A review of local and international heat stress indices, standards and limits with reference to ultra-deep mining

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Synopsis

Mining up to depths of 5 000 m would be a world first and, accordingly, no previous experience in the determination of acceptable heat stress limits, criteria or indices is wholly applicable. However, some South African gold mines are already operating at depths beyond 3000 m and much of the knowledge gained in reaching and working at such depths will be helpful in making adequate provision for acceptable environmental control at the greater depths being contemplated. Accordingly, it is necessary to take cognisance of the industry's experience in deep-level mining and of standards and regulations already established in South Africa and elsewhere in order to ensure acceptable working conditions and control standards, that compare favourably and defensibly with those in other mining industries.

The local and international use of heat stress limits, criteria and indices were investigated as it was necessary to determine to what extent any other indices, limits or criteria would be applicable to South African deep mine conditions. In addition, it was necessary to establish whether there was a single heat stress index that could be used for South African ultra deep mining conditions.

It was found that an appropriate combination of heat stress indices would be required in planning for and ultimately controlling thermal conditions in ultra-deep mining. The depths being contemplated and the concomitant potential heat hazard present too great a risk for reliance on a single environmental component of heat stress, such as wet-bulb temperature at present in common use locally. The study recommends that a heat stress index, preferably Air Cooling Power (ACP), be used to design an ultra deep mine's ventilation system and that wet-bulb temperature be used to monitor and control the system once it is implemented.

Introduction

In order to plan effectively for ultra-deep mining (UDM) projects, a number of issues must be addressed, not the least of which is the provision of workplace environmental conditions that are conducive to safe and productive mining operations. Although many aspects of an ultra-deep mining environment would be much the same as those already prevailing in deep-level gold mines, the variations in barometric pressure to which workers are exposed would increase by virtue of increased depth. Of even greater concern are the anticipated engineering requirements to contend with a tendency towards higher workplace temperatures, which will result from the auto-compression of air and higher virgin rock temperatures at greater depth and will be complicated by longer delivery routes for cooling media and ventilation air.

The costs of providing acceptable thermal conditions will be crucial for assessing the viability of ultra-deep mining, and will ultimately prove to be a major determinant in the decision on whether or not to proceed with such projects. It is, therefore, essential to determine what conditions can be regarded as acceptable, as well as the criteria and limits that should be adopted in assessing them. The important issues are clearly worker health, safety and productivity and, accordingly, an evaluation of local and international thermal standards is essential. This will satisfy the need for soundly based standards, criteria and limits for ultra-deep mining that are aligned with established norms, in order to ensure that UDM projects yield the required results without undue risk to workers, or the perception of such risks among workers, regulatory authorities or potential investors.

A detailed review of the literature and other sources of information relating to standards and regulations and certain environmental limits, and of various heat stress indices and their use (both locally and in other countries) were investigated. This investigation was done to establish what heat stress indices do exist locally and internationally and which would be most applicable to the UDM environment. In establishing this, a comparison was done to find out what standards and limits relating to these identified heat stress indices were used in

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other countries. The paper therefore offers some guidelines for the use of heat stress indices, standards and limits as would be applicable for UDM.

Background to the investigation

Thermal conditions and the heat stress imposed on workers will be the most significant environmental consequences of mining at ultra-deep levels, indicating a need to quantify the effects of heat on workers' health and their work performance. This represents a difference in purpose from the traditional concern with heat stress. The principal motivation in efforts to evaluate and control heat in the workplace has been to minimize its detrimental health effects on workers. This has resulted in the development of standards; heat stress indices and exposure limits based more on physiological tolerance and health considerations than on work performance criteria. Given the critical impact that performance and resultant productivity will have on the success or failure of ultra-deep mining, worker performance criteria should form part of the fundamental basis for determining the thermal standards and exposure limits to be applied.

Furthermore, given the crucial balance between the costs and potential returns of ultra-deep mining, ensuring its viability would appear to require the inclusion of worker performance criteria in assessments of hot workplaces, rather than basing such assessments solely on physiological tolerance, as is presently the case. It is equally important to create investor confidence in ultra-deep mining projects, not only in terms of viability, but also in terms of minimizing future compensation claims and litigation. Accordingly, it is important to ensure, as far as is practicable and advantageous, that environmental standards for ultra-deep mining are aligned with international norms and practice.

In the past, a number of heat stress indices have been devised in attempts to combine various thermal-related characteristics of the environment into a single number indicative of the heat stress imposed on workers. Although such a number can provide some measure of environmental heat stress, there are many and varied criteria for evaluating the acceptability of thermal conditions for safe work (Schutte *et al.*[1]).

Aim of heat stress indices

Heat stress is the aggregate of environmental and physical work factors that constitute the total heat load imposed on the human body. A heat stress index is a composite measure used for the quantitative assessment of heat stress. It is aimed at integrating into a single number the components of the thermal environment and/or the physical and personal factors that influence heat transfer between the person and the environment. Unfortunately, an index that integrates all these parameters and hence correlates them precisely to one or more physiological responses had not yet been developed (Ramsey and Beshir[22]). However, there are several indices for measuring heat stress, each with special advantages that make it more suitable for use in a particular environment.

The common aim of all heat stress indices is therefore to relate man's physiological and other responses to environmentally imposed thermal stress, in order to enable it to be assessed, predicted or controlled. As a result of differences in their treatment of various environmental parameters, commonly used indices tend to vary somewhat in their assessments of a given environment. In addition, continuous personal monitoring to assess workers' responses to heat exposure in the workplace is unpractical. It is nevertheless essential to accommodate personal factors and physical characteristics that could potential affect an individual's ability to work in heat. Emphasis should, therefore, be placed on comprehensive screening mechanisms, such as risk-based medical examinations and heat tolerance screening, to determine overall fitness for work in heat. The heat stress management procedures used in the South African mining industry is a prime example of such an approach.

The above temperature ranges from DME's South African Mines Occupational Hygiene Programme (SAMOHP) handbook and DME's Guideline for the compilation of a mandatory code of practice for an occupational health programme (Occupational Hygiene and Medical Surveillance) on thermal stress. NB: No temperature limits in Regulations.

Classification of heat stress indices

Heat stress indices can be classified into three types according to their basis, namely single measurement, empirical and rational indices. In order to quantify the three types of indices, it must be noted that no single psychrometric parameter can, by itself, provide a reliable prediction of workers' physiological responses, unless other psychrometric factors are confined to a relatively narrow range of values, as is the case in South African mines. In hot and

Table I

References for SA 'limits'

Category	Temperature range	Interpretation	General action
A: Abnormally hot	WB≥ 32.5°C or DB ≥ 37.0°C or Globe temperature ≥ 37.0 °C	Unacceptable risk of heat disorders	Work may be undertaken only on a basis of expert risk assessment, supervision and protocols
B	29.0 ≥WB≤ 32.5°C and DB ≥ 37.0°C Globe temperature: as for DB	Potentially conducive to heat disorders	HSM mandatory
C	27.5 ≥WB≤ 29.0°C and DB ≤37.0°C Globe temperature: as for DB	Potentially conducive to heat disorders	HSM mandatory
D	WB ≤27.5°C and DB ≤32.5°C Globe temperature: as for DB	Risk of heat disorders negligible	No special precautions. Environmental monitoring must be sufficiently sensitive to detect critical upward drifts in the environmental heat load. The monitoring programme to satisfy this requirement should be specified

humid environments (as anticipated in ultra-deep mining) where the predominant mode of heat transfer is evaporation, the wet-bulb temperature of the ambient air is the most influential variable affecting body cooling.

Heat stress indices

A historical overview

During the 1930s and 1940s, a number of attempts were made within the context of the workplace to investigate the effects of heat stress on the productivity of mineworkers, none of which withstood criticism. The first genuinely scientific studies on the effects of heat stress on human performance were those conducted by Mackworth at the Medical Research Council (MRC), Applied Psychology unit in Cambridge, followed by the work of Pepler at the MRC's Tropical Research unit in Singapore. The common conclusion of these two researchers was that human performance, irrespective of the complexity of the task or the skill and motivation of the individual, diminishes significantly at an effective temperature (ET) between 27°C and 30°C (Wyndham[3]).

Perhaps the most significant contributions to knowledge of human responses to heat stress, particularly within the context of mining, were made by the South African mining industry through the Chamber of Mines Research Organisation and its predecessor, the Rand Mines Research Laboratories. At the Crown Mines research facility, variously named the Human Sciences Laboratory, Applied Physiology Laboratory and the Industrial Hygiene Laboratory, a number of definitive studies were conducted over a 40-year period, which investigated and quantified human responses to heat and work stress. These results enabled the development of various selection and protection procedures, including climatic room acclimatization (CRA), heat tolerance testing (HTT) and heat tolerance screening (HTS), as well as the determination of safe thermal and work rate limits for mineworkers.

Notable among the many outcomes of research in the South African mining industry since it first identified heat stress as a problem are:

- Rational methods for assessing heat stress based on thermal transfer
- Definitive thermal transfer equations
- Heat stress limits for mineworkers based on physiological tolerance
- Worker selection and protection procedures, including (CRA), HTT and HTS.

It was demonstrated that heat stress and its limits could be quantified in terms of the environment's cooling power. This is possible, provided values for mean skin temperature and sweat rate (upon which cooling power depend) are linked to a safe upper limit for body temperature (Stewart and Whillier[4]).

From the perspective of international standards the main objectives in reviewing the literature and the thermal standards applied in other countries were to:

- Provide background information to be used in selecting appropriate criteria on which to base thermal limits for UDM workplaces
- Ensure the alignment (to an appropriate extent) of selected criteria with limits established elsewhere specifically where hot underground conditions occur
- Enable evaluation of the validity of standards and limits, both local and international, by determining the bases on which they were established.

Inasmuch as environmental heat stress is ultimately determined by environmental cooling power, it was important to determine the limits for face air velocities in various mining industries and how these were established.

An international comparison

The purpose of the investigation was to establish what heat stress indices do exist nationally and internationally and to what extent some of them would be applicable to ultra-deep-level mining. It was also important to try to derive from these indices a single index that would be applicable for South African conditions. In addition it was necessary to establish whether there was an index used internationally that could be applied to the South African mining environment and that had not been used in the South African mining environment before.

Numerous national and international standards have been produced to provide uniform means of specifying and assessing thermal comfort or heat stress. As a result of renewed concern regarding workplace environments, there has been increased activity in this area, although mainly with regard to offices and factories. Thermal comfort standards and their associated heat stress indices define conditions for thermal comfort and, accordingly, can be used to determine the likely degree of discomfort or stress imposed on the occupants of a given environment. Some standards for heat stress attempt to specify conditions conducive to health, as well as to comfort and work performance. Standards can also offer guidance in the design of environmental control systems, as they provide uniform bases and methods for evaluating critical parameters, thus enabling meaningful and quantitative assessments to be made for existing conditions and those resulting from engineering interventions.

Recognized national and international institutions that have produced such standards or guidelines include (Parsons[2]):

- The American Conference of Governmental Industrial Hygienists (ACGIH)
- The American Industrial Hygiene Association (AIHA)
- The American Society for Heating, Refrigerating and Air Conditioning Engineers (ASHRAE)
- The Chartered Institute of Building Services Engineers (CIBSE) in the UK
- European Standardization under the CEN
- The Hardcoal Industry of the Federal Republic of Germany
- The International Labour Organisation (ILO)
- The International Standards Organisation (ISO)
- The Occupational Safety and Health Administration (OSHA) in the USA
- The Standards Advisory Committee on Heat Stress (SACHS)
- The World Health Organisation (WHO)
- The National Institute for Occupational Safety and Health (NIOSH) in the USA
- Various national standards bodies and institutes.

Comparison of relevant heat stress indices

In the course of the investigation more than 20 different indices used internationally were identified, but not all of them are applicable to the South African mining environment, especially considering the expected environmental conditions for UDM. A heat stress index that is going to be used for a specific environment, should satisfy the following criteria before being considered as a standard for industrial use:

- Be applicable to and accurate within the range of conditions for which it will be used
- Take cognisance of all relevant parameters of heat stress
- Be applicable through simple measurements and calculations
- Apply valid weighting to all factors considered, in direct relation to their contribution to total physiological strain
- Provide an appropriate and practical basis for designing regulatory standards.

In addition to meeting these criteria, any index considered must incorporate, directly or indirectly, the 20 or more factors that contribute to heat strain, preferably in the form of a numerical scale. The criteria stated by the National Institute for Occupational Safety and Health (NIOSH) emphasize the requirement that measurements and calculations must be simple and predictive of workers' physiological strain. The wet-bulb globe temperature (WBGT) meets the requirement for simple measurements and calculations, as well as those listed above.

For hot industrial situations, the requirement is to choose a heat stress index that most accurately indicates the overall stress imposed on workers reliably and validly, while being relatively easy to use and requiring minimal expenditure for manpower and instrumentation. When all of these factors are considered and appropriately weighted, the best index for a hot, humid environment is not necessarily that having the highest multiple correlation coefficients with overall physiological strain (Pulket *et al.*[5]).

The mining industry's experience has been that work in hot, humid conditions results in greater physiological strain than work in hot, dry conditions, due to limitations on evaporative cooling. The use of separate heat stress standards for hot, dry and for hot, humid conditions may be useful in controlling heat stress and strain, with a similar approach for different workloads. This would indicate that distinctions based on environmental conditions and workload must be defined in practical terms, to facilitate the valid application of heat stress indices, with exposure limits defined and indicated on the relevant psychrometric charts.

Result of comparison of heat stress indices

In considering various heat stress indices, it would appear that for South African conditions, and specifically for ultra-deep mining, six indices bear relevance. Those most applicable are: the WBGT, the wet globe temperature (WGT), both being empirical indices, air cooling power (ACP) and specific cooling power (SCP), rational indices, and wet-bulb temperature and wet-kata indices (direct measurement).

Empirical and direct measured indices

Mines are generally designed to provide a specified workplace air temperature, determined in accordance with criteria that relate to worker health, safety, productivity and comfort, legal and regulatory requirements, as well as engineering constraints which invariably entail financial considerations. The provision of appropriate refrigeration capacity, which will be an essential aspect of environmental control in ultra-deep mining, will depend greatly on the design temperature and also have a critical impact on costs. Janse van Rensburg[6] has indicated that formal controls in the form of a structured heat stress management (HSM) programme are required where the wet-bulb temperature (T_{wb}) reaches 27.5°C. Furthermore, it has been recommended that routine work should not be permitted where T_{wb} exceeds 32.5°C or the dry-bulb temperature (T_{db}) exceeds 37°C (COMRO[7]). The ideal situation, therefore, would be to design for and achieve workplace wet-bulb temperatures at least as low as 27.4°C and dry-bulb temperatures not greater than 37.0°C. This would minimize the risk of heat illnesses and enhance labour force productivity, without reliance on formal and costly HSM programmes. Such an approach would effectively amount to eliminating the hazard, rather than expending resources to contend with it.

However, the cost of pursuing the ideal situation described above can be prohibitive in the case of deep mines, and may be particularly so in the case of an ultra-deep mine. Accordingly, it is essential to critically evaluate proposed design temperatures for ultra-deep mines, in order to balance the requirements of 'thermal well-being' (and all that the term implies) with the financial viability of ultra-deep mining (Janse van Rensburg[6]).

All of these provide an accurate indication of heat stress for typical underground gold mining environments. The empirical as well as direct measured heat stress indices are compared by means of an example constructed from a specific set of underground conditions as indicated in Table II.

The assessment results in Table I indicate the level of heat stress for the given set of environmental conditions, which are then characterized in Table III.

The comparison shows that for a certain set of conditions underground one may find that the acceptability of choosing

Table II

Underground thermal conditions for comparison of empirical and direct measured heat stress indices

Measured input parameter	Value (as indicated)
Wet-bulb temperature (T_{wb})	29.0°C
Dry-bulb temperature (T_{db})	36.0°C
Natural wet-bulb temperature (T_{nwb})	30.0°C
Globe temperature (T_g)	40.0°C
Botsball or wet-globe reading (WGT)	31.8°C
Wet-kata (K)	9
Wet-bulb globe temperature (WBGT), no radiant heat load	$0.7\ T_{nwb} + 0.3\ T_g$ or 1.044 (WGT)—(0.187) = 33.0°C
Metabolic heat load for light work rate	100 W (assumed)
Air velocity	0.25 m/s
Barometric pressure	87.1 kPa

Table III

Characterization of given thermal environment based on results from four heat stress indices (empirical and direct measures)

Heat stress index	Result	Characterization of conditions
T_{wb}	29.0°C	Only acceptable with formal heat stress management (1.6°C higher than non-heat stress management (HSM) limit of 27.4°C)
Wet-kata	9	Distinctly oppressive environment, with normal body temperature maintained only through profuse sweating. Skin is flushed and wet; pulse rate is high
WGT	31.8°C	Unacceptable conditions
WBGT	33.0°C	Unacceptable conditions in terms of minutes of work permitted per hour of exposure

a specific heat stress index will change according to specific guidelines for that index. In the example quoted it is obvious that if the WBGT and/or WGT indices were used, it would indicate that conditions would be unacceptable for mining. In the case of the WBGT index, work could be permitted in terms of minutes work per hour of exposure. The wet-bulb temperature shows an indication for acceptable working conditions only if formal heat stress management is in place. The wet-kata based on the set conditions as stated in Table I would indicate an oppressive environment.

In the above example it would be advised to consider at least two heat stress indices to highlight certain problem areas, such as a too low air velocity available (wet-kata) or to introduce formal HSM to comply to acceptable working conditions (T_{wb}).

Rational heat stress indices

When using rational indices such as ACP or SCP, the effect of clothing (unclothed, heavy or light clothing and its fabric or material) becomes pertinent, due to its insulating effect on heat transfer and the resultant body temperature. This and other information necessary for applying rational indices is normally derived from purpose-designed nomograms. In defining the ACP and SCP, there is one problematic factor that comes into the definition thereof and that is the skin wettedness, i.e. the percentage of the surface area of the body of a worker that is wet with sweat. This aspect cannot be readily quantified and should be kept in mind in the discussion of these particular heat stress indices.

Air cooling power (ACP)

Reference is made to Figure 1 in considering ACP's assessment of the given environment. Note that the Figure assumes that $T_{db} = T_{wb} + 5$ and therefore yields slightly different results, as the given environment (Table I) has a T_{db} 7°C higher than the T_{wb}. The relevant values for ACP (M scale), as read from Figure 1 are approximated in Table IV.

For a metabolic heat load of 100 W, corresponding to the light work rate assumed in the example, the given environment's ACP of 105 W/m^2 would be marginally acceptable even for heavily clothed workers. However, lightly clothed workers ('normal underground attire') would be cooled at a rate of 135 W/m^2, making the given environment only marginally acceptable, even at the lower limit of the range for moderate work (130–200 W/m^2). Furthermore, the only way for workers engaged in heavy work (200–260 W/m^2) to be sufficiently cooled by the given environment would be to perform their duties without clothing (clearly an unreasonable requirement) and to avoid working at a rate that approaches the upper limit of the range.

Specific cooling power (SCP)

Figure 2 can be used to determine the Specific Cooling Power (SCP) for the same conditions considered above (air velocity 0.25 m/s and T_{wb} 29°C). As was the case for the ACP nomogram, the Figure assumes T_{db} to be a function of T_{wb} (T_{wb} + 2°C in the present case), inducing a slight error in the assessment. SCP is read from the graph as approximately 150 W/m^2, indicating the given environment's acceptability for the light work rate assumed in the example, as well as for work rate in the lower portion of the moderate range.

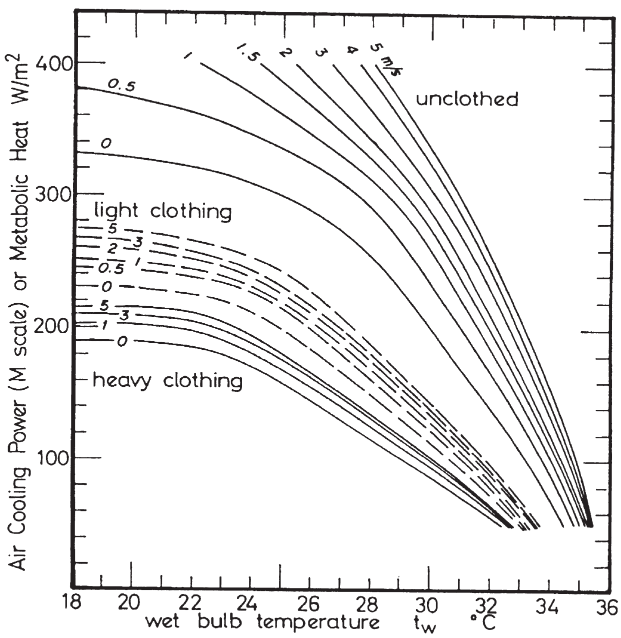

Figure 1—Air Cooling Power (M scale) or ACPM (after McPherson[8])

Table IV

Air Cooling Power for a given thermal environment in relation to clothing

Clothing	ACP for a given environment (W/m^2)
Unclothed	245
Lightly clothed	135
Heavily clothed	105

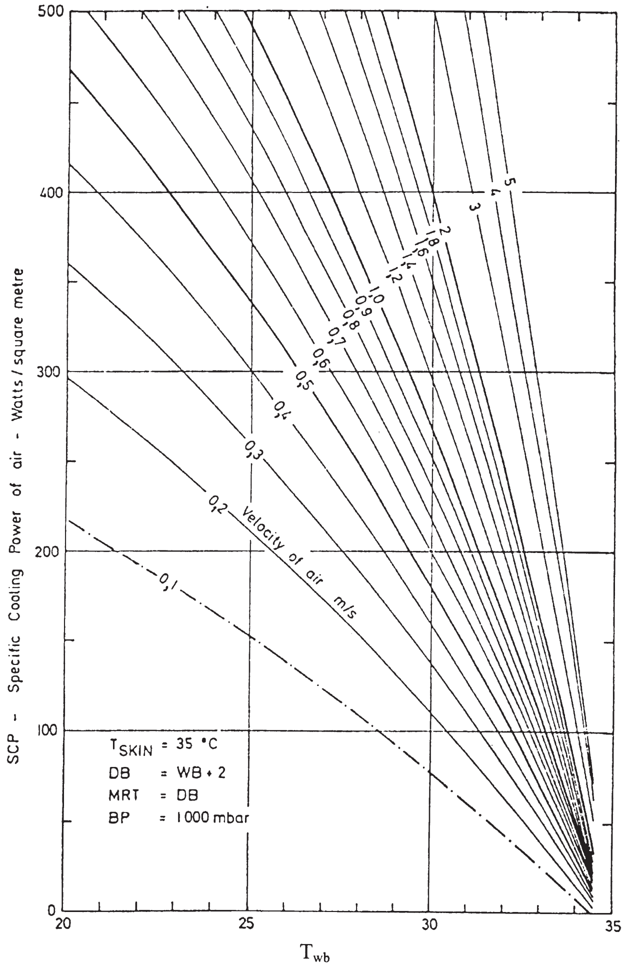

Figure 2—SCP values for various air velocities (after Dumka[9])

However, the given environment's SCP would be inadequate for mid-moderate and heavy work, which requires approximately 160–200 and 200–260 W/m², respectively.

Air Cooling Power (ACP) appears to be the most useful, as it is a rational index combining all the determinants of environmental cooling capacity and relates directly to engineering design parameters. ACP is chosen as it contains all the relevant environmental parameters pertaining to the cooling ability of the air and is not as simplified as the SCP. For planning purposes, an ACP level of 300 W/m² should be considered the minimum requirement. The ACP index (with its associated nomograms) allows various combinations of wet-bulb temperature and air velocity to be applied in achieving the required level of environmental cooling power. Unfortunately, ACP's requirement for accurately determining a number of environmental parameters renders it less than practicable for routine monitoring and assessments in underground workplaces. Although this is the recommended index for the design and planning of UDM ventilation and cooling systems it can be simplified to use air velocity and the wet bulb temperature, which are ideal parameters to use in routine monitoring.

International standards and limits

Based on the various indices identified, it was necessary to identify the various standards and limits used locally and internationally to quantify the conditions in a specific workplace and to specifically identify those standards and limits applicable to the UDM environment. Various regulatory bodies were consulted and some of the most important findings are quoted in the sections to follow.

International Labour Organisation (ILO)

Guidelines obtained from the ILO offices in Pretoria indicate nothing specific with regard to thermal limits for hot underground mines. They do, however, specify that the services of a qualified environmental engineer are available in-house or, alternatively, that appropriate arrangements are made with a larger mining company. Emphasis is placed on the need for suitable computerized software for solving ventilation network problems.

Recommendation 183, from the International Labour Organisation's Conference on Safety and Health in Mines (ILO[10]), contains only general requirements for ensuring workers' safety and health, with no direct reference to heat stress limits or standards or to heat-related hazards.

World Health Organization (WHO)

The World Health Organization states that it is inadvisable to exceed a rectal temperature (T_r) of 38°C during prolonged exposure to heavy work (WHO[11]). However, a T_r of 38 to 39°C is allowable under closely controlled conditions, the rationale being that once 38°C is exceeded, the risk of heat casualties increases.

NIOSH and ACGIH standards

NIOSH defined hot workplaces as having any combination of air temperature, humidity, radiant temperature and air velocity that exceeds a Wet-bulb Globe Temperature (WBGT) of 26.1°C. The ACGIH has adopted threshold limit values for various workloads in hot environments as indicated in Table V (ACGIH[12]).

Higher exposures than those specified by the NIOSH and ACGIH threshold limit values (TLVs) can be endorsed, provided certain work practices are adhered to and medical surveillance is applied to ensure that workers' body temperatures do not exceed 38°C.

OHSA standards

OHSA heat stress standards were developed in an attempt to establish work conditions that would ensure that workers' body temperatures do not exceed 38°C. This limit was based

Table V

ACGIH Wet-bulb Globe Temperature TLVs, various workloads in hot environments

	WBGT limit (°C) for given workload and work pattern		
Work pattern	**Light**	**Moderate**	**Heavy**
Continuous work	30.0	26.7	25.0
75% work and 25% rest each hour	30.6	28.0	25.9
50% work and 50% rest each hour	31.4	29.4	27.9
25% work and 75% rest each hour	32.2	31.1	30.0

on recommendations by a panel of experts from the World Health Organization who considered the WBGT index as the most suitable means of specifying the work environment. They recommended threshold limit values in terms of a WBGT for three different workload ranges and two different ranges of air velocity. The WBGT index was chosen to specify the environment because it employs relatively simple measurements in its determination. It also consolidates into a single value the four environmental factors of dry-bulb temperature (T_{db}), vapour pressure or relative humidity (RH), mean radiant temperature (T_{mr}) and air velocity (V). For indoor environments with no solar load, the following relation for WBGT is applicable:

$$WBGT = (0.7\ T_{nwb}) + (0.3\ T_g)$$

where:

T_{nwb} = natural wet-bulb temperature obtained with a wetted sensor subjected to natural air movement, and

T_g = globe temperature measured in the centre of a 15 cm sealed and hollow sphere, painted with a matte-black outer finish.

An advantage of the WBGT index is the fact that air velocity need not be measured directly, since its value is reflected in that of the natural wet-bulb temperature, T_{nwb}.

One deficiency of the WBGT index is the fact that natural wet-bulb temperature is not a thermodynamic property, which means that anomalous assessments sometimes result. Consequently, different combinations of environmental conditions can yield the same WBGT, with certain combinations causing heat stress beyond tolerable limits, despite their compliance with OSHA limits (Azer and Hsu[11]).

OSHA standards specify that during any two-hour period of the workday and for a specified workload, workers should not be exposed to environments having WBGT values higher than the threshold limit values indicated in Table VI.

Assessment of hot environment using ISO standards

A hypothetical example from Parsons[2] is presented below to demonstrate the use of ISO standards in assessing a hot environment.

Workers in a steel mill perform work in four phases. They don clothing and perform light work for 1 hour in a hot radiant environment. They then rest for 1 hour, after which they perform the same light work for 1 hour while shielded from the radiant heat source. Finally, they perform work involving a moderate level of physical activity in a hot radiant environment for 30 minutes.

Table VI

OHSA-recommended WBGT TLVs for various workloads

Workload	TLVs, WBGT for	
	Air velocity <1.5 m/s	Air velocity >1.5 m/s
Light	30.0°C	32.2°C
Moderate	27.8°C	30.6°C
Heavy	26.1°C	28.9°C

The simple method specified by ISO 7243 for monitoring the environment using the WBGT index is applied. If the calculated WBGT levels are less than the WBGT reference values in the standard, no further action is required. If the levels exceed the reference values, the heat stress imposed by the environment and the work must be reduced. This can be achieved through engineering controls and/or work-modifying practices. A complementary or alternative action would be to conduct an analytical assessment in accordance with ISO 7933.

An overall assessment predicts that unacclimatized workers who are fit for the work being performed could complete an eight-hour shift without undergoing unacceptable physiological strain. If greater accuracy is required or if individual workers are to be assessed, ISO 9886[14] and ISO 9920[15] offer detailed information related to metabolic heat production and clothing insulation. ISO 9886 describes methods for measuring physiological strain on workers and can be used to design and assess environments for specific populations of workers. Mean skin temperature, internal body temperature, heart rate and body mass reduction through fluid loss would be of interest in such instances. ISO CD 12894[16] provides guidance on medical supervision for such investigations (ILO[10]).

Regulatory requirements

Various regulatory bodies, both local and international, were consulted to ascertain their standards and recommendations regarding heat stress limits and indices. These are summarized in the sub-sections that follow.

South Africa

Controlled gold mines in South Africa are required to conduct quarterly inspections of the ventilation system and environmental conditions in all workplaces. These inspections include the measurement of wet- and dry-bulb temperatures, air velocity and wet-kata cooling power (or its calculation from the other parameters). Accordingly, mine personnel normally monitor the levels of environmentally imposed heat stress, as reflected by these measurements. The results are routinely submitted to the Department of Minerals and Energy (DME) and to the Chamber of Mines. The Chamber compiles these data on an annual basis to reflect the number of workplaces within each of the various ranges of wet-bulb temperature, together with other information, much of which relates to production levels and labour deployment. Up to 1994 this information was disseminated to the mining industry in the form of the Annual Mine Ventilation Report.

Despite the effort invested in the surveillance of workplace thermal conditions, effective use is not made of the data on temperature, humidity and air velocity, mainly due to assessments of heat stress being made in only the crudest terms. Consequently, it is not possible to predict with any accuracy the effects of heat stress in workplaces on the health and productivity of workers (Wyndham[17]). Although this comment was made nearly 25 years ago, the same criticism could still be made today and is supported by the fact that the Annual Mine Ventilation Report is no longer produced.

On mines having workplaces with environmental conditions potentially conducive to heat stroke, i.e. where T_{wb} reaches a level of 27.5°C, a formal heat stress management (HSM) programme governed by an approved (by the Department's Chief Inspector) code of practice is required.

From reference to the legislation and discussions with officials of the Department, a summary of the requirements for environmental conditions in South African mines was compiled, the salient points of which are:

- *Regulation 10.6.2*—The workings of every part of a mine where people are required to travel or work shall be properly ventilated to maintain safe and healthy environmental working conditions for the workmen, and ventilating air shall be such that it will dilute and render harmless any flammable or noxious gases and dust in the ambient air.
- *Regulation 10.7.1*—The velocity of the air current along the working face of any stope shall average not less than 0.25 m/s over the working height.
- *Regulation 10.7.2*—The quantity of air supplied at the working face of any development end such as a tunnel, drive cross-cut, raise or winze which is being advanced and at the bottom of any shaft in the course of being sunk, shall not be less than 150 cubic decimetres per second for each square metre of the average cross-sectional area of the excavation.
- *Regulation 10.12*—No person shall work or permit any other person to do any work in any part of any mine where the conditions are conducive to heat stroke, unless such work is carried out in accordance with a code of practice approved by the Principal Inspector of Mines.

From the above regulations, it is quite apparent that ultimate responsibility for ensuring a safe and healthy working environment and for satisfying the requirements of the law rests with the mine manager. Schutte and Kielblock[18] provide useful guidelines for establishing safe thermal limits and determining thermal comfort for workers in hot, humid underground environments. Although these guidelines were not specifically formulated for application to ultra-deep mining operations, they were designed for current deep-level operations, and they do specifically address the requirements for ensuring workers' health, safety and productivity.

In this regard, there is nothing in the way of research findings, current or previous, to support a substantial expansion of workplace thermal limits beyond those found to be acceptable, most notably, by the South African mining industry. On the contrary, recent moves within the industry to implement multi-skilling and multi-tasking indicate a possible need to reconsider current thermal exposure limits on the basis of performance-based criteria, rather than physiological tolerance criteria.

Australia

The following regulations relate to ventilation and temperature limits and to requirements for underground environmental control in Australian mines:

- *Regulation 9.14.1—Air in underground workplaces*
  The manager of an underground mine must ensure that ventilating air provided for the mine is of sufficient volume, velocity and quality to:
  - Remove atmospheric contaminants resulting from blasting and other mining operations in the time allowed for that purpose, and
  - Maintain a healthy atmosphere in workplaces during working hours by reducing the level of atmospheric contaminants in the workplace to levels as low as practicable.
- *Regulation 9.15.1—Air temperature*
  Each responsible person at a mine must cause all necessary measures and precautions to be taken to ensure that employees do not suffer harm to their health from the adverse effects of extremes of heat or cold.
  If conditions in any workplace are or are likely to be hot and humid, each responsible person at the mine must ensure that:
  - All employees are provided with training in measures to be taken to avoid harmful effects from those conditions
  - Appropriate workplace environmental controls (including ventilation) and monitoring are implemented and, if appropriate, a programme for monitoring the health of employees in the workplace is implemented.
- In any workplace in an underground mine, and in any tunnel under a surge stockpile on the surface of a mine, the manager of the mine must ensure that:
  - If the wet-bulb temperature exceeds 25°C, an air velocity of not less than 0.5 m/s is provided, and any appropriate action referred to in Sub-regulation (2) is implemented.

(Note: It was not possible to determine the basis for stipulating a wet-bulb temperature limit of 25°C in the regulation. An effective temperature (ET) of 29.4°C is also used as a benchmark to establish equivalent limits for acceptable workplace environments. No indication of the basis for these limits, scientific or otherwise, was apparent.)

- *Ventilation Regulation 4.13—Hot conditions underground (State of Victoria)*
  The Australian State of Victoria's requirements for thermal limits in underground workplaces state that when the underground temperature of the air in a place where a person is required to work or enter exceeds 28°C wet-bulb, the manager must take precautionary measures to prevent, as far as practicable, the risk of heat stress-related injuries or outcomes.
  In Australia certain actions are prescribed for various levels of air cooling power, as indicated in Table VI. ACP is also applied for design purposes. In considering the tabulated values, it must be appreciated that levels of mechanization in Australian mines are considerably higher than in South Africa and that the Australians make extensive use of air-conditioned cabins for equipment operators. Accordingly, and depending on the extent of mechanization and on the micro-environments ultimately applied in ultra-deep mining, the ACP limits indicated in Table VII may not be sufficiently conservative for application to ultra-deep mining.

Table VII

Australian prescribed actions for various levels of ACP

ACP (W/m^2)	Prescribed course of action
<115 W/m^2	Remove workers from area
115—140 W/m^2	Monitor conditions
140—220 W/m^2	Acclimatize exposed workers
>220 W/m^2	Acceptable conditions

United States

A report by Misaqi *et al.*[19] of the US Department of the Interior stated that hot mines should conduct ongoing environmental surveys concurrently with heat strain measurements among miners and that these measurements should be substantiated by epidemiological studies. The need for a sufficient number of workers to be included in such studies was referred to, but the number or basis for determining such a number was not specified.

Other recommendations were that underground or surface areas should be classified as hot when the WBGT equals or exceeds 26.1°C for men or 24.4°C for women, and that employees should not be subjected to combinations of thermal conditions and physical work that raise body core temperature beyond 38.0°C. These limits are still retained and enforced by the Mines Safety and Health Administration.

Other countries

Table VIII compares the heat stress indices and limits used internationally (including some of those already discussed), as compiled by Graveling *et al.*[20]. Although some of the information considered in the preceding sections is more recent than that in the Table, no substantial differences are apparent in the specified criteria.

In addition to the summary of heat stress criteria presented above, criteria for various work rates, in relation to BET and the NIOSH/ISO WBGT limits for acclimatized mineworkers, are graphically represented in Figure 3.

Conclusions

Workplace monitoring should be performed on an ongoing basis and without undue reliance on specialized equipment or personnel, indicating the need for a highly practicable empirical index. Internationally, WBGT is the most widely used heat stress index, being endorsed by ISO, the American Conference of Governmental Industrial Hygienists and the National Institute of Occupational Safety and Health (USA). Despite its high correlation with physiological responses to work in hot, humid environments, WBGT is less than practicable as a means of routinely assessing environmental heat stress underground, mainly due to the number of parameters that need to be measured and the relatively high cost of purpose-designed instrumentation. Although WBGT estimates of heat stress become progressively less accurate under conditions of reduced humidity and where air velocity exceeds 1.5 m/s, this would not necessarily be a disadvantage in critical workplaces where humidity levels are likely to be high and air velocities low. Contra-indications for the use of WBGT in ultra-deep mining relate to its limited practicability underground and the availability of more suitable alternatives.

The wet-kata is an improvement over the wet-bulb temperature as a means of determining cooling power and assessing heat stress in a particular environment as it considers the combined effects of convection, radiation and evaporation. A wet-kata reading of 5 is the lower limit for accurate indications of the environment's cooling power, while a reading of 8 should be regarded as the absolute minimum level for productive work (levels of 10 and higher would be more conducive to productivity). Despite its merits as an accurate means of assessing the environment's cooling capacity, practical constraints on its application make the wet-kata thermometer a somewhat specialized heat stress evaluation tool, not practicable for routine workplace monitoring by production personnel.

Currently, a number of heat stress indices used internationally and locally meet the specified requirements, but only a few address the criteria for underground applications satisfactorily. Among those potentially suited to the design of cooling and ventilation systems, Air Cooling Power (ACP) appears to be the most useful. For planning purposes, an ACP level of 300 W/m^2 should be considered the minimum requirement. Unfortunately, ACP's requirement for accurately determining a number of environmental parameters renders it less than practicable for routine monitoring and assessments in underground workplaces and air velocity and the wet bulb temperature should be used in routine monitoring.

The wet-bulb temperature, as a single environmental component of heat stress, provides the best combination of practicability and accuracy, the latter indicated by its high correlation (0.8–0.9) with physiological strain among exposed workers. The instrumentation required for measuring wet-bulb temperature is inexpensive and amenable to use by non-specialists; hence, production personnel are familiar with its application. Also, given the common use of wet-bulb temperature as an environmental design criterion and the fact that it is a principal determinant of Air Cooling Power, its use for monitoring and assessment should not result in serious discrepancies between ACP design levels and the conditions ultimately achieved in the workplace. In addition to this the measurement and specification of the air velocity underground is a very basic exercise and very important in terms of specifications needed for the real cooling power requirements for the working environment.

Although it is not uncommon, both locally and internationally, for wet-bulb temperatures in underground workplaces to exceed 32°C, the acceptable limit for design purposes should be between 27°C and 28°C. Temperatures in excess of 28°C wet-bulb should be defined as 'abnormally high' and the Emergency Heat Stress Index (EHSI), as described in SIMRAC Project GAP 505, should be used under such conditions.

The above represents a more stringent approach in terms of setting heat stress limits but since it takes the impact of heat stress on worker performance and cognitive ability into account, and is an obvious pre-requisite to ultra-deep mining if meaningful productivity, health and safety targets are to be attained. At these depths it will be very important to optimize between the quantity of air supplied and the amount of cooling needed. Furthermore, the importance of mining

Table VIII

Comparison of heat stress criteria used in various countries

Country	Source	Criteria	Comment
USA	ACGIH AIHA OSHA NIOSH (1986)	T_r = 38.0°C	All sources provide comparable values, with some minor differences in their means of determination
Australia	Victoria Trade Council	ACGIH TLVs	Includes guidance on heat stress measurement, medical requirements, heat acclimatization and other protective measures, as well as regulations for work in heat
France	Government Regulation	Those mines with temperatures above 28°C are considered to be particularly hot	Official requirements stated, with discussion of workload effects
Germany	Federal Mining Decree (1984)	*Non-salt mining:* **1.** for T_{db} >28°C or BET >25°: • 6-h max. shift if ≥3 h at: T_{db} >28°C (to max. BET of 29°C), **or** BET 25-29°C. • 5-h max. shift if >2.5 h at BET of 29-30°C. **2.** Personnel should not be exposed to BET ≥30°C, except for a 4-month max. period directly followed by a 6-week break **and** if BET = 30°C, a max. 5 h daily exp. **or** if BET >30°C, 2.5 h max. daily exp. **3.** In face operations, only 1/3 of employees can be exposed to a BET ≥30°C.	BET = Basic Effective Temperature Provisions made for rest breaks, period of acclimatization, workers' age and work to be performed during emergencies, e.g. mine rescue operations
		Salt mining: **1.** For T_{db} >28°C: • 7-h max. shift if: more than 5 h at T_{db} of 28-37°C, **or** more than 4.5 hours at T_{db} of 37-46°C. • 6.5 h max. shift if 4 h at T_{db} of 46-52°C. **2.** Personnel should not be exposed to T_{db} >30°C or T_{wb} 27°C except where special means ensure that physiological effect is less than that of T_{db} 52°C or T_{wb} of 27°C.	Provision for special precautions to ensure that physiological effects of the work environment equate to a BET<30°C.
Great Britain	National Coal Board (1980) National Coal Board (1963) Lind (1963) WHO (1969)	BET >28°C for 1.5 hours during any shift incurs a heat allowance payment. 27.2°C part. mechanized 28.3°C fully mechanized BET 30.2°C: 210 W BET 27.4°C: 349 W BET 26.9°C: 490 W BET 30.0°C: light work BET 28.0°C: mod. work BET 26.5°C hard work	Watts as the product of metabolic work rate and body surface area, typically 1.8 m^2 Not highly acclimatized but well trained for work BET = Effective temperature, basic scale

methods conducive to establishing optimum thermal environments in ultra-deep mining is obvious.

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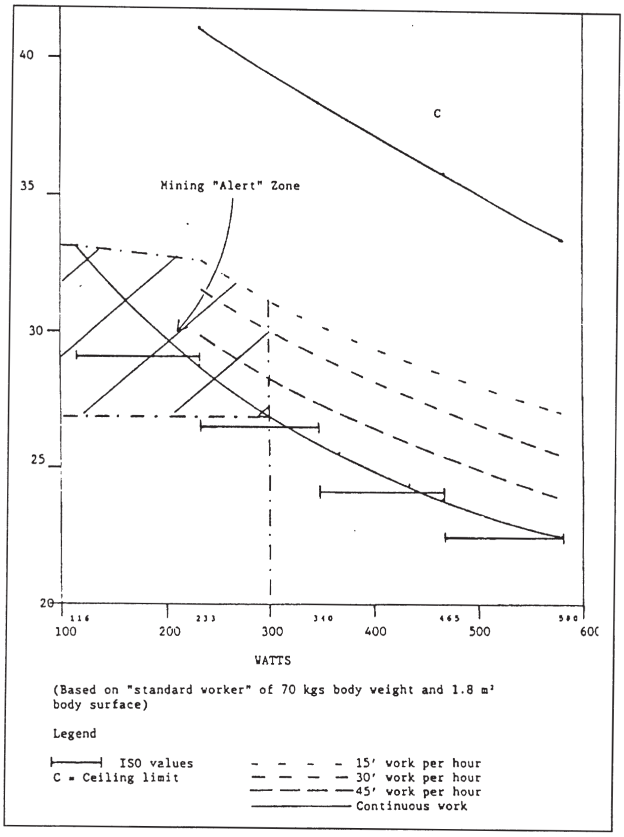

Figure 3—NIOSH and ISO heat stress limits for acclimatized mineworkers in terms of WBGT and metabolic heat load (after Graveling *et al.*[20])

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