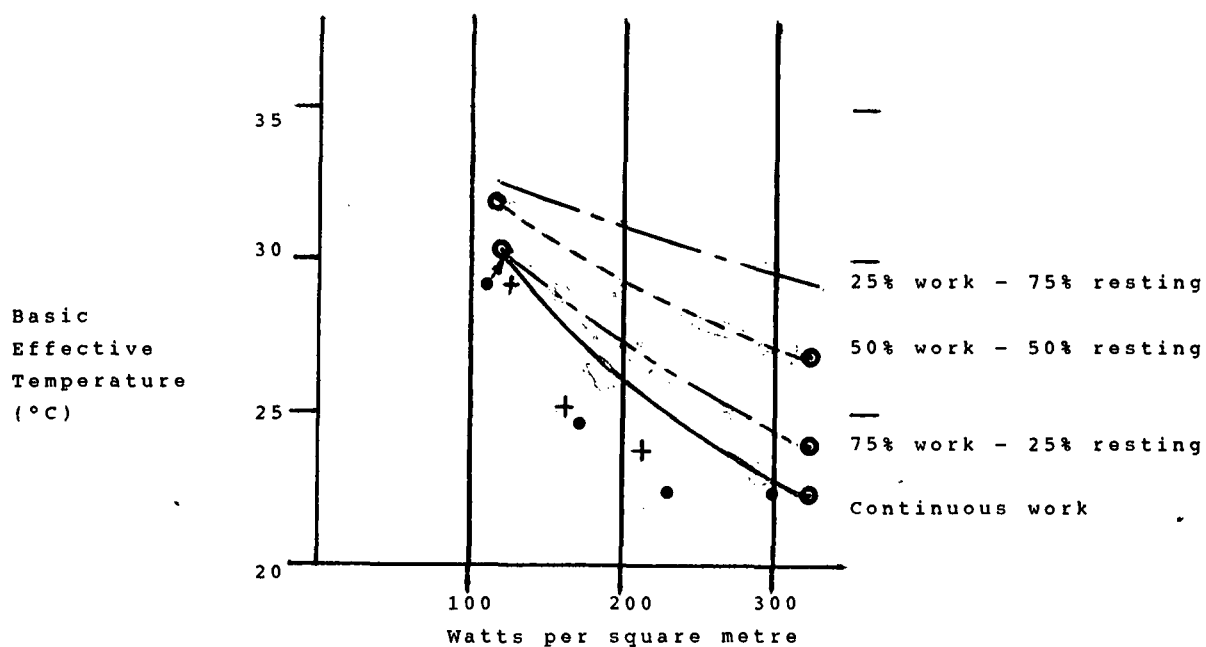
Table 4 summarises criteria, recommendations and working practices from within various countries. It can be seen that a number of organisations from these countries utilise similar values at which some form of action is required to be taken. It is clear that this does not necessarily mean that work will stop, but that a more careful assessment of conditions other than the calculation of thermal indices is needed or that various forms of remedial action are implemented. This is in accordance with the approach illustrated in Figure 5.



*1 Requires a minimum level of training.

*2 Requires detailed experience and professional training.

FIGURE 5 - RELATIONSHIP BETWEEN OPTIONS AND OUTCOMES RELATING TO THE
ERGONOMICS OF THE THERMAL ENVIRONMENT

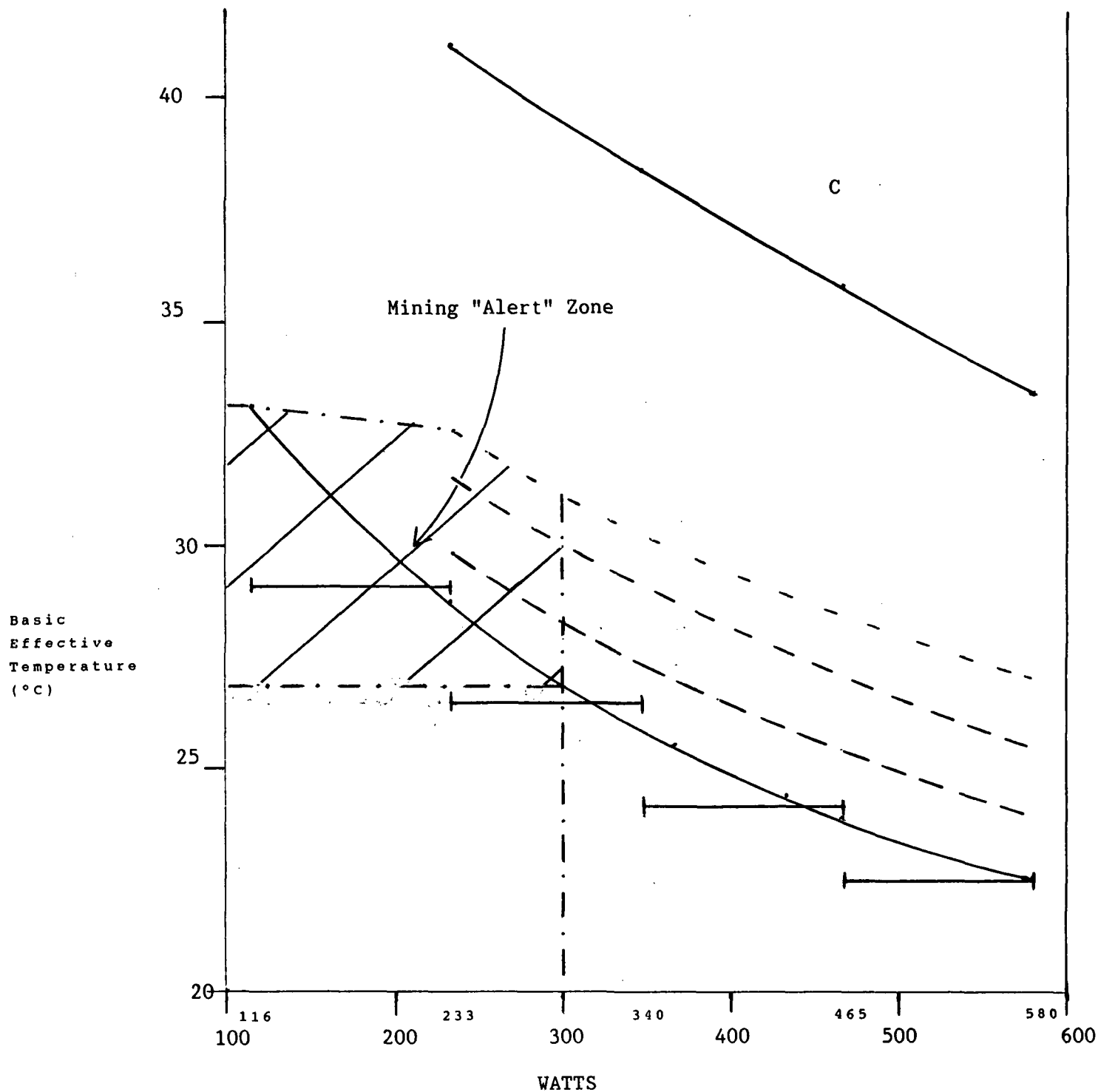


		Work Rate Value in Watts			
Work rate	Source	ISO	ACGIH	OSHA* ¹	AIHA
L		180	230	230	Similar values to ISO for continuous 75% and 50% work
M		297	230-405 (317)	230-345 (287.5)	
H		414	450 +	345 +	
VH		522	550* ² (25°C)	-	

*¹ 120 minutes time-weighted average

*² Estimated by authors

FIGURE 6. Criteria and Work Rates from American Sources in Relation to the ISO WBGT Standard



(Based on "standard worker" of 70 kgs body weight and 1.8 m² body surface)

Legend

— ISO values
C = Ceiling limit

- - - 15' work per hour
- - - 30' work per hour
- - - 45' work per hour
— Continuous work

FIGURE 3. NIOSH and ISO Limits for Heat-acclimatized Workers
(Adapted from NIOSH, 1986; DHHS (NIOSH) Publication No. 86-113)

TABLE 4.

Summary of Heat Stress Criteria from Various Countries

Country	Source	Criteria	Comment
America	ACGIH AIHA OSHA NIOSH (1986)	)) See Figure 6) See Figure 7	All have comparable values, although there are some differences.
Australia	Factories Regulations and Department of Labour (1974)	Globe Temperature < 25°C Outside Temperature plus < 2.8°C. Remedial action if temperature and humidity likely to be injurious to health.	Outside < 22.2°C " > 22.2°C
	Victoria Trade Hall Council and Australian Health and Medical Research Council	ACGIH TLVS (see Figure 6) Hazard money not an acceptable policy.	Includes guidance on heat stress, measurement, medical requirements, heat acclimatisation, protective measures, and hot work regulations.
Belgium	Royal Decree (1975)	Same values as ISO and ACGIH for various work activities stated in Effective Temperature.	On advice of industrial doctor and agreement with worker safety representative, these values can be exceeded subject to safeguards.

France	Government Regulation	Those mines which have a Resultant Temperature (t_r) above 28% are considered to be particularly hot (see A.1.3.10).	Official requirement. There is discussion of the effects of workload
Finland	Guidance Limits	Similar to ACGIH TLV.	Not Official
Germany	Federal Mining Decree	Non salt mining: 1. DB >28°C or 25° BET (a) 6 hours maximum work if 3 hours at: (i) DB 28°+ up to to BET 29°C or (ii) >25-29°C BET. (b) 5 hours max work if more than 2½ hours at < 29-30°C BET. 2. Personnel should not be employed at BET >30°. Exceptions: (i) exposed to BET of >30° for a maximum of 4 months/break 6 weeks, (ii) maximum of 5 hours daily exposure, 2½ hours at BET of 30°C+, and (iii) in face operations, a maximum of 1/3 employees exposed to BET of 30°+. Salt mining: 1. DB >28°C (a) 7 hours maximum work if: (i) more than 5 hours at > 28-37°C DB or (ii) more than 4½ hours at 37-46°C DB. (b) 6½ hours maximum if 4 hours at DB 46-52°C. 2. Personnel should not be employed at > DB 52° or WB 27°C in salt mining. Exceptions: if it is ensured by special means that physiological effect is < DB 52°C or < 27°C.	Introduction effect January 1984. Provision made for extra breaks, acclimatisation period, age, groups and work in emergencies, e.g. mines rescue for non and salt mining. Provision for special equipment, etc so that physiological effects of climate < 30°C BET.

Great Britain	National Coal Board (1980)	Basic Effective Temperature > 28°C for at least 1.5 hours in any one shift will incur a heat allowance payment.	Not highly acclimatized but well trained for work.
	National Coal Board (1963)	27.2°C (partially mechanised). 28.3°C (fully mechanised).	
	Lind (1963a)	30.2°C BET 210 watts 27.4°C BET 349 watts 26.9°C BET 490 watts	
	WHO (1969)	30°C BET light work 28°C BET moderate work 26.5°C BET hard work	
Japan	Association of Industrial Health	Same values as ISO and ACGIH for similar work activities given in both WBGT and Corrected BET.	Not official
Romania	Occupational Health Protection Standards	Microclimatic conditions at work site to be such as to allow worker to maintain thermal equilibrium during normal work.	
Sweden	Department of Occupational Safety	NIOSH (1986) estimate maximum heat stress levels to be two degrees lower than ISO and ACGIH values.	
USSR	Heat Stress Standard (1963)	Similar to Romania but probably lower values.	Differing work rates. Emphasis on environments with radiant heat.

Criteria in Relation to Mining Conditions

There are a series of questions which need to be answered in order to assess the relevance of the criteria quoted above in relation to mining conditions. These are:

- (a) are the values likely to be appropriate to the mining workforce;
- (b) can these values be interpreted easily in relation to the workloads and practices found in mining;
- (c) what impact would the implementation of these values have on mining practice.

The heat stress criteria are based on a deep body temperature (rectal) of 38°C. It has been predicted that an increasing number of the working population will have heat stress problems above this core temperature. Comparable criteria designed to keep the worker's core temperature at or below this value in the form of thermal index values related to work rate have been produced by a number of authorities. These have been regarded as "alerting limits", i.e. above these index values more detailed measures should be taken to determine whether there will be a problem at the workplace and, if so, that changes should be made. Although most of the sources use WBGT, there are no technical reasons for the mining industries to abandon BET. Indeed, there are sound practical reasons for BET to be continued to be utilised. In the range of climatic values likely to be found in the mining industries, equivalent BET values could be substituted for the WBGT values quoted.

The selection of the appropriate index values depends upon the crucial question of whether the typical coal mining population should be regarded as acclimatised.

In the original work of LIND (1963a), the coal miners (mines rescue men) were not deliberately acclimatised; "it was impossible to achieve or maintain a standard degree of acclimatisation". As the experiments were based on three hours of work per day with varying climates, it is probable that the miners became accustomed to the conditions as the study continued. It could be argued that a similar situation occurs in normal mining and so the typical coal miner will be "acclimatised" to the climatic conditions resulting from his normal work. Also, research has shown that workers adjust their work rate and patterns to minimise the effects of the climate. These factors and the fact that Lind's work probably underpins the majority of the standards, would allow the use of the acclimatised scales for miners who have previously worked in hot conditions. Others (e.g. ISO, 1982) view acclimatisation similarly. However, the non-acclimatised scales would need to be applied to those who had not been so exposed, until an appropriate period had elapsed.

The time-weighted average of 300 watts has been cited as being at the upper limit of coal mining workload, so typical metabolic loads will vary depending upon actual work carried out. MORRIS and GRAVELING (1986) examined the typical ratios of physical to non-physical work or inactivity derived from an analysis of records of 171 man-shifts. The data showed that 50% of the occurrences had ratios of 50% work and 50% rest or inactivity. An examination of the total time working in relation to non-physical work and periods of rest showed that 39% was spent working. Such data can be used to provide time-weighted exposures in conjunction with Figure 6 to estimate coal mining work-rest regimes.

In section 5.3.2, it was concluded that shift averaged work loads of 300 watts (167 w m^{-2}) probably represented the upper limit of modern coal and potash mining tasks. Using Figure 7, the metabolic heat value of 300 watts and the time-weighting as above, it is likely that the curves outlined by the hatching are those which would be applicable to coal mining. Where a shift weighted average work rate of 300 watts is used, then curve a-a, Figure 7, should be utilised. This should result in action being taken at 26.8°C BET (28.2°C WBGT) for the acclimatised worker at the work rate of 300 watts. Incidentally, the NIOSH (1986) report does not appear to mention that the 60 minutes per hour curve is used where only shift weighted metabolic heat estimates are available; which is included in the ACGIH document from which the curves are derived.

Where the time-weighted work-rest regime is 25-75% at 300 watts (hourly time-weighted), then the NIOSH curves would suggest that action should be taken at approximately 31°C ET (31.5° WBGT) for acclimatised workers.

Assuming a work-rest regime of 50-50% hourly time-weighted, then at 300 watts the "action values" would be 29.9 (30.5° WBGT) for acclimatised workers. The time-weighted shift average of 300 watts can provide an upper limit of the range of metabolic cost of typical mining work. Also the earlier estimates of between 50-39% time spent working provides further information from which to determine the implications of work rate and work pattern on mining action BET values. This information indicates that there is a zone where the derived ET values from NIOSH (1986) are particularly relevant to coal mining. This "mining alert zone" (MAZ) lies between the 60 minute/hour curve and the top "cut-off curve" produced by extending the 15 minute hour across to the intersection where curve a-a meets the BET axis.

From the MAZ, it would appear that BET "action values" can be derived for acclimatised miners carrying out normal work practice at the upper limit of the typical work rate. This value would lie between 29.9 - 31.2°C BET where it is possible to provide hourly time-weighted values. Where only shift

averaged work rate values are available, then the BET action value for this upper limit would be 26.8°C (28.2°C WBGT).

Earlier it was seen that in UK coalmining, "common practice is to use a 26°C BET design in ventilation planning to keep climatic conditions below 28°C" (ALDRED *et al.*, 1984a) and that "it is generally accepted that values below 28°C (BET) produce suitable working conditions" (ALDRED *et al.*, 1984b). In view of the importance of the work rate component, both in terms of work rate and work-rest regimes, such statements need to put into context.

It is probable that the above quoted BET values are derived in part from the classic Lind work (see Table 4). Values of 28.3°C BET for fully mechanised conditions, and 27.4°C BET for moderate work are mentioned. The latter is stated as being approximately 349 watts which is higher than the suggested top of the range for typical modern mining work. The latter workload could be said to be the equivalent of a 60 minute/hour time-weighted average. Examination of the NIOSH (1986) 60 minute/hour curve indicate that the BET value at 349 watts is 26.5°C BET for an acclimatised worker. This is lower than the Lind value. These differences are probably due to the way that the workload component is compensated for. However, it is clear that the coal mining industry recognises that it is good practice to keep ventilation design targets to below 28°C BET.

In conclusion, the NIOSH (1986) scale for the acclimatised worker could be used to determine values at which action should be taken. At the minimum, this would entail a more careful analysis of work-rest regimes. The values which can be determined in this way accord with recognised good mining ventilation practice. NIOSH recommend a medical surveillance programme for those working above BETs of 23°C (calculated for the upper value of 300 watts for mining, but using the scale for unacclimatised workers). Although this is good practice, there is little evidence that coal miners have experienced adverse medical effects despite the fact that there is a proportion of the working population which is exposed to BETs above this figure.

On the basis of the estimated upper limits and pattern of modern mining work, where shift averaged data only are available, then a more detailed analysis of working conditions would be good practice above 26.8°C. Where the hourly time-weighted values are available and the work pattern reflects a work-rest range of between 50-25% time spent working, then the BET action values could be much higher. The application of these values assumes that the population is medically fit and careful monitoring of the working conditions is maintained to confirm the work pattern and hourly weighted workrate values.

8. CONTROL MEASURES: THEIR IMPLICATIONS FOR THE WORKFORCE

8.1 Introduction

In the mining industries of the world, considerable research and practical effort has been directed towards reducing the environmental heat load in deep mines and a considerable wealth of literature on this topic has been published. It is beyond the scope of this review either to examine detailed aspects of the various approaches which have been investigated or to comment extensively on their relative merits. This section provides an overview of some of the major approaches which have been investigated, concentrating primarily on their potential impact on the workforce (other than that for which they were intended).

8.1.1 Increased air flow

In coal mines, the quantities of air flowing round districts have been increased in recent years, partly to reduce methane levels where these are a problem and partly to reduce the environmental heat load. Reference to the nomogram used in the determination of BET (ELLIS *et al.*, 1972) clearly shows that, at higher temperatures, increases in air flow have a proportionately smaller effect on BET than at lower temperatures. The benefit of increasing air flow will not therefore be as great. The increased air flow also brings attendant problems such as increased dust pick-up generally, and increased 'chock-dust' on faces in particular. In addition, the high air velocities outbye could be expected to produce cold stress problems for the men working in these areas (GRAVES *et al.*, 1981). SHAW (1978) showed that a 5% increase in face air flow resulted in a 16% increase in annual fan power costs. Because of the relatively high cost of ventilation changes, it was calculated for the particular case under study that it would be more economical to reduce the ventilation flow and introduce some form of district cooling as an alternative solution.

ROBINSON (1983) considered the feasibility of increasing air flow in the bord and pillar mining system employed in the UK potash mine. It was estimated that raising the air flow by 50% would result in an increase in fan power costs of 340% (a similar order of magnitude to the estimates of SHAW (1978)) due to the relative inefficiency of bord and pillar ventilation. As with coal mining, it was also considered that dust problems would be exacerbated by such increased air flows. Consequently, increasing the air flow was rejected as a viable cooling solution.

8.1.2 Bulk air cooling

Various methods of cooling the general body of intake air were investigated by ROBINSON (1983) for the UK potash mine. It was

concluded that achieving an adequate drop in temperature at the working area would result in cold problems in the intake area and would only benefit the first few panels, as the pick-up of heat through these would largely negate any further benefit. These problems, coupled with the high capital costs, resulted in the rejection of bulk air cooling.

Although bulk air cooling has been considered in some countries for coal mining (e.g. VOSS, 1985) the problems of unacceptably cold conditions outbye will be much the same. Additionally, it has been calculated (VOSS, 1985) that, for high output faces, an adequate drop in dry bulb temperature by air cooling requires the cooling to be provided at the face. VERMA (1984) referred to air cooling outbye as a waste of money because of the comparatively rapid uptake of heat by the cooled air. Attention was also drawn to the 'uncomfortably cool' conditions which would be encountered closer to the cooling source.

8.1.3 District and local cooling

Considerable attention has been directed within the UK mining industry towards direct reduction of environmental heat load by cooling the ambient air at a more local level. This has been achieved either directly with the passage of air over heat exchangers or indirectly by cooling dust suppression water. BROWNING *et al.* (1982) reported three such investigations, a small-scale (30 Kw) cooler, providing direct cooling of a single gate-end, a larger (100 Kw) heat exchanger cooling heading, and a 500 Kw unit cooling the dust suppression water for a longwall district.

Two trials were reported with the 30 Kw cooler which resulted in typical reductions in Effective Temperature of 1.5-2°C in the cooled area. However, particularly in one location, the extracted heat was reported to have an adverse effect on temperatures outbye with a mean increase of 1.5°C BET.

The 100 Kw heat exchanger was supplied from a cooling unit situated away from the working area. Air was ducted into the heading through the heat exchanger and discharged at the face of the heading. In this case, the unit produced a reduction in discharge temperature of approximately 2°C BET. This was mainly achieved by a reduction of the relative humidity of the inlet air by 22%; however, the discharged air readily picked up moisture, resulting in a reportedly negligible benefit to those working away from the immediate discharge area.

The 500 Kw cooler system was designed to function primarily by cooling the dust suppression water with additional cooling from the circulating pipes. Average reductions in dry bulb temperature of 1°C at the inbye end of the return gate and 1.5°C at the face machine were reported. These improvements were less than the expected reductions of 3-4°C.

These cooling systems do appear generally to produce some local

benefit at the point of application. However, the rate at which heat is picked up again from the surroundings minimises the extent of any benefit. In addition, with local systems, the heat discharged by the cooling unit may produce problems for other workers.

ALDRED *et al.* (1984b) described a number of local air-conditioning installations employing direct evaporators or chilled water units. Reductions in Effective Temperature have typically been of the order of 2.5°C although a value of 7.1°C was reported for one installation. However, this benefit was lost within 150-200 metres of the cooling source due to heat pick-up from the strata. The use of some form of 'incremental cooling' rather than a single large cooler was advocated. This has the additional benefit to the workforce of preventing the very low output temperatures sometimes associated with the larger devices. The problems associated with reject heat can be reduced by not discharging the heat at the cooler but transferring it to main returns or even to fire fighting water ranges (ALDRED *et al.*, 1984b; VERMA, 1984). A proposal has also been put forward for a 3 MW surface refrigeration plant (thus avoiding any problems with waste heat underground). This is intended to supply cooled water to heat exchangers around districts and to dust suppression sprays.

Face cooling, either from local coolers or from a central chilled water plant was also investigated by ROBINSON (1983) for the potash mine. A centralised plant, either on the surface or close to the pit bottom upcast shaft was regarded as an expensive option compounded by the restrictions on the use of water underground due to the solubility of the ore. As with coal mines, problems occur with local cooling due to both the rapid reheating from the strata and the problems of heat rejection. A further problem was encountered with evaporative coolers as these tended to increase the relative humidity of the air, resulting in worse climatic conditions when the air was reheated by the strata. The sensitivity of the mined ore to moisture also limits the amount of moist air which can be rejected into the return roadways. Other local cooling strategies such as cooling cabs on machines or air-conditioned rest cabins were considered for the mine but rejected (ROBINSON, 1983).

8.1.4 Work reorganisation

The total thermal load depends not only on the environmental load, but also on the metabolic heat generated by the work being carried out. LIND (1963a) reported the relationship between workload and the environmental temperature. He identified three combinations of BET and steady, continuous workload above which the body was unable to maintain a stable internal temperature. These were 26.9°C (heavy workload), 27.4°C (medium workload) and 30.2°C (light workload). Various solutions for controlling this metabolic heat component have been proposed in the literature. They generally involve the

calculation of a time-weighted average of heat load due to both metabolic and environment factors. For example, RAMSEY (1978) described a method based on the use of the WBGT thermal stress index to quantify the thermal load. Where the time-weighted WBGT exceeds a threshold limit based on the average metabolic cost, then work/rest regimes or some other modifications of the working pattern can be introduced to reduce the total load below this threshold.

A hybrid form of voluntary work/rest scheduling and job rotation is reportedly operated at the potash mine (ROBINSON, personal communication). Mineworkers have a degree of freedom to pace themselves, taking breaks in slightly cooler zones as appropriate. As stated earlier, MAIRIAUX and MALCHAIRE (1986) found that such self-regulation could be an effective method of reducing heat strain. Alternatively, job flexibility within the workforce allows supervisory staff to move miners between tasks/machines, allowing the men to work in slightly cooler locations for a period. This appears to be at the discretion of the supervisory staff and it may be appropriate to consider procedures to indicate when such rotation should be employed.

In coal mines, many mineworkers do have a certain degree of flexibility to pace themselves although drives towards greater productivity/machine utilisation may erode that freedom. One limitation is clearly that of job demarcation, particularly with reference to machine operation. Development operations have been observed where more than one member of the team has been able to operate the machine and this has allowed roadway advance to be maintained while permitting individual members of the team to gain some respite from particular jobs. However, current job/wage structures do not generally permit this flexibility and this would be a barrier to the implementation of such practices in coal mining.

In some industries (e.g. MILLICAN et al., 1981) further benefit has been derived from formal or informal work/rest scheduling by the provision of cool refuges, an approach also advocated by NIOSH (1986). The logistics of providing a mobile refuge, suitable for advancing with a face, militate against their use in mining particularly in the already relatively cramped conditions of a longwall face-end, although they have been used in some German coal mines. However, the introduction of chilled water circuits may allow the generation of a limited cool spot by the incorporation of a simple 'cold radiator' or some such device at an appropriate point in the circuitry.

8.1.5 Individual cooling systems

An alternative procedure for reducing the influence of environmental conditions on man is that of providing personal protection to reduce the load at the wearer rather than at source. Thermal protective garments can either function by providing a barrier between the source and the body, such as in the use of aluminised garments as protection from high radiant

heat loads (CROCKFORD, 1962) or by removing heat from the immediate vicinity of the wearer (frequently referred to as the microclimate). This cooling of the microclimate by removal of environmental and/or metabolic heat has been achieved by the use of cooled garments. A considerable body of work has been done on these in relation to mining industries, military conditions (e.g. aircraft cockpits), glassworks and other industries with some success (EDWARDS and HARRISON, 1978; STRYDOM et al., 1974; RAVEN et al., 1979).

NICHOLL et al. (1983) examined a number of different systems for cooling the individual. These could be categorised into three groups: (i) those where the cooling source is an integral part of the garment, (ii) those where the cooling source is external to the garment but carried on the body and (iii) those where the cooling source is situated away from the body and connected to the garment by tubing. Because of their greater direct influence on the individual, these garments are discussed in somewhat more detail than the engineering solutions.

8.1.5.1 Integral cooling

Three different cooling agents have been employed in integrally-cooled garments: water, water-ice and dry-ice.

HAUSMAN (1980) described the results of studies within the Belgian coal mining industry into the efficacy of a terry towelling garment (jacket and hood), soaked in water as a cooling method. Laboratory studies at an Effective Temperature of 31.2°C (chosen as representative of conditions in Belgian mines and comparable to the upper limit of those in British mines) showed a reduction in the Belgian Mines Rescue Fatigue Index of 17.4% from a mean of 180 to 148.6 when cooling was provided during rest periods. The Fatigue Index, derived from a combination of heart rate, rectal temperature, sweat loss and subjective ratings, showed little difference in efficacy between direct ventilation with cooled air, a ventilated jacket or a wetted jacket with or without direct ventilation. Consequently, as the wetted jacket was considered to be the most practical (not requiring a ventilation source) this was selected by HAUSMAN for evaluation underground. In a series of underground trials, however, no significant difference was found in the results obtained with or without the wetted jacket.

The use of water-ice jackets for reducing the heat load of men working in hot conditions has been investigated by STRYDOM et al (1974) in the South African gold mines, by SWEETLAND and LOVE (1974) in the British Mines Rescue Service, by DE ROSA and STEIN (1976) for mines rescue teams in the USA and by MÜCKE (1982) on behalf of the German mining industry. The garments used in all these studies consisted of sleeveless jackets fitted with sealed water pockets, which were frozen in commercial freezers (freezing time 6-8 hours).

The climatic conditions under which they were tested were generally more severe than those reported above for British mines. In all cases, the ice jackets were found to retard the progressive rise in core temperature during their effective cooling period, thus permitting the wearer to work significantly longer in the adverse conditions. The garments also increased comfort levels considerably. However MÜCKE, for example, found it necessary to replace the ice jackets every hour of the four-hour test. In addition, STRYDOM et al. (1975) using 4.8 Kg jackets, and MÜCKE (1982), using 2.75 Kg and 3.5 Kg vests, showed that the weight of the garment significantly increased the energy expenditure of the wearers, therefore reducing the overall effectiveness of the garment. The bulk of the ice pockets in the jackets was also found to reduce the wearers' mobility in some circumstances.

The use of dry-ice (solid CO₂) for personal cooling has the advantage over water-ice in that its thermal properties are such that it requires only 71% of the mass of water to provide the same amount of cooling. A dry-ice jacket, similar in design to the water-ice jackets mentioned above, was examined by KONZ et al. (1974). It was found to be effective in controlling body temperatures in environments of 43.3°C DB at 45% or 55% relative humidity. ROBINSON (1983) carried out a trial of dry-ice cooling jackets on machine operators in the potash mine. In temperatures of up to 35°C BET the jackets maintained lower physiological responses (oral temperature and pulse rate) than those encountered without cooling although it should be noted that, with a single exception, oral temperatures remained at acceptable levels even without cooling. Although comments were made about the weight of the jacket (4 Kg) and the restrictions to arm movement produced by the jacket, it was decided to implement them on a larger scale. However, after the initial enthusiasm, problems such as those described above began to reduce their acceptability. In addition, the men complained that they were becoming too cold when in the cooler areas. Ultimately, the use of the jacket was discontinued. It may also have been that the jackets were resented as they apparently reduced the need to take breaks. Problems of acceptability of such jackets have also been described by MILLICAN et al. (1981). Although such garments have an apparent advantage in that a lower weight of dry-ice than of water-ice is required, extra insulation is necessary which offsets this difference. In addition, CO₂ sublimates at -78.5°C and can cause considerable damage to the skin if touched.

8.1.5.2 External cooling source, carried on the body

Three systems where the cooling source is carried on the body but is not an integral part of the garment have been described in the literature. They all involve the use of a liquid medium to transfer heat from the microclimate within the garment to an external heat sink (cooling source), a process known as active cooling.

ENGEL et al (1981) described a system manufactured by Draeger in which silicon oil, cooled in a dry-ice reservoir in a back pack, was circulated through tubes in a coverall. The coverall was an integral part of a total protection garment incorporating a breathing mask which allowed men to work in very severe temperatures (up to 100°C, 100% RH). A smaller scale version of this, using a cooling vest, has been produced for use in less severe climates.

This unit was studied by MÜCKE (1982). It was found to have an effect on rectal temperature comparable to that of the ice jackets studied. However, the garment, with its back pack containing a solid CO₂ reservoir, heat exchanger, silicon oil and pump weighed 13.7 Kg, compared with 4.5 to 6 Kg for ice jackets. This additional weight was sufficient to offset most of the cooling benefit obtained from the unit. MÜCKE also reported the use of a garment known as an Apollo vest (having been developed during the US space programme). This was described as a waist-length, sleeveless garment containing an extensive network of tubes through which cold water was circulated by means of an electric pump. The total unit weighed 6.5 Kg. It was tested in two conditions, hot-humid and hot-dry. In the humid climate there was no effect on heart rate or sweat rate although body temperature was slightly lower than in the no-cooling condition. In the hot-dry climate only rectal temperature was reported, and again the increase was reduced in comparison with a no-cooling control. In both cases, the weight of the unit was considered to offset the physiological benefit. As with the other water-ice garments tested, the ice was replaced every hour.

A similar garment, consisting of a water-cooled jacket and/or hood, using a ice canister-container as the heat sink was described by WEBBON et al. (1977). The batteries, pump and canister-container are worn as two packs on the chest or belt, and water is circulated through the garment and the heat exchanger (which consists of polythene bag lining the box into which the frozen canister is placed). The jacket alone weighs 0.7 Kg when full of water, and the complete system weight is 5.0 Kg. The rate at which the fluid is circulated can be adjusted by the wearer. The life of the canister is 1-2 hours, depending on the metabolic rate of the wearer and the climatic conditions. Battery life is either 6 hours (disposable batteries) or 2 hours (rechargeable batteries).

All garments reduced both heart rate and the rate of rise in rectal temperature in comparison to the no-cooling condition, but no statistical analyses of the data were reported.

8.1.5.3 External cooling source with umbilical connections

The major disadvantage of self-contained cooling sources is the limited cooling available before recharging is necessary. Rate of cooling is inversely related to length of useful life and

consequently rate and duration of cooling are always compromised to allow a reasonable duration between recharges. The use of an externally connected cooling source obviates this disadvantage. For example, during the development of their self-contained system, WEBBON et al. (1977) tested the waistcoat and hood with a laboratory cooling unit linked to the wearer via a pair of umbilical tubes. This was stated to produce more comfortable temperatures than the portable unit, although no physiological comparison was reported. Such systems can however limit the range of movement of the wearer due to the umbilical connections between the source and the garment worn.

Two different cooling media have been employed for such garments, air and water. Air cooling involves the supply of compressed air to a garment, either directly or via a Ranque vortex tube which cools the supplied air. The use of air-ventilated garments for adverse industrial environments was reviewed by RAVEN et al. (1979) who reported that the use of full pressurised suits increased the metabolic costs of "simple tasks" by two to four times. A report by ROGAN (1968) was also cited in which a ventilated jacket was investigated. Unspecified work at a dry-bulb temperature of 33.3°C with the ventilated jacket resulted in lower heart rates and comparable rectal temperatures to those obtained during the same work at 29.4°C wearing the jacket unventilated. The Ranque vortex tube was used by VAN PATTEN and GAUDIO (1969) to supply air at 13°C to a ventilated garment. Trials with resting subjects at temperatures of 54°C dry bulb and 40°C wet bulb showed that the cooled air significantly reduced heart rate, rectal temperature and sweat loss, more than doubling the tolerable exposure time. However, the vortex tube used produced noise levels well in excess of 100 dB and, although considered by the authors to be acceptable for subjects wearing aircrew headgear, this would not be generally acceptable.

NUNNELEY (1970), in a review of cooling systems, concluded that for any reasonable air inlet temperature (unspecified), nearly all the cooling was by evaporation of sweat rather than convection, "causing heat stress and eventual dehydration". For example, astronauts working on the Gemini 9 and 11 missions using air-cooling ended up with high pulse rates and fatigue, necessitating abrupt termination of their activities. On future missions, astronauts were provided with water-cooled garments which proved considerably more effective.

The concept of a garment supplied with tubes through which cooled water was circulated was first introduced by BILLINGHAM (1959). Preliminary studies showed the effectiveness of water-cooled garments, with an external cooling unit, in reducing heart rate, rectal temperature and sweat loss in a wide variety of climatic conditions. The conditions used in these studies ranged from 30°C to 60°C dry bulb, with and without a radiant heat load of approximately 65°C Globe temperature. SHVARTZ (1970) reported the effectiveness of a

liquid-cooled garment in reducing heart rate and rectal temperature with subjects exercising in a hot, dry environment (50°C dry bulb, 20% relative humidity).

NICHOLL *et al.* (1983) examined the feasibility of using such garments in UK coal mines. Initial experimentation showed a water-cooled coverall to be effective in reducing the physiological and subjective effects of working in a typical hot mining climate. However, studies of the operators of development machines (the initial target population) showed that, because of the time spent off the machine, a full coverage garment would not be suitable for mining conditions. An examination of various forms of limited coverage garment resulted in the selection of a waistcoat which, although less effective physiologically than the full coverall, produced some physiological benefit and a marked subjective benefit in subjects working in a typical hot mining climate.

This pattern of slight physiological benefit coupled with substantial subjective improvement was repeated when the garment was tested in a simulated development task. This latter test was carried out using the prototype water chiller for use underground which had been developed during the course of the project.

8.2 Coping with Heat Stress

Although not strictly a means of controlling heat stress - the actual heat load to which individuals are exposed; administrative measures intended to reduce the risk of harmful strain responses are dealt with at length in the NIOSH guidelines (NIOSH, 1986) and have been described by others (e.g. MILLICAN *et al.*, 1981). Measures include: Medical surveillance, 'Posting' of hazardous areas and Worker information and training together with work and hygiene practices. The latter include work-rest scheduling and providing cool havens, both of which can be regarded as reducing the heat load and which have been described previously.

Medical surveillance includes pre-employment screening and periodic (at least annual) medical examinations in employment. The primary medical indication would appear to be a previous history of heat illness. The standard describes a need to record 'relevant information on the cardiovascular system', without any indication of what constitutes relevant information. Although further details of the rationale for this examination is given in the background document which is published with the recommended standard, additional guidance would probably be required for UK Medical Practitioners if any such scheme were to be implemented in this country. Reference is made in the proposed standard to 'an estimate of the individual's tolerance to withstand hot working conditions'. However, no suggestion is made of an actual test for tolerance or intolerance of heat. The

need for research for such a test was recommended by ZENZ following a NIOSH workshop (ZENZ, 1980). Such tests have been reviewed by KENNEY (1985) and have been used in some mining industries, notably the South African gold mines (STRYDOM, 1982). Some European mining industries also utilise a heat tolerance test for mines-rescue workers.

Education and training is seen as an on-going activity in hot work for both new and existing workers. Training encompasses the likely effects and how to recognise them, together with an awareness of how other factors such as illness, over-indulgence in alcohol, etc. can decrease heat tolerance and how self-pacing, etc. can help an individual to cope. The NIOSH standard also provides for signposting of hazardous areas. This training can be seen as an adjunct to other practices such as making saline drinking water readily available and extends to training supervisors, etc. to recognise the symptoms in others. Saline drinks have been made available at times at UK coal mines although it is not known how widespread the practice is. ROBINSON (1983) described difficulties in implementing ice-jackets in potash mining. From the reported comments it would appear that, as with much personal protective equipment, a lack of awareness of the risks attached amongst the workforce could have contributed to this.

Acclimatisation can also be seen as an administrative control although neither MILLICAN (1981) or NIOSH (1986) recommend any specific regime. Such acclimatisation is regularly applied in South Africa (STRYDOM, 1982). In addition to such specific 'heat tolerance training', the NIOSH proposed standard also provides for increasing tolerance by increasing physical fitness. It is conceivable that the progression of jobs which a new entrant to the UK coal mining industry frequently undergoes before working on the coalface or in a development team may constitute a form of training. As these areas are also where the hottest conditions are likely to be encountered, it may also provide a form of acclimatisation. Problems may occur however when fully-trained men transfer from cooler collieries.

At present, it does not appear that any of the above procedures are systematically practiced in the hot UK mines. Although an element of self-selection may occur, current conditions of fewer men on the workforce at collieries and the reduced likelihood of employment outwith the mining industry makes that more difficult. The NIOSH proposed standard recommends administrative controls wherever the recommended alert limits for unacclimatised workers are exceeded.

8.3 Overview of Control Methods

In conclusion, both engineering and administrative controls exist to assist in alleviating the physiological effects of working in hot conditions. Provided careful attention is paid to potential 'knock-on' effects, engineering controls can be

effective where time and cost scales permit. Administrative controls such as job rotation can work where jobs involving less thermal strain exist and where working practices permit. They can also provide a means of lessening the impact of a given level of thermal stress.

The potential benefits of cooling garments are questionable. Although largely effective over the short term in controlling thermal strain, the useful life of such garments creates considerable logistical problems even on a relatively small scale of use and there are deleterious non-thermal effects which largely detract from their suitability. Where mobility is not a premium such as with some machine operators (or, looking ahead, at a remote control station) active cooling may be a solution. Indeed, it has been suggested (MASSEY, 1986) that protecting the worker from the environment may be the only solution for future workings at great depth.

9. CONCLUSIONS

1. Hot working conditions are encountered in coal and potash mines in the UK.
2. In such mines, radiant heat is seldom a factor. The climatic variables which make the major contribution to heat load are therefore the dry bulb temperature, humidity (normally measured as the wet bulb temperature) and air velocity.
3. In coal mining, relatively high humidities and low air velocities are encountered and these make a disproportionate contribution to the heat load because of their interference with heat loss through sweating. Effective Temperatures as high as 32°C (BET) have been recorded although these are peak values rather than shift averages. Average exposures over a working shift have not been determined.
4. In UK potash mining, although the humidities are lower, the major determinants of heat load are still the humidity and low airflow. Peak temperatures of 33°C BET have been recorded in current workings. However, where relative humidities of less than 30% are encountered, dry bulb temperature should be used to give a better indication of physiological strain.
5. Effective Temperatures in working districts frequently fluctuate with periods of machine operation, largely due to changes in humidity. Appropriate care should therefore be taken to obtain representative temperature readings and not to rely on 'spot' samples.
6. Temperatures also vary with location. In particular, local variations in airflow can create 'hot-spots' out of the main flow which are considerably warmer than adjacent areas in terms of Effective Temperature.
7. The other major source of heat stress is metabolic heat load. Estimates of both coal and potash mining suggest a maximum average workload of 300 watts although that will probably not be encountered in the hottest areas of potash mines.
8. At the typical hot temperatures encountered in coal and potash mining, work rate becomes a major factor in determining the likely ability to continue working safely. Any factor which reduces work load such as work-rest scheduling or increased mechanisation may increase the heat load which can be tolerated. However, as machine heat is a major source of heat load, if increased mechanisation results in an increase in ambient temperatures any benefit may be lost.
9. In mining, more especially in coal mining, clothing is normally kept to a minimum. Both coal and potash mining industries operate work-wear schemes and it may be necessary to supplement these with 'hot clothing' such as shorts in the same way as duffel coats, etc. are issued to those working in cold conditions. Where a

requirement to wear additional clothing occurs (e.g. when handling cementitious products for pump packing) an additional thermal burden will be placed on those involved. Particular attention may be required for these individuals.

10. Despite the high peak temperature readings recorded, no reports of heat-related illnesses have been received in recent years although the potash mine did encounter a few such problems when temperatures exceeded 35°C BET.
11. The prime direct measurement of heat strain is body (core) temperature. Individuals vary widely in their ability to tolerate elevated core temperatures. However, a value of 38°C is usually adopted as a reasonable limit for industrial work although higher values can usually be tolerated.
12. The environmental temperatures in which individuals can maintain their body temperature below this level vary widely and the ideal monitoring procedure would involve direct physiological monitoring. This is seldom practicable on a large scale and many thermal indices have been developed as alternatives to direct monitoring. These allow the prediction of responses with varying degrees of accuracy.
13. The Basic Effective Temperature scale is widely used in both the coal and potash mining industries. As a 'first order' monitoring index the scale would appear to predict heat strain with an acceptable degree of accuracy across the range of environmental conditions encountered. Although other indices have a better predictive ability, their complexity tends to militate against their regular use.
14. Where temperatures are high enough to give cause for concern then alternative approaches such as applying a more accurate index or direct monitoring should be adopted.
15. All heat stress/strain indices assume that the level of physiological strain increases with stress. A widely used physiological criterion is 38°C rectal temperature, above which the risk of heat casualties increases.
16. The criteria and standards derived from research are not "absolute" but provide values above which a more detailed assessment of the conditions may be needed to see whether physiological criteria would be exceeded in practice.
17. A number of standards and criteria used internationally have similar criteria and climatic values at which some form of action should be taken.
18. Although standards in use internationally use WBGT extensively, Basic Effective Temperature provides a useful, well understood thermal index for a range of hot conditions found in mining.
19. Miners can be viewed as being "acclimatised" where they have worked

in or have been exposed to hot conditions. However, it is unlikely that they will be properly acclimatised physiologically.

20. The NIOSH (1986) Heat Stress Exposure curves for acclimatised workers can be used to derive a Mining Alert Zone. The values in this will be used in conjunction with typical mining work to determine values at which detailed assessment of conditions should be carried out. For example, coal mining work averages up to 300 watts in work rate and involves working 39-50% of the shift.
21. The action values derived from the MAZ are similar to those accepted as good ventilation practice.
22. The solution of choice in reducing heat stress and subsequent heat strain must be engineering efforts to reduce heat 'at source'. However, care must be taken to ensure that solutions which provide local benefit do not exacerbate conditions elsewhere.
23. Reductions of metabolic heat load by work-rest scheduling or job rotation can make a considerable difference to the conditions which people can safely work in, particularly if the rests can be in cooler conditions.
24. Individual protection by providing personal cooling garments may be effective in some instances. However, many problems remain to be solved before they can readily be employed as a cooling measure. Problems include the logistics of providing an adequate supply of ice-jackets to remote areas and the design of garments to minimise adverse effects such as interfering with work or over-cooling on occasions. Such redesign will also aid in fulfilling the other requirement which will have to be met if such garments are to be successfully implemented; that of worker acceptance.
25. The issue of worker acceptance of cooling garments relates in part to the wider question of risk perception. Experience from the potash mine suggests that the workforce did not appreciate the need for ice-jackets.
26. Training of the workforce in a variety of issues including hazard awareness, recognition of symptoms, ways in which behaviour can influence heat stress or strain, etc. is one of the administrative controls which can be applied to minimise the impact of a given level of heat stress. Monitoring, surveillance and education all have a potential role to play in ensuring the safety of the mineworker when working in hot conditions.

10. PROPOSALS FOR FUTURE RESEARCH

10.1 Survey of Environmental and Metabolic Heat Stress

The last comprehensive assessment of thermal conditions in coal mining was carried out over 10 years ago. Although limited evaluations have been carried out since then, they have each covered a limited sample. No such assessment has been carried out in the potash mine. Such surveys as have been commissioned, in coal or potash, have comprised 'spot' samples of temperature. Virtually no data of time histories of temperature over a shift exist. Similarly, only limited data have been collected either relating to work patterns and levels, or to the physiological reactions to the ensuing combined environmental and metabolic heat loads.

Such climatic and metabolic data as have been collected indicates that both coal and potash mines may be at or near levels where problems may be encountered more frequently. One urgent requirement is therefore to carry out a systematic survey of hot locations in both coal and potash mines. An initial screening survey would be used to select a representative sample of coal mines to be included with the single potash mine in a more detailed analysis. This main analysis would examine the time course of climatic conditions over a shift and look at any cumulative effect over a week. This latter is an important element as the proposed introduction of six-day working in some locations will reduce the 'recovery period' usually available at the weekend when major plant is idle. In addition, the survey would monitor activity patterns and record the physiological reactions to the ensuing levels of heat stress.

Such research would:

- (a) Establish the current position regarding levels of potential environmental and metabolic heat stress.
- (b) Indicate the extent to which physiological responses mirrored what would be expected from the conditions.
- (c) Allow the optimum sampling frequency to be determined for environmental monitoring purposes.

In addition, procedures developed during the survey could readily be adapted to produce the basis for monitoring procedures which could subsequently be implemented within the industries.

10.2 Determination of Monitoring Procedures

In the expectation that, if not already necessary, some form of monitoring procedure will be required in the future, there is a need to initiate work with the two industries concerned to prepare for that eventuality. Figure 4 (section 7), which is to form part of an ISO standard would appear to be an appropriate starting

point as it provides the basis for monitoring procedures of gradually increasing complexity/specialism. Further work would be needed to establish agreed procedures for more detailed assessment. These may initially just constitute more detailed monitoring of environmental conditions, replacing routine 'spot' sampling with an agreed protocol for time-weighted averaging to determine the load more accurately. Training in hazard awareness and other administrative procedures may also form part of this protocol. Should physiological monitoring be required, then the first recourse could perhaps be to a 'non-specialist' package which could be applied by colliery personnel with a minimal level of training before a full, detailed monitoring package needs to be implemented.

As part of this research, it would clearly be beneficial to examine the implementation and effectiveness of legislative/control procedures employed in other countries.

The potential benefit from developing such a package would be considerable as it would allow mining to continue safely in conditions which, without the use of more accurate mining procedures, might otherwise be regarded as unacceptable.

10.3 Heat Tolerance Testing

Ultimately, it may be desirable to select men for working in particularly adverse conditions as is already done in some European Mines Rescue Services. It may be sufficient to screen out the relatively small percentage who are particularly heat "intolerant" rather than aiming to identify the 'supermen'. This work could also examine the extent to which the heat intolerant men voluntarily screen themselves out of such conditions.

10.4 Additional Fundamental Research

Finally, in addition to these more practically orientated proposals, there are some areas where further fundamental research is required.

- (a) It is by no means clear what limiting level of physiological strain should serve as a cut-off. Such limits as have been proposed are largely based on rectal temperature measurements which display a considerable time-lag over the other sites currently used for reasons of social acceptability. Indications for this research would be provided from the physiological surveys incorporated in proposal 10.1.
- (b) Although it is clear that heat does have an adverse effect on performance and safety, what is less clear is how much heat and how much effect! This area has also been identified by NIOSH as warranting further research and some form of collaborative effort, possibly with the USBM, may be desirable. The outcome of such research could be guidance values which could be used in a similar way to the Mining Alert Zone concept.

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APPENDIX 1

THERMAL INDICES : THEIR DEVELOPMENT AND USE

A1.1 Introduction

This appendix derived extensively from MORRIS (1984) examines the development and application of a wide range of thermal indices. The indices are classified according to their line of development. Two main developmental series are shown in Figures A1 and A2.

A1.2 Instruments Designed to Simulate Human Heat Exchange

A1.2.1 Dry bulb temperature

Although not strictly a thermal index, dry bulb or ambient temperature has been included as it remains the most commonly adopted means of assessing the thermal environment (MacPHERSON, 1962). Its limitations as a predictor of human responses appears to have prompted the development of more integrative measures (FOX, 1965).

A1.2.2 Wet bulb temperature

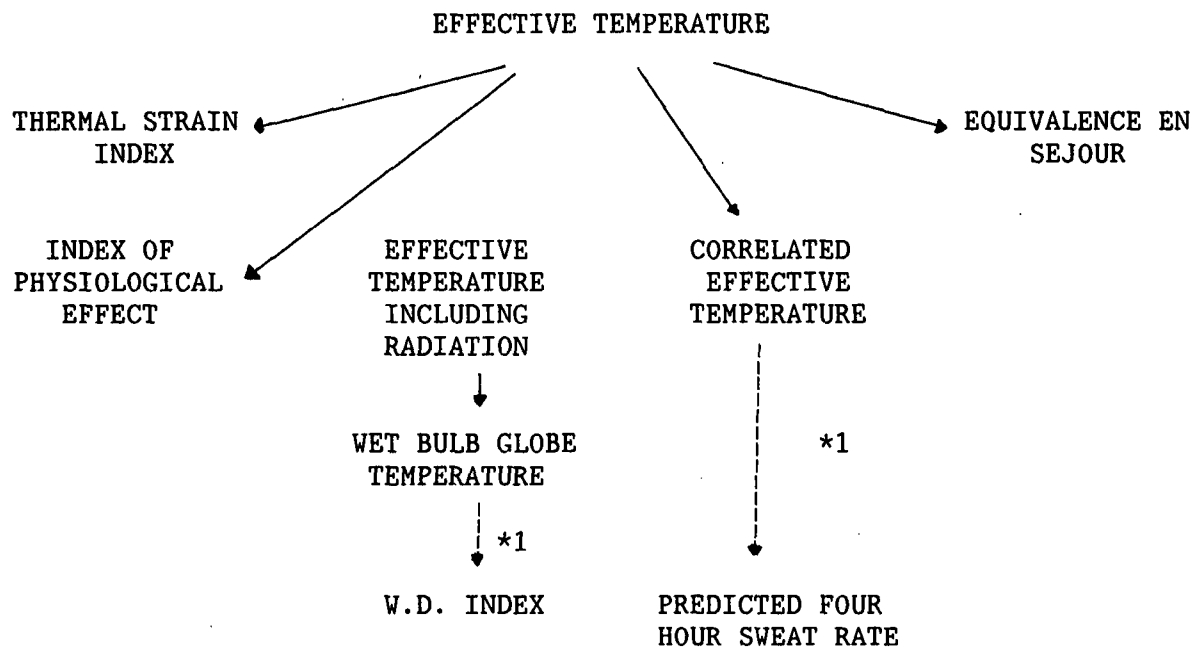
The psychrometric wet bulb temperature was proposed as an index of mine climate by HALDANE (1905) as a result of physiological studies in the Cornish tin mines. It was found that a subject's body temperature increased while at rest in still saturated air if the wet bulb temperature was in excess of 31°C. If moderate physical activity were undertaken, however, this limiting value fell to 25°C.

While wet bulb temperature has been included in many complex indices, it has rarely been used as a climatic index in its own right. WYNDHAM (1962), however, showed that the incidence of heat stroke among Bantu labourers in the South African gold mines was related to the wet bulb temperature. Climatic limits based on wet bulb temperature subsequently proved valuable in the prevention of heat stroke (WYNDHAM and HEYNS, 1973).

A1.2.3 The kata thermometer

The kata thermometer was developed by HILL and his colleagues (1916), its defined purpose being "to determine if the atmospheric conditions are healthy and comfortable and if this is not the case, the observations may be used as an indicator of whether the room is too hot or too cold, too stuffy or too draughty". In effect the instrument measured the cooling power of the air on a surface with a temperature close to that of the human body (MOSS, 1927).

The instrument consisted of a large-bulbed thermometer terminated in a small bulb at the top. The kata thermometer was operated by heating it in hot water till the top bulb filled and then allowing it to cool in the test environment. A kata cooling power (in millicalories $\text{cm}^{-2} \text{sec}^{-1}$) was then derived from the time taken to cool from 100 to 95°F and the instruments cooling factor (MOSS, 1927).



*1 = Dotted lines indicate similar conceptual development but no direct link between indices.

FIGURE A1. Historical Development of Empirical Scales Relating Physiological and Subjective Responses to Climates

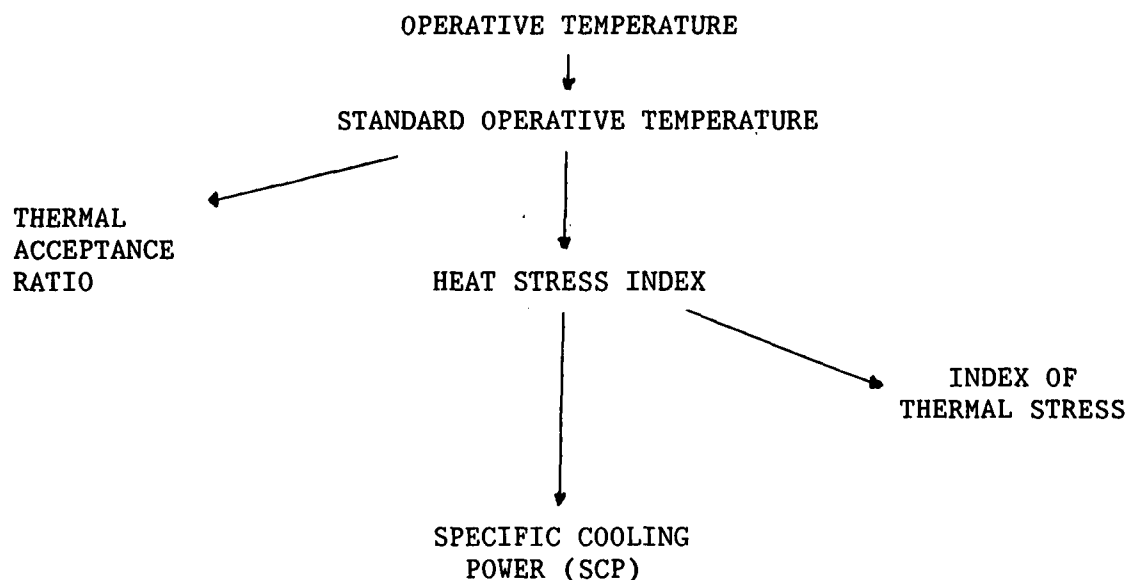


FIGURE A2. Historical Development of Indices Based on Mathematical Analysis of Heat Exchange

HILL et al. (1916) proposed limiting values of dry and wet kata cooling powers (the wet kata cooling power was obtained by covering the large bulb with a wetted silk net fingerstall) and these were frequently used in the mining industry (HALDANE, 1929). Experience showed that the kata thermometer was oversensitive to changes in air velocity (BEDFORD, 1937) and it subsequently became less popular as an index of mine climate. LE ROUX (1977), however, reported that the wet kata cooling power (in a slightly amended form) was still widely used in the South African mining industry.

A1.2.4 Globe temperature

VERNON (1932) developed the globe thermometer as an instrument for measuring the combined effects of air temperature, air movement and mean radiant temperature. The instrument consisted of a hollow copper sphere painted matt black and containing a mercury-in-glass thermometer.

Globe temperature has largely been abandoned as an independent measure of thermal stress but remains an important component of several heat stress indices (MacPHERSON, 1962).

A1.2.5 Equivalent temperature

DUFTON (1929) devised an instrument known as the eupatheostat in order to determine the equivalent temperature of an environment. It consisted of a blackened copper cylinder containing a heater and a thermostat. When placed in a given thermal environment, the surface temperature of the device changed according to the relative influences of air temperature, radiation and air velocity, mimicking to some degree effects on the clothed human body (FOX, 1965). The amount of current consumed by the heating element was used to determine the equivalent temperature of the environment.

BEDFORD (1936) subsequently prepared a nomogram for the determination of equivalent temperature, based on dry bulb temperature, mean radiant temperature and air velocity. The index does not appear to have been widely used and this may have been attributable to the limited range of conditions covered by the nomogram (BEDFORD, 1964).

A1.2.6 The thermo-integrator

This device was developed as a by-product of the partitional calorimetry research carried out by Winslow and his coworkers (e.g. WINSLOW and HERRINGTON, 1949). The thermo-integrator consisted of an evacuated, blackened, copper cylinder through which a heating element was threaded. A constant heat input was maintained to the interior of the instrument and thermocouples on the outer surface measured the mean surface temperature when an equilibrium between heat input and heat loss was achieved.

The thermo-integrator was intended to measure the combined effects of air temperature, air velocity and radiation on human comfort and although frequently cited in the literature appears to have been seldom

used in practice (MacPHERSON, 1962).

A1.2.7 Wet globe temperature (WGT)

The wet globe thermometer was developed by BOTSFORD (1971) as an instrument which exchanged heat with its surroundings in a similar manner to the human body. The wet globe temperature was stated to be a function of dry bulb temperature, relative humidity, air speed and radiant heat load.

The concept of the instrument does not appear to have been entirely new, a similar instrument having been developed by Linsel and Weuthen in the early 1950s (described by LEHMANN, 1953).

Botsford's thermometer, known colloquially as the "Botsball", consisted of a small, black, cloth-covered copper globe containing a temperature sensitive element. The method of operation involved saturating the cloth layer with water and suspending the instrument in the test environment for a least five minutes.

A number of researchers have evaluated this instrument and their comments have been summarised by BESHIR (1981). The following advantages were claimed for the instrument:

- (a) simplicity of operation;
- (b) short equilibration time;
- (c) robust construction;
- (d) low cost;
- (e) WGT was found to correlate well with other heat stress indices, in particular the WBGT;
- (f) the WGT value was easily understood by plant management.

Beshir stated that the instrument had the following disadvantages however:

- (a) Poor correlation between WGT and physiological strain.
- (b) Oversensitive to air velocity changes.
- (c) Errors were introduced if the cloth covering was not adequately saturated.

GOLDMAN (1980) stressed the practical advantages of the instrument however, as a simple index of heat stress in military operations where rapid decisions were required. BESHIR *et al.* (1982) have also found WGT to be a practical measure of heat stress in industrial environments.

Despite its limitations as a predictor of physiological strain, WGT has been recommended by a NIOSH working group (DUKES-DOBOS and HENSCHER,

1980) for use in industrial conditions.

A1.3 Empirical Indices Based on Human Responses

A1.3.1 Effective temperature (ET)

The effective temperature scale was originally developed by Houghten and his colleagues at the research laboratory of the American Society of Heating and Ventilating Engineers with the cooperation of the US Bureau of Mines (HOUGHTEN and YAGLOGLOU, 1923). The scale was based on the subjective equivalence of thermal environments to reference conditions which were saturated (100% relative humidity).

In order to allow for the effects of clothing, two scales were eventually developed: the basic scale (BET) for men stripped to the waist (also referred to as the Effective Temperature (American) or ETA) and the normal scale (NET) for men wearing light industrial clothing. Index values were conveniently determined from nomograms based on dry bulb temperature, psychrometric wet bulb temperature and air velocity. SMITH (1952) has pointed out that the two scales were not equivalent in terms of warmth sensation.

In their original form, the scales did not satisfactorily take account of radiant heat load. Bedford suggested that this situation could be remedied by substituting globe temperature for dry bulb temperature on the nomograms. In this form the scales were known as Corrected Effective Temperatures (CET) and they were widely used in Britain. MacPHERSON (1960) believed this correction to be valid in physiological terms when the results of a number of studies were considered.

YAGLOU (1950) did not agree with Bedford's correction however, and proposed a new modification; the Effective Temperature including Radiation (ETR). Derivation of the index value involved a complex procedure which KERSLAKE (1972) believed to be unjustifiable given the lack of precision of the scale.

Further modifications to the scales were proposed by SMITH (1952) who showed that it was feasible to correct effective temperature to take account of work rate (metabolic rate). By re-analysing data from the MRC wartime experiments, he produced supplementary work rate nomograms for the basic and normal scales. These gave Modified Effective Temperature (MET) values and were valid within the range of conditions investigated by the MRC team (i.e. effective temperature $> 28^{\circ}\text{C}$).

Although the original scales were based on subjective assessments of environments, YAGLOU (formerly Yagloglou) (1927) stated that they could be used to predict physiological responses. However, a number of experimental studies have demonstrated the limitations of the scales in this respect. BENSON et al. (1945) claimed that effective temperature:

- (a) underemphasised the part played by still air (air speed $\sim 0.05 \text{ m sec}^{-1}$) in increasing environmental stress;
- (b) failed to indicate the deleterious effects of high air speeds;

- (c) overemphasised the contribution of dry bulb temperature as opposed to wet bulb temperature to the imposed heat load in severe hot-humid conditions.

The latter point was not substantiated however by later, more extensive investigations (MacPHERSON, 1960).

ELLIS *et al.* (1953) believed that effective temperature was of limited value in severe climatic conditions where there was a risk of collapse. This conclusion was supported by the findings of LIND and HELLON (1957) and of BREBNER, KERSLAKE and WADDEL (1958), which demonstrated the limited predictive ability of effective temperature in severe hot-humid climates.

YAGLOU (1949) however had previously claimed that "the real value of ET is in the warm and humid atmospheres". SMITH (1952) supported this view, stating that the effective temperature scale could be used with acceptable accuracy up to a level of 31°C.

A1.3.2 Température Effective Limite (TEL) or Belgian Effective Temperature

The acknowledged limitations of the effective temperature scale as a predictor of heat tolerance led BIDLOT and LEDENT (1947) to propose a formula for calculating an upper limit of heat load, the température effective limite (TEL):

$$TEL = 9.9 t_p + 0.1 t_a$$

where t_p = psychrometric wet bulb temperature (°C)

t_a = dry bulb temperature (°C)

Bidlot and Ledent considered that this formula could be used to limit mining work and proposed the following limits:

TEL < 34°C, Continuous mining work possible
TEL = 34-35°C, Continuous mining work difficult
TEL = 35-36°C, Continuous mining work impossible

The formula was subsequently adopted by the Belgian mining industry and a limit of TEL = 31°C instituted.

HOUBERECHTS *et al.* (1958) criticised the formula on the grounds that it did not take account of air velocity changes. These authors compared Bidlot and Ledent's formula with those derived from a heat balance analysis (Heat Stress Index, BELDING and HATCH, 1955). The wet and dry bulb weightings in these formulae were found to be a function of the air velocity and this led the authors to propose a new equation which allowed a limiting value to be calculated for a given air speed. These formulae were not formally adopted by the Belgian mining industry, however.

METZ (1967) stated that TEL was valid only within the restricted envelope of conditions found in Belgian coal mines. The index has also been found to be applicable to the conditions found in German salt and ore mines (SCHWARZ, 1977).

A1.3.3 Resultant temperature (Équivalences en Séjour)

MISSENDARD (1948) believed that the original effective temperature scale was inappropriate for use in steady state conditions and it was based on sensations reported immediately after transfer from one environment to another. He stated that the subjective equivalence of two environments could be defined in two ways:

- (a) "Équivalences de passage" - equivalence judged by a trained observer immediately after passing from one environment to another.
- (b) "Équivalences en séjour" - equivalence judged after remaining in the second environment for more than 30 minutes.

Missenard favoured the second approach and constructed two nomograms (for nude and clothed subjects respectively) for resultant temperature (équivalences en séjour (ES)) based on dry bulb temperature, psychrometric wet bulb temperature and air velocity. Although reasonably accurate descriptors of the thermal environment for a subject at rest, the ES nomograms have been seldom used in industry or in research, perhaps because of their similarity to the ET scales (KERSLAKE, 1972).

A1.3.4 Predicted Four Hour Sweat Rate (P4SR)

The predicted four hour sweat rate was an empirical scale developed as a result of wartime research at the National Hospital for Nervous Diseases (McARDLE et al., 1947). The scale was intended to replace the corrected effective temperature scale as a means for prescribing heat stress limits in shipboard compartments.

Previous experiments carried out by DUNHAM et al. (1946) showed that a subject's sweat rate gave a reliable indication of heat strain and the development of clinical symptoms. The P4SR scale was therefore based on the volume of sweat secreted by fit, acclimatized young men during a four hour period (the duration of watch in the Royal Navy).

The scale took the form of a complex nomogram, calculation of the P4SR taking place in three stages. The scale covered only the conditions used in the original series of experiments:

Dry bulb temperature	-	27 to 54°C
Wet bulb temperature	-	15 to 36°C
Air velocity	-	0.05 to 2.5 ms ⁻¹
Work rate	-	63 to 232 Wm ⁻²
Clothing assemblies	-	shorts, shorts and overalls

P4SR correlated well with rectal temperature, sweat loss and a clinical comfort-fitness index and was found to have greater predictive ability

than effective temperature in the test conditions (McARDLE et al., 1947). The physiological accuracy of the scale was subsequently confirmed by more extensive studies at the Royal Naval Tropical Research Unit, Singapore (MacPHERSON, 1960). These studies also showed P4SR to be valid in conditions where mean radiant temperature was greater than air temperature.

The scale was criticised by MacPHERSON (1960) on the grounds that it overestimated sweat loss in severe climatic conditions (P4SR 5 litres). KERSLAKE (1972) however argued that while the scale could not be used to predict actual sweat losses in severe conditions, it represented an integrative measure of thermal stress based on a number of physiological factors. It has been suggested that potential confusion could be avoided by expressing P4SR as a dimensionless index value (MacPHERSON, 1960).

A1.3.5 Index of Physiological Effect (Ep)

The index of physiological effect was developed by ROBINSON, TURRELL and GERKING (1945) as a means of expressing the climatic load on an individual in terms of his thermoregulatory responses. The index was derived from the results of extensive climate chamber investigations and was based on the combined responses of rectal temperature, pulse rate, skin temperature and sweat rate. These responses were weighted according to the following equation:

$$e = \frac{100}{(\theta_2 - \theta_1)} \cdot (\theta_3 - \theta_1)$$

where, e = effect of the environment on a given physiological response

θ_1 = subject's baseline value

θ_2 = subject's maximum level of response (in an environment tolerable for more than two hours)

θ_3 = subject's response to test environment

The overall Ep value was given by the sum of the individual 'e' components.

Robinson and his colleagues prepared charts indicating the severity of response to different combinations of dry and wet bulb temperatures for five levels of clothing and activity. Limiting Ep values at which body heat accumulation occurred were also indicated on the charts (Ep = 200 for working subjects, Ep = 300 for subjects at rest).

The basis of the index has been criticised by YAGLOU (1949), who stated that the simple additive model did not take account of the complex inter-relationships between the physiological responses. He argued that one component could reach a critical value without greatly changing the overall Ep value. A further criticism by Yaglou was that the index could not be used for unacclimatized men for whom it was difficult to

establish consistent physiological maxima.

The general applicability of E_p has been found to be limited by the fact that radiant heat and air velocity factors were not included in the charts (JONES, 1970; LEE, 1980).

A1.3.6 Wet Bulb Globe Temperature (WBGT)

YAGLOU and MINARD (1957) originally developed the wet bulb globe temperature for military use in conditions where there was a high radiant heat load. It was designed to replace the ETR scale in a heat casualty prevention programme at military training camps (MINARD, BELDING and KINGSTON, 1957).

The WBGT index value was calculated initially from the following equation, the coefficients having been derived for the olive drab clothing worn by military recruits:

$$\text{WBGT} = 0.7 t_p + 0.3 t_g$$

where, t_p = psychrometric wet bulb temperature

t_g = Vernon globe temperature

The index was subsequently revised, however, (MINARD and O'BRIEN, 1964) to give greater weighting to the effects of air velocity. Two equations were recommended for the determination of index values:

$$\text{WBGT} = 0.7 t_n + 0.2 t_g + 0.1 t_a \text{ (outdoor environments with solar radiant heat)}$$

$$\text{WBGT} = 0.7 t_n + 0.3 t_g \text{ (indoor environments)}$$

where, t_n = natural wet bulb temperature

t_g = Vernon globe temperature

t_a = dry bulb temperature

The major advantage claimed for the WBGT by its originators was its operational simplicity, both in terms of instrumentation and its ease of interpretation.

While the WBGT was successful in its original application (MINARD, BELDING and KINGSTON, 1957), the index has been criticised by several authors. MacPHERSON (1962) claimed that WBGT underestimated the climatic heat load in conditions where air temperature exceeded skin temperature and air speed was high.

RAMANTHAN and BELDING (1973) examined the relationship between WBGT and physiological strain in conditions similar to those found in industry. They found that the subjects' responses (heart rate, rectal temperature, skin temperature and sweat loss) were not independent of the combination

of climatic factors at a given level of WBGT and concluded that two WBGT scales were required (for hot-dry and hot-humid environments respectively).

More recently, PULKET et al. (1980) examined the predictive ability of WBGT in a hot-humid environment ($t_a = 36^\circ\text{C}$, $P_a = 4 \text{ kPa}$) and found that it was poor in comparison with other indices tested.

Despite its poor predictive ability WBGT has been used as the basis for several heat stress standards (HENSCHHEL, 1980).

A1.3.7 Swedish Wet Bulb Globe Temperature (SWBGT)

The use of the natural wet bulb thermometer in the determination of the WBGT value has been criticised by ERIKSSON et al. (1974) on the grounds that it required a 30 minute equilibration time and that it was difficult to keep the thermometer's wick clean. The psychrometric wet bulb thermometer was considered by these authors to be a more practical instrument in Swedish industrial conditions. They proposed revised formulae for the derivation of the index which was termed the Swedish wet bulb globe temperature:

$$\text{SWBGT} = 0.7 t_p + 0.3 t_g \text{ (air velocity } > 0.5 \text{ ms}^{-1}\text{)}$$

$$\text{SWBGT} = 0.7 t_p + 0.3 t_g + 2 \text{ (air velocity } < 0.5 \text{ ms}^{-1}\text{)}$$

where, t_p = psychrometric wet bulb temperature ($^\circ\text{C}$)

t_g = Vernon globe temperature ($^\circ\text{C}$)

ASTRAND et al. (1975) stated that a good correlation existed between SWBGT and WBGT and that the index values could be interpreted in the same way.

A1.3.8 Wet-Dry or Oxford Index (WD)

The wet-dry index was developed by LIND et al. (1957) as a means of comparing severe saturated and non-saturated environments approaching the limits of human tolerance. It was used as the basis for the permissible tolerance times for mines-rescue personnel using breathing apparatus in hot conditions. The index value was given by the following equation:

$$\text{WD} = 0.15 t_a + 0.85 t_p$$

where, t_a = dry bulb temperature ($^\circ\text{C}$)

t_p = psychrometric wet bulb temperature ($^\circ\text{C}$)

KERSLAKE (1972) stated that the index reconciled the results of several physiological investigations of heat tolerance with acceptable accuracy. KLEMM and HALL (1982), however, believed that WD was only valid in severe hot-humid conditions in which men were engaged in heavy, physical work.

A1.3.9 Equatorial Comfort Index or Singapore Index (ECI)

From the results of a comfort vote survey conducted in Singapore, WEBB (1959) developed an equation to derive a still air temperature which was subjectively equivalent to a given thermal environment. The range of this index (ECI) was extended by including the results of other investigations and a nomogram was prepared (based on dry bulb temperature, psychrometric wet bulb temperature and air velocity).

MacPHERSON (1962) believed that the index gave an accurate measure of environmental warmth in tropical conditions as it was based on the subjective assessment of an acclimatized population. The applicability of the index was limited, however, by the factor that it did not include a radiant heat component (BEDFORD, 1964).

A1.3.10 Resultant Temperature (Température Résultante Minière)

The concept of this resultant temperature was developed from a reappraisal of the effective temperature prime data based on heat exchange principles (MISSENARD, 1946). Resultant temperature was defined as the temperature of a still, saturated environment (air temperature being equal to wall temperature) which was thermally equivalent to a given environment.

This index has a special significance for the French mining industry, having been adopted as an official index of mine climate in the mining regulations (SEELEMANN, 1973). In this form, the index value was given by the following equation:

$$t_r = 0.7 t_p + 0.3 t_a - V$$

where, t_p = psychrometric wet bulb temperature (°C)

t_a = dry bulb temperature (°C)

V = air velocity (ms^{-1})

A1.4 Indices Based on Mathematical Analyses of Heat Exchange

A1.4.1 Operative temperature and its derivatives

(a) Operative temperature (T_o)

The concept of operative temperature developed from the work on partitioned calorimetry at the J.B. Pierce Foundation Laboratory, Yale (WINSLOW and HERRINGTON, 1949). It was intended to be an objective index of the physical heat stress on man and was independent of skin temperature and clothing insulation. The index was defined as the temperature of a uniform black enclosure in which man would exchange the same heat by radiation and convection as in the environment in question. Operative temperature was given by the following expression (KERSLAKE, 1972):

$$T_o = \frac{h_c t_a + h_r \bar{t}_r}{h + h}$$

where, t_a = ambient temperature ($^{\circ}\text{C}$)

$\bar{t}_r$ = mean radiant temperature ($^{\circ}\text{C}$)

h_c = coefficient for convective heat exchange
($\text{Wm}^{-2} \text{ }^{\circ}\text{C}^{-1}$)

h_r = coefficient for radiant heat exchange
($\text{Wm}^{-2} \text{ }^{\circ}\text{C}^{-1}$)

It has been shown, however, that operative temperature can be measured directly using a skin coloured Vernon globe thermometer (GAGGE et al., 1967).

As originally conceived, operative temperature did not take into account the effects of humidity and was a measure of dry (sensible) heat exchange only. This omission has limited the applicability of the index in practice (LEE, 1980).

The operative temperature concept has proved valuable, however, as a means of reducing the number of factors in more complex indices (VOGT et al., 1982).

(b) Standard operative temperature (T_{so})

The original concept of operative temperatures was subsequently extended to take account of changes in air movement (GAGGE et al., 1941). This modified index, known as the Standard Operative Temperature, was defined as the temperature of a black isothermal environment in which a man wearing standard clothing and exposed to standard air movement and barometric pressure would exchange the same heat by radiation and convection as he would with the same skin temperature in the actual environment (described by operative temperature). KERSLAKE (1972) gave the following updated expression for the determination of the index value:

$$T_{so} = \frac{h_o}{h_o^1} \cdot T - \frac{h_o}{h_o^1} \cdot T_s$$

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

T_s = mean skin temperature ($^{\circ}\text{C}$)

h_o = combined coefficient for convective and
radiant heat exchange in test environment
($\text{Wm}^{-2} \text{ }^{\circ}\text{C}^{-1}$)

h_o^1 = combined coefficient for convective and
radiant heat exchange in reference
environment ($\text{Wm}^{-2} \text{ }^{\circ}\text{C}^{-1}$)

Although standard operative temperature was an important development in that a given environment could be related to a standard environment, humidity was still neglected.

KERSLAKE (1972) criticised the index on the grounds that it was not independent of physiological changes, being a function of the subject's mean skin temperature.

(c) Humid operative temperature (T_{oh})

Humid operative temperature was developed by NISHI and GAGGE (1971) as a biophysical index of the strain caused by the physical environment on the regulatory sweating system. It was defined as the temperature on an imaginary, uniform, black saturated enclosure in which a man exchanged the same total heat (sensible and insensible) from the skin surface at the mean skin temperature and wettedness levels observed in the actual environment.

Although the index value was originally determined by the iterative solution of a complex mathematical expression, GAGGE (1981) recommended the use of a graphical method. In practice, humid operative temperature values have been found to be numerically similar to those given by the effective temperature scale (GAGGE, 1981).

(d) The new effective temperature scale (ET^*)

GAGGE et al. (1971) believed that an index based on a saturated reference environment (T_{oh}), gave numerical values which did not accord with the common experience of people living in North America and European climates. An index based on reference conditions with 50% relative humidity was thought to be a more useful approach.

A new index was developed and was described as an effective temperature scale (ET^*) even though it had no connection with the original scales developed by HOUGHTEN and YAGLOGLOU (1923). This index had a similar definition to that of humid operative temperature with the exception that the imaginary isothermal environment had a relative humidity of 50%. As with T_{oh} , ET^* could be determined either by solving a complex mathematical expression or by a graphical method (GAGGE et al., 1971).

A standard version of the new effective temperature scale (SET) was also developed so that a wide variety of climate, clothing and work rate conditions could be related to a standard reference condition. A chart was also developed to simplify the determination and interpretation of SET values sensation with acceptable accuracy over a wide range of climates (GAGGE et al., 1972).

GONZALES et al. (1978) examined the relationship between subjective discomfort and ET^* during exercise in a wide range of climates. A good correlation ($r = 0.92$) was found between "warm discomfort" and ET^* during exercise.

A NIOSH working party (DUKES-DOBOS and HENSCHER, 1980) while

acknowledging the physiological accuracy of the index, considered it too complex for industrial use.

A1.4.2 Thermal acceptance ratio (TAR)

The thermal acceptance ratio (IONNIDES, PLUMMER and SIPLE, 1945) represented a new approach to the assessment of thermal load. It was defined as the ratio of the maximum heat load that could be safely tolerated to the actual load imposed by climate and physical activity. This ratio was estimated from the following expression:

$$\text{TAR} = \frac{H_a'''}{M - L} = \frac{E \pm C \pm R}{0.75 M}$$

where, H_a = the heat acceptance of the atmosphere, i.e. the quantity of heat which a given atmosphere could remove from a nude man if his skin temperature was maintained at a safe level of 36°C (97°F)

M = metabolic rate sustained by an acclimatized man

L = heat loss from the lungs, assumed to be 0.25 M^*

E = evaporative loss from wet skin at 36°C, with an assumed upper limit of 581 Wm^{-2}

C = convective heat loss

R = radiant heat loss

* The assumed level of L would appear to be rather high. KERSLAKE (1972) has estimated that respiratory heat loss does not exceed 0.1 M .

The index appears to have been seldom used despite the good correlations obtained between TAR and the physiological responses to physical work in hot conditions (YAGLOU, 1949).

YAGLOU (1949) criticised the index on the basis that it could not be used in cold conditions or where subjects were clothed. He also doubted the validity of the assumption that skin temperature was a limiting factor in heat tolerance.

A1.4.3 Heat stress index (HSI)

The heat stress index was developed by BELDING and HATCH (1955). An engineering approach was used in the construction of the index with the aim of making it practicable for industrial use.

The index was based on the ratio of the rate of evaporation of sweat required to maintain heat balance (E_{req}) to the maximum evaporative capacity of the environment (E_{max}). The index value was given by the following expression:

$$\text{HSI} = \frac{E_{\text{req}}}{E_{\text{max}}} \times 100$$

An HSI value of 100 (i.e. when $E_{\text{req}} = E_{\text{max}}$) was defined as the upper limit of heat stress which could be tolerated by a healthy, young, acclimatized man for a period of 8 hours. It was claimed that this level of heat stress would result in a sweat loss of 1 litre hr^{-1} .

When E_{max} was in excess of 380 Wm^{-2} (capacity required to evaporate a sweat loss of 1 litre hr^{-1}), the index value was given by the following expression:

$$\text{HSI} = \frac{E_{\text{req}}}{380} \times 100$$

In order to simplify calculation, BELDING and HATCH (1955) devised a nomogram for the determination of HSI based on climate and work rate variables. They also gave a table of index values with corresponding physiological interpretations.

In their attempts to make the index practicable for industrial use, several simplifying assumptions were made by the authors and these have attracted some comment. LEITHEAD and LIND (1964) believed that the assumed skin temperature of 35°C and body surface area of 1.8 m^2 and the absence of respiratory heat exchange and body heat storage terms, restricted the general applicability of the index. The assumed skin temperature of 35°C was also criticised by PETERSON (1970) who stated that the predictive ability of the index could be considerably improved by using the observed skin temperature in the determination of E_{req} .

Although an industrial evaluation of HSI in non-ferrous foundries (TURNER, 1958) showed a close relationship between predicted and observed sweat losses, a later study by BELDING *et al* (1960) showed that the index overestimated physiological strain in clothed subjects. This latter finding pointed to an error in the construction of HSI; the heat exchange coefficients were taken from the results of experiments on nude subjects. Coefficients modified to take account of the effects of clothing were subsequently proposed by HERTIG and BELDING (1963). Hatch (1963) proposed additional changes to the heat exchange equations and these were incorporated together with those of Hertig and Belding in revised nomograms prepared by McKARNS and BRIEF (1966) and by KERSLAKE (1972). Further changes in the coefficients were proposed as a result of experimental work by BELDING and KAMON (1973) and these have been incorporated in revised equations for the calculation of HSI (BELDING, 1973). An alternative approach to dealing with clothing effects was proposed by LUSTINEC (1965) who derived HSI equations for a variety of clothing assemblies.

FOX (1965) criticised the index on the grounds that it did not bear any simple relationship to physiological strain. He stated that physiological responses were not independent of the combination of climatic factors at a given level of HSI. This anomaly was subsequently acknowledged by BELDING (1970).

Despite its shortcomings in the prediction of strain, the heat balance approach of the HSI has proved valuable in resolving industrial heat stress problems as it involves an evaluation of the various components, (LEITHEAD and LIND, 1964; HUMPHREYS, 1971; KERSLAKE, 1972). This "engineering approach" to the problem of heat stress also inspired the development of other thermal indices (LEE, 1980).

A1.4.4 Relative heat strain (RHS)

LEE and HENSCHER (1965) were in agreement with the basic principles adopted in the formulation of HSI, but criticised the index on the grounds that no allowance was made for the effects of clothing on heat exchange. They proposed a new index of relative heat strain (RHS), based on the HSI but including clothing factors.

In its original form, the RHS index value was determined from a complex mathematical expression but this was later simplified so that RHS became a function of dry bulb temperature and the partial pressure of water vapour in the air. This enabled RHS isotherms for a set of standard conditions to be plotted on the psychrometric chart. RHS values for other conditions could be obtained by modifying the dry bulb temperature to take account of differences in clothing, activity level, air velocity and radiant heat load, before entering the chart (for details see LEE, 1980).

The authors suggested that RHS values could be interpreted in terms of six criteria: discomfort, distress, failure, performance and tolerance. These criteria were broadly defined in the original paper (LEE and HENSCHER, 1965) and it was intended that they would be updated as further information came to light. One interesting feature of this approach was that the criteria could be modified to take account of the effects of age, obesity, sex and health status on heat tolerance (HENSCHER, 1971).

Although an accurate predictor of physiological strain in hot and humid conditions (PULKET *et al.*, 1980), RHS does not appear to have supplanted HSI in either industry or research.

A1.4.5 Index of thermal stress (ITS)

GIVONI (1963) devised the index of thermal stress as a biophysical model of heat exchange from which the total heat load on the body could be determined. ITS was based on the assumption that within the range of climates where heat balance was possible, sweat was secreted at a sufficient rate to achieve the evaporative cooling required to balance the environmental and metabolic heat loads. The relationship between sweat secretion and evaporative clothing was shown by Givoni to be a function of the cooling efficiency which in turn was dependent on wettedness (E_{req}/E_{max}), i.e. at high levels of wettedness, not all the sweat secreted was effective in cooling the body.

ITS was similar to HSI in structure, with the exception that it included a sweating efficiency term. The index value represented the sweat rate (gh^{-1}) required to achieve thermal equilibrium and was given by the

following expression (KERSLAKE, 1972):

$$ITS = \frac{E_{req}}{0.37 \lambda_{sc}}$$

where, E_{req} = evaporation rate required to balance the metabolic and environmental heat loss (Wm^{-2})

λ_{sc} = sweating efficiency for a clothed subject; a function of E_{req}/E_{max} (dimensionless)

Although the ITS heat exchange equations were based on a fixed skin temperature of 35°C, the errors introduced by this assumption were minimised by fitting the coefficients to experimental data (KERSLAKE, 1972). The index has proved an accurate predictor of sweat loss over a wide range of experimental conditions (GIVONI and BERNER-NIR, 1967). GIVONI (1969) stated, however, that ITS was valid only for conditions in which heat balance was possible, in thermally comfortable to severe climates (wettedness ~ 2.2).

The index has been criticised by LEE (1980) on the grounds of its operational complexity. VOGT *et al.* (1981) however, believed that this disadvantage was more than compensated for by comprehensive nature and physiological accuracy of ITS.

A1.4.6 Required sweat rate (S_r)

The original concept of required sweat rate was devised by Vogt and Metz and was defined as the sweat rate required in order to maintain heat balance in a given thermal environment (METZ, 1967). The index was intended for industrial use and was similar in principle to the ITS.

In its original form, the index value was determined from a complex nomogram (VOGT and METZ, 1967), similar in layout to the HSI nomogram enabled safe exposure times to be calculated in addition to the index value. METZ (1967) claimed that the nomogram though complex, represented a flexible approach to the assessment of heat load in that potential solutions to environmental problems could be evaluated.

The index has recently been revised by VOGT *et al.* (1981). The basic structure remained unchanged but improved heat exchange coefficients were incorporated. In this revised form, S_r was obtained from a series of equations and the nomogram was replaced by a computer program. As in other heat balance indices, the wettedness exceeded unity, the environment was deemed to be unsafe as the required evaporation could not be realised. Safe exposure times were then computed from the rate of body heat storage (equivalent to the difference between E_{req} and E_{max}) so that body temperature would not increase by more than 1.2°C.

Where wettedness was less than unity, the required sweat rate, S_r was determined from the following equation:

$$S = E_{\text{req}} / \eta \lambda$$

where, S = required sweat rate ($\text{gm}^{-2} \text{s}^{-1}$)

E_{req} = rate of evaporation required to maintain heat balance (Wm^{-2})

η = efficiency of sweating (dimensionless)

λ = latent heat of vaporisation of water (J g^{-1})

S_r , as defined above, took account of both evaporated and unevaporated sweat and was interpreted by comparison with the maximum physiological sweat rate, S_p (dependent on the subject's acclimatisation status). Where S_r was in excess of S_p , safe exposure times were derived from the difference ($S_r - S_p$). In less severe conditions, S_r was compared with a thermal comfort criterion (FANGER, 1970).

An important feature of the revised index was that it took into account the effects of clothing; the thermal efficiency factor and permeation efficiency were included in the heat exchange equations.

The predictive ability of S_r has been examined in industrial conditions (VOGT *et al.*, 1981). Calculated S_r values were compared with observed sweat losses in potash miners working in hot-dry climates ($t_a = 24-46^\circ\text{C}$, $t_r = 26-48^\circ\text{C}$, $t_p = 19-31^\circ\text{C}$, $V = 0.1-4.2 \text{ ms}^{-1}$). Highly significant correlations were obtained between observed sweat losses (shift and work period averages) and calculated S_r values. It was concluded that the index could be used with acceptable accuracy in industry, though it slightly underestimated actual sweat losses when calculated on an hourly basis. The index has not yet been evaluated in other industries but this work is in hand as part of an ECSC programme on thermal environments.

A1.4.7 Specific cooling power (SCP) and air cooling power (ACP)

The specific cooling power was developed by MITCHELL and WHILLIER (1972) for use by ventilation engineers in the South African gold mines. The concept of SCP resulted from a mathematical analysis of heat exchange, using an approach similar to that of the HSI. The latter index had been rejected as an index of gold mine climate as it was felt that the heat transfer coefficients were inappropriate for South African conditions (WYNDHAM, 1974).

Derivation of the SCP involved determination of the components E_{req} and E_{max} , but these were treated in a different manner from the HSI. MITCHELL and WHILLIER (1972) argued that the ratio, $E_{\text{req}}/E_{\text{max}}$ had no physiological meaning and that it was the difference between the two components which determined the heat load. This difference, claimed to represent the degree of disturbance to thermal equilibrium, was used as the basis for SCP.

In the formulation of SCP, a quantity known as the maximum cooling power (Q_{max}) was initially defined. This represented the difference between metabolic heat production and the rate of heat transfer to the environment and was given by the following expression:

$$Q_{max} = - (R + C + E_{max})$$

where, Q_{max} = maximum cooling power (Wm^{-2})

R = radiant heat flux (Wm^{-2})

C = convective heat flux (Wm^{-2})

E_{max} = maximum evaporative capacity (Wm^{-2})

The heat transfer equations for Q_{max} had previously been derived for acclimatised subjects working in simulated mine climates. By simplifying these equations and assuming a constant skin temperature of 35°C, MITCHELL and WHILLIER (1972) derived a more practical index, the specific cooling power.

SCP was later found to be a function of psychrometric wet bulb temperature and air velocity, within the envelope of gold mine climates and this led to the development of a nomogram from which index values could be determined for specified work rates.

MITCHELL (1973) stated that SCP overestimated heat transfer in severe climatic conditions where skin temperature was in excess of 35°C. He proposed that a predicted equilibrium skin temperature (PEST) could be used in these conditions, this being derived from the component functions of Q_{max} . PEST was also found to be a function of wet bulb temperature and air velocity and a nomogram was prepared for this index.

SCP and PEST were subsequently evaluated in hot underground workplaces in the gold mines (MITCHELL, 1973) where manual work output was found to be significantly correlated ($r = 0.84$ $p < 0.001$) with SCP. PEST, however, was found to overestimate skin temperatures and this was attributed to errors in the estimation of metabolic heat production by the observers.

There have been few published studies of the predictive ability of the two indices. WYNDHAM (1974) found that although both indices predicted fourth hour rectal temperature with acceptable accuracy, the modified effective temperature was superior in this respect.

Further studies within the gold mining industry showed that SCP underestimated the cooling power of the air, particularly at low air speeds (STEWART and WYNDHAM, 1975). This led to several modifications to the SCP equations, including an increase of the fixed mean skin temperature to 36°C. STEWART and Van RENSBURG (1977) showed, however, that considerable errors were introduced by assuming a fixed skin temperature and proposed a new version of the cooling power, the mine cooling power (MCP), based on a variable equilibrium skin temperature.

Although interest has been shown in these indices in other mining industries (e.g. MacPHERSON, 1974), they do not appear to have been used outside South Africa. WELLER (1981) did however derive a nomogram version of the maximum cooling power for use in a potash mine which he described as the air cooling pressure. As with the specific cooling power, this utilises psychrometric wet bulb and air velocity entered into the nomogram to obtain an air cooling power value. The nomogram is, in the author's own admission, limited as it is based on skin temperature measurements of one individual. Although the nomogram is commendably effective in comparison with direct calculations of the maximum cooling power, no studies have been carried out to examine the effectiveness of the index in predicting physiological strain and it does not appear to have been adopted for use in the mine for which it was developed.

A1.4.8 Q_S Index

The Q_S index was developed by RUBLACK *et al.* (1981) and was based on the well established heat balance principle. It was defined as a global heat stress index and represented "the algebraic sum of sensible heat fluxes":

$$Q_S = M + C + R$$

where, Q_S = index value (Wm^{-2})

M = metabolic heat production (Wm^{-2})

C = convective heat flux (Wm^{-2})

R = radiant heat flux (Wm^{-2})

By definition, positive Q_S values indicated the evaporative heat loss required to maintain heat balance whereas negative values indicated the required additional heat gain (whether by increased metabolism or by reduced convective and radiant heat flux).

to facilitate estimation of Q_S in industrial conditions, RUBLACK *et al.* (1981) developed an instrument (based on a miniature analogue computer) which integrated direct readings of dry bulb temperature, humidity, radiant heat flux and air velocity. Appropriate values for metabolic heat production, clothing insulation and skin temperature were entered by the operator in order to obtain the Q value.

The predictive ability of Q_S has been tested in an extensive series of climate chamber experiments (RUBLACK *et al.*, 1981) where good correlations were obtained with sweat rate ($r = 0.93$), heart rate ($r = 0.76$) and increase in body temperature ($r = 0.63$).

An earlier version of Q_S , the " Q_{TR} " has recently been examined by GOEDECKE and PÜHLFURST (1983) in simulated hot-dry mining conditions (found in deep potash and salt mines). The index was found to give accurate predictions of sweat loss over a wide range of ambient

temperatures. They concluded that the index would be suitable for use in hot-dry mines if it were simplified by assuming fixed values for the heat exchange coefficients.

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