

1. Introduction

1.1. Background

Ultra-deep mining (to depths of 5 000 m and greater) 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 3 500 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 cognizance 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 standards to control them, that compare favourably and defensibly with those in other mining industries.

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.

The purpose of the research is to provide information on environmental criteria and limits relevant to ultra-deep mining, with particular reference to thermal designs and associated costs. A detailed review of the literature and other sources of information relating to standards and regulations, and of various heat stress indices and their use (both locally and in other countries) provides the basis for this document. Important input from industry ventilation and environmental control experts has also been taken into account. In order to evaluate the financial implications of various environmental design criteria and standards, a detailed cost analysis, which includes various aspects relating to the recirculation of return air, also forms part of this investigation.

1.2. Problem statement

The physical and economic impact of environmental design criteria for ultra-deep mines are to be determined.

1.3. Objectives

The objectives of this project can be subdivided as follows:

- ❖ Undertake a literature search to establish and identify the various factors that will influence ultra-deep-level mining.
- ❖ Assess and evaluate the relevance of environmental factors and their dependence on depth.
- ❖ Analyse the effect of identified environmental factors on workers.
- ❖ Carry out a literature search on the various heat stress indices used in the mining industry, nationally and internationally.
- ❖ Identify the most important heat stress indices applicable to the South African mining industry.
- ❖ Establish a single heat stress index for the South African mining industry, if possible.
- ❖ Determine the heat stress limits for work in ultra-deep South African mines.
- ❖ Assess the relevance of international heat stress standards.
- ❖ Compare South African standards and regulations with those of other countries such as Australia, the USA and countries in Europe.
- ❖ Investigate the various physical aspects relating to the recirculation of air.
- ❖ Investigate the cost implications of thermal standards and limits.
- ❖ Investigate the effect of global and local recirculation on the total cooling, as well as air supply costs for ultra-deep-level mines.
- ❖ Compare global and local recirculation costs.
- ❖ Establish guidelines and standards to ensure a cost-effectively safe and healthy underground working environment.

2. Methodology

The research and work done for this project was approached in the following way:

- ❖ A literature search was done to identify all the various factors that will influence ultra-deep level mining. The library of the CSIR's Division of Mining Technology (Miningtek) was contacted and other sources such as the Internet, the World Health Organization, the United Nations and embassies of various countries were also consulted.
- ❖ A literature search was also done to find the various heat stress indices related to deep mining, nationally and internationally, and the most common indices relating to South African mining were identified. The effect of these indices was also investigated.
- ❖ All relevant environmental factors were then compiled to identify the major parameters that will have a direct influence on ultra-deep-level mining.
- ❖ A standard simulation, using the program "ENVIRON", of a typical South African deep mine (excluding recirculation of air) was done to establish the air flow and cooling requirements for an ultra-deep-level mine and the various cost factors related to it.
- ❖ Also with the aid of ENVIRON, the effect of the recirculation of air underground on ultra-deep-level mines (longwall follow-behind mining layout) was determined in terms of air available, cooling needed, as well as the costs related to recirculation.

The results of all the findings and the conclusions drawn are given in this document. The methodology approach can be summarised as shown in Table 2 below.

Table 2
Methodology for achieving objectives

| No | Description of objective | Expected result | Deliverable |
|----|--|---|---|
| 1 | Literature search, communication with experts and workshop involving collaborators/ subcontractors Identification of relevant environmental factors Clarification of local and international standards and procedures in dealing with identified factors | Understanding of the impact of various environmental factors and of local and international standards and regulations | Consideration of environmental factors and the various local and international standards applicable to each |
| 2 | Assessment of the dependence of identified factors on depth | Understanding of the effect that depth has on each of the factors. These include heat transfer, heat stress, air contaminants, barometric pressure changes, noise, illumination, etc. | Assessment of the dependence of environmental factors on depth |
| 3 | Analysis of the effect of the identified environmental factors on workers (individual, cumulative and collective effects) | Qualitative and quantitative understanding of the safety and health implications of relevant environmental factors at great depth | Detailed review of the physiological effects of environmental factors, with particular emphasis on heat stress and pressure changes |
| 4 | Assessment of the standards identified with regard to their applicability and practicability in terms of broader deep-level mining issues and anticipated Deep Mine designs | Understanding of the problems associated with providing an acceptable working environment | Summary of all relevant information |
| 5 | Detailed costing exercises to determine the financial impact of applying relevant standards Computer simulations | Detailed understanding of the cost implications of applying and maintaining various standards | Investigation reflecting the costs associated with providing and maintaining various standards |
| 6 | Extraction of appropriate design criteria for environmental conditions at depth. Final report/ technology – information transfer | Guidelines and standards to ensure a cost-effectively safe and healthy underground working environment | Compilation of final report |

3. Literature search

The purpose of doing such extensive literature searches was to ensure complete globalisation of the findings. Various institutions and other information sources were contacted and are listed below. All information gathered in this way forms part of this document.

- ❖ The South African Labour Organisation
- ❖ The World Health Organization - South African Branch
- ❖ The International Labour Organisation
- ❖ The Australian Industrial Relations Department
- ❖ The German Embassy to South Africa (Pretoria)
- ❖ The United States of America Information Services (USAIS)
- ❖ CSIR Miningtek library
- ❖ Environmental Department at Oryx Mine, Free State
- ❖ Department of Minerals and Energy.

The purpose and objectives of each literature search will now be discussed briefly.

3.1. Identification of factors influencing environmental conditions

The purpose of this literature search was to try to establish all the environmental factors that could possibly influence ultra-deep-level mining and then, from the information gathered, to identify all those factors that would play a major role in the feasibility of ultra-deep-level mining. The objective therefore was to categorise these various parameters or factors and rank them from lowest to highest priority.

3.2. Heat stress indices - an international comparison

The purpose of this literature search 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 before. Heat stress indices also have certain cost implications and these became evident from a comparison of the results obtained by specifying certain indices, such as the wet-bulb temperature and the air speed.

3.3. Recirculation of mine air

From the literature search to establish the factors that would influence ultra-deep-level mining it became obvious that the recirculation of air underground would play a very important role. A further literature search was therefore also needed to determine all the various aspects related to the recirculation of air underground and from the information obtained in this way a basic guideline was established for carrying out simulations of the recirculation of air with the help of the ENVIRON simulation program. The literature search also gave an insight into all the advantages and disadvantages of recirculating air underground, as well as the application strategies.

4. Factors influencing environmental conditions

4.1. Literature review and evaluation of previous research

The main objectives in reviewing the literature and the environmental criteria applied in other countries were to:

- ❖ Provide background information to be used in selecting appropriate criteria on which to base environmental standards and limits for workplaces in ultra-deep mining.
- ❖ Ensure the alignment (to an appropriate extent) of selected criteria with limits established elsewhere, particularly where hot underground conditions occur.
- ❖ Enable the validity of standards and limits, both local and international, to be evaluated by determining the bases on which they were established.
- ❖ Ensure that appropriate account was taken of current knowledge and past experience in planning for the application of environmental control to ultra-deep mining.

The resources employed included research reports, journal articles, various textbooks, handbooks and industry guidelines, as well as papers presented at conferences and symposia, using inter-library loan facilities where the required references were not immediately available.

4.2. Environmental factors - assessment of their depth-dependence

This aspect of the work relied on input from members of the Deepmine project team and from ventilation practitioners in the mining industry. The initial task was to enumerate all aspects and factors of the work environment having any relevance to workers' health, safety and productivity, initially without regard to the influence of depth. It was also important to classify the relevance and importance of the various factors identified in relation to ultra-deep mines. The resultant list of potential environmental issues/factors/hazards/concerns that could influence ultra-deep-level mining included the following:

Potential environmental factors that could influence ultra-deep-level mining

- ❖ Air quality, including dust, gases and fumes
- ❖ Barometric pressure
- ❖ Fires and explosions, including escape and rescue strategies
- ❖ Heat stress
- ❖ Illumination and visibility
- ❖ Noise
- ❖ Radiation
- ❖ Vibration.

These issues were then considered in relation to factors that had the potential to constrain or contribute to operational performance. It was now necessary to determine which of these factors were likely to be influenced, either directly or indirectly, by the greater depths being contemplated for ultra-deep mining. The operational constraints and contributors identified as having the potential to impact on environmental issues were as follows:

Ventilation-related factors that could influence ultra-deep-level mining

- ❖ Air velocity and air mass flow
- ❖ Leaks and pressure drops
- ❖ Pollutant levels and TLVs
- ❖ VRT gradients
- ❖ Heat transfer, including the thermodynamic properties of the ore body
- ❖ Rock insulation and heat load
- ❖ Cooling strategies - their current limitations and costs
- ❖ Wet-bulb/dry-bulb gap and humidity
- ❖ Choice of heat stress indices
- ❖ Cooling power of the environment
- ❖ Use of micro-environments, including zone and personal.

Physical factors and stresses, including barometric pressure

?

Mining and engineering-related factors and their associated constraints

- ❖ Backfill and support systems
- ❖ Mining methods
- ❖ Transport systems
- ❖ Use of hydropower
- ❖ Possibility of underground mineral processing
- ❖ Needs of specialist operations, including outfitting, maintenance, and escape and rescue.

Worker-related factors, including physical, psychological and physiological effects

Health
Safety
Productivity

Socio-legal and governmental considerations

Legislation and regulations
Social acceptability.

Investors' concerns

Social acceptability and legal liability
Returns on investment.

Environmental factors were considered in relation to operational constraining/contributing factors by means of a simple matrix in order to identify those environmental factors that would have a critical impact on, or would be likely to be negatively influenced by, greater mining depths. Such effects could be either a direct result of increased depth or a secondary

consequence of the methods and systems required for ultra-deep mining. An analysis of the relevance of operational constraints and contributors as they relate to environmental factors at increased depth is summarised in the matrix comprising Table 4.2. As indicated in the table, a “Y” indicates likely interaction between the combination of the operational constraint/contributor and environmental factor or hazard being considered, and the relative importance (RI) of such effects is indicated as Low (L), Moderate (M) or High (H). This table was assembled to highlight the importance and relevance of the various factors to ultra depth.

Table 4.2
Relevance of operational constraints and contributors to environmental factors at increased depth

| Operational factor & Relative Importance (RI) (Low/Moderate/High) | | Environmental factor or hazard Are interactions likely between the given environmental factor or hazard and the indicated operational constraint/contributor? Y=Yes | | | | | | | |
|---|----------|---|------------|-----------------|-------------|-----------------------|------------------------|----------------------|-----------|
| Constraint or contributor | RI L/M/H | Dust fumes gases | Air press. | Fires & explos. | Heat stress | Illumin. & visibility | Noise | Radiation | Vibration |
| Air velocity & air mass flow | H | Y | Y | Y | Y | Y Fogging | | Y | |
| Ventilation leaks/pressure drops & differences | H | Y | Y | Y | Y | Y Fogging | | Y | |
| VRT gradients & rock properties | H | | | Y | Y | | | Y Rock properties | |
| Heat transfer: conductivity & contact temperature | H | Y | | Y | Y | | | Y | |
| Rock insulation & heat load | M | Y | | Y | Y | | | Y | |
| Cooling strategies: current limitations & costs | H | Y | Y | Y | Y | | | Y | |
| WB/DB gap | H | Y | Y | Y | Y | | | Y | |
| Heat stress indices | H | | Y | | Y | | | | |
| Aspects of environment's cooling power | H | Y | Y | Y | Y | | | Y | |
| Micro-environments: personal & zone | M | Y | Y | Y | Y | Y | Y | Y | |
| Support systems, including backfill | M | Y | Y | Y | Y | | Y Acoustic environ. | Y | |
| Mining methods & eng. Constraints | H | Y | Y | Y | Y | Y | Y | Y | Y |
| Transport systems & eng. constraints | M | Y | Y | Y | Y | Y | Y | Y | Y |
| Hydropower | H | Y | | Y | Y | Y Fogging | Y | Y Fogging | Y |
| U/G min. processing & eng. constraints | L | Y | | Y | Y | Y | Y | Y | Y |
| Specialist operations, incl. eng./mining/rescue | H | Y | Y | Y | Y | Y | Y | Y | Y |
| Health vs. environ. conditions & ventilation systems | H | Y | Y | Y | Y | | Y | Y | |
| Safety vs. environ. conditions & ventilation systems | H | Y | Y | Y | Y | Y | Y | | |
| Productivity vs. environ. conditions & ventilation systems | H | Y Re-entry times | Y | Y | Y | Y | Y | Y Face advance | |
| Socio-political acceptability | H | Y | Y | Y | Y | Y | Y | Y | Y |
| Legislation & regulations | H | Y | Y | Y | Y | Y | Y | Y | Y |

An inspection of the table indicates that *Heat stress, Fires and explosions, and Dust, gases and fumes* were the environmental factors/hazards most frequently identified by respondents as being affected by or interacting with operational constraints/contributors. This indicates their critical importance in planning an acceptable work environment in ultra-deep mines, as well as the likely complexity thereof. The frequency with which *Air pressure* (including barometric and induced fan pressures) was identified is largely attributable to the relationship of this issue to ventilation arrangements.

Radiation was also frequently identified as a result of concern that ventilation arrangements (e.g. controlled recirculation of re-cooled air) and interactions between radon and dust in a humid environment would be likely to have an effect on the workers' long-term health.

Noise, vibration and lighting/visibility were infrequently identified as concerns and where they were, it was often in relation to specific situations and largely in isolation from depth. Examples were concerns about possible increases in noise and vibration levels for equipment operators or maintenance personnel in the event of new types of equipment being deployed, the perceived need to improve lighting arrangements, e.g. for pre-entry inspections, and misting as a result of ventilation effects.

With regard to the respondents' apparent perception of the relative importance (high, moderate or low) of each operational constraint/contributor in planning for ultra-deep mining environments, this rating is more a function of the influence of a constraint/contributor on environmental conditions than of the prevalence of its interactions with environmental factors.

4.3. Practitioners' input

In addition to the identification of interactive relationships or associations between environmental factors/hazards and operational contributors/constraints, respondents offered comments with regard to various aspects of planning for environmental control in ultra-deep workplaces. The issues addressed and a summary of respondents' comments are presented in Table 4.3.

Table 4.3
Practitioners' comments regarding planning for environmental control in ultra-deep mines

| Issue | Respondents' comments |
|------------------------------------|--|
| Air mass flow | Limited by dimensions of intake airways, indicating likely reliance on recirculation Plan for 3,5 m ³ /s/ton of rock for fresh downcast air as starting point, possibly reduced through controlled recirculation of re-cooled air Dedicated cooling/heat sinks for winders, i.e. do not use intake air |
| Air velocity | Limited by practical and economic constraints. Aim for 0,5 to 1 m/s in stopes, 5 to 7 m/s in travelling ways and 18 to 20 m/s in non-travelling returns |
| Ventilation leaks & pressure drops | Uncontrolled leakage will be more critical Fan capacity/power must be used efficiently Make specific provision for ventilating hoists, pumps etc. isolated from intake air. Up-front provision for leakage at hoist and pump chambers and at fridge plants Provide for overall leakage: suggestions ranged from 20 to 40% Match airway size and required flows to control pressure drops |
| Pollutant & stress levels & TLVs | Design for elimination or reduction at source, as these are difficult to control later Rigorous health-based risk assessments needed in advance Need to quantify impact on productivity and on safety to provide impetus/motivation for effective control measures |

| Issue | Respondents' comments |
|---|---|
| VRT | Accurate values essential to planning. Measured levels often higher by 5°C than predicted/calculated, possibly attributable to rock property anomalies or unknowns such as fissure water Database for VRT, gradients and rock properties is essential |
| Fires & explosions and Escape & rescue | Contingency required for encountering pockets of high-pressure flammable gas, with consideration given to increased BP and precautions for the intersection of hot water Refuge bays will require provision for: Cooling: consider hydropower and compressed air O ₂ supply: consider cylinders and O ₂ candles Easy access to escape routes fundamental to design of mine layouts Mine designs must consider whether SCSRs, refuge bays and intermediate refuge bays are to be provided Air-conditioned man-carriages could be used as refuge bays |
| Heat transfer | Plan for effective use of insulation where benefits are feasible Ensure that artificial heat sources are rationally situated and ventilated Consider using evaporative cooling from hot rock surfaces by allowing higher T _{db} |
| Cooling strategies | Open-circuit pumping is too costly vs. Open-circuit pumping is viable Ensure that amount of air cooled and air used does not exceed requirements Energy recovery will be important and should be used even with hydropower Energy recovery systems should include Pelton turbines Ice is best option for cooling medium vs. Chilled water is the best option Heat rejection should be on surface vs. Heat rejection should be in return airways Refrigeration to be optimised according to mine design and ambient conditions Reject temperatures are critical and must be decided with due consideration to health, safety, productivity, practicability and cost |
| Wet-bulb/dry-bulb gap | Should be as high as possible without T _{db} exceeding the 37°C general limit, except where a greater gap could enable evaporative cooling from wetted rock surfaces Higher T _{db} could be countered by air-conditioned conveyances for hot haulages |
| Heat stress indices | Differing views regarding choice of heat stress indices: SCP should be 250 W/m ² vs. ACP should be 300 W/m ² T _{wb} provides best combination of practicability and accuracy SCP and ACP are more rational indices but difficult and expensive to apply SCP and ACP are dangerous criteria in the event of ventilation/power failures where undue reliance is placed on air velocity; T _{wb} is less susceptible to breakdowns |
| Mining methods | Use concentrated mining on dip rather than on strike Focused use and control of cooling and ventilation resources is essential Increased use of mechanisation, using electricity and not diesel Control measures to ensure efficient utilisation of air, water and refrigeration |
| Environmental control & ventilation planning | Advance knowledge of geology essential Genuinely based on intended mining method Multi-disciplinary team approach to planning, with equal decision-making authority input from geologists, rock mechanics, Mining, ventilation, medical, safety and engineering personnel, with consensus from all the experts involved |
| Workers' health | Sub-standard conditions will be unacceptable to workers, unions and investors Effective planning and appropriate advance engineering controls vital to reducing the risk of long-term financial impact from expensive and ineffective <i>ad hoc</i> control measures and from consequent compensation and "danger pay" wage scales |
| Workers' safety, productivity and performance | Favourable working environment is conducive to safety and to productivity Spend the money up-front to ensure conditions that enable productive, profitable mining and to avoid wasting money in future on expensive, ineffective control measures and compensation |
| Legislation and regulations | Must be reasonable and practicable, with provision for cost-effective compliance Ensure a balance between protectiveness and costs Must enable and not cripple mine operators Must not be seen as a deterrent by investors Based on scientifically sound information and epidemiology |

| Issue | Respondents' comments |
|--|---|
| Rock insulation and heat load | Major component of the cost of mining Research essential: Significant research investment in advance of ultra-deep mining could yield massive savings in capital and operating costs for cooling mines |
| Micro-environments | Should be implemented as far as practicable More cost-effective than total mine cooling Use would be in alignment with the principles of concentrated mining Consider use of in-stope coolers and hydro-powered venturis Air-conditioned conveyances could obviate or reduce the need to cool haulages and travelling ways Consider use of air-conditioned operator cabins and control rooms to ensure favourable thermal environment and air quality |
| Support systems | Potential for higher temperatures and possible consequences of fires are contra-indications for timber-based support Concrete should be used rather than timber Extensive use should be made of backfill Backfill is a source of heat and its significance must be determined Past experience with hydraulic props and the possibility of seal failure at higher temperatures are causes for concern |
| Transport systems for workers, ore, equipment and material | Essential to minimise walking in long, hot haulages in order to reduce the need for cooling and ensure that workers are productive on reaching the workplace Air-conditioned carriages would address the above need and could be used as temporary or intermediate refuge bays when required Use of heat-generating equipment to be avoided in intake airways, indicating use of electric-powered and not diesel-powered transport Need for genuinely systematic means of transporting commonly used equipment and materials to minimise handling and concomitant exertion/injuries/damage |

4.4. Dependence of environmental factors on depth

By analyzing their mechanisms of impact and considering the input from the industry's environmental control practitioners, a number of environmental factors were deemed unlikely to be materially affected by increased depth. These included visibility/lighting, noise and vibration and, to a lesser extent, radiation, which is expected to be indirectly influenced by alternative ventilation arrangements, e.g. where controlled recirculation of recooled ventilation air is employed.

Noise, by virtue of its quantification in terms of sound pressure *level*, is a ratio of the sound pressure generated in relation to the prevailing ambient pressure. Although air would be denser at greater depth as a result of auto-compression, its properties as a noise transmission medium would not be affected to the extent that appreciable differences would occur in the transmission of acoustic energy or in its measured levels. Such effects would require a transmission medium of much greater density than air, and even the auto-compression effect would be insufficient to raise the density of air to levels approaching that of other sound transmission media, e.g. water. Accordingly, noise levels and their impact on workers are not expected to differ materially from what prevails in current mining operations, indicating that standards for hazard control/hearing conservation measures and the exposure limits presently deemed effective should be sufficiently protective for ultra-deep mining.

The same can be said of **vibration**, be it whole-body or hand-arm, i.e. no change from current levels is expected in ultra-deep mining unless the equipment and machinery deployed change significantly and, accordingly, no revisions to present TLVs are indicated.

Lighting and visibility in ultra-deep mining is another aspect of the workplace environment that is not expected to differ from the current situation. Current lighting standards should only be considered for revision to the extent that may be indicated by currently recognised shortcomings.

4.5. Environmental effects on workers

This portion of the investigation considered the documented effects of environmental stresses on workers, again focusing on thermal aspects and largely excluding those involving changes in barometric pressure owing to the fact that they are being specifically addressed by other Deepmine research tasks. While the physiological effects of heat on workers are well understood, largely as a result of research performed by the South African mining industry, the effects of heat on work performance in mining have not been adequately investigated. Given the critical importance of productivity in the success of ultra-deep mining, the need to quantify performance effects is most apparent and also requires investigation.

5. Heat stress indices

5.1. Literature search

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, 1973).

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 CRA, HTT and 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, 1979). The objective of this part of the research was to gather information on environmental parameters and criteria relevant to ultra-deep mining, with particular reference to heat and thermal limits.

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.

In addition to conventional sources of information, i.e. journal articles, textbooks and research reports, the Internet was used to identify institutions and organisations possessing information relevant to the research task's objectives. Such approaches, in addition to yielding information directly, led to the identification of individual resource people who were then contacted for the purpose of obtaining information on workplace thermal limits.

A number of organisations were consulted, including:

- ❖ The International Labour Organisation in Pretoria to obtain information relating to labour legislation and standards/limits for thermal conditions in underground mines
- ❖ The United Nations World Health Organization (WHO) to determine their recommendations for thermal limits and standards intended to protect the health of workers
- ❖ The South African Department of Minerals and Energy to obtain background information on legislation and regulations relevant to thermal conditions in underground workplaces.

The information obtained from the literature and the various sources listed above was compiled and consolidated for incorporation in this dissertation/report.

5.2. Background

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 minimise 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 provide the fundamental basis for determining the thermal standards and exposure limits to be applied.

The assessment of thermal environments requires a basis that is appropriate for the prevailing environmental conditions and the nature of the work being performed. This is normally provided through the application of some or other heat stress index. The difficulty in devising practicable heat stress indices has been rooted in the complex nature of human heat stress and resultant heat strain responses. Heat stress is the total heat load, both environment- and task-related, that must be dissipated in order for the body to maintain thermal equilibrium, whereas heat strain can be regarded as the physiological and, at times, the patho-physiological disturbances resulting from heat stress.

There are more than a dozen factors that are instrumental in the transfer of heat between the human body and the environment. These include air temperature, barometric pressure, the temperature and emissivity of solids in the work area, air velocity, water vapour pressure, skin temperature, skin vapour pressure, the effective surface area of the skin, skin colour, pulmonary ventilation, clothing and work posture. Heat transfer takes place through several avenues, including evaporation, radiation, convection and sometimes conduction. The physiological strain of dissipating metabolic heat from the body core is the result of the physiological effort required to maintain various necessary functions, including the circulation of blood to vital organs, to the muscles and the skin, as well as the production of sweat.

Given the complexity of human heat strain responses and their variations among individual workers, it is clear that some method of advance evaluation of hot work environments (rather than post-evaluation of exposed workers' responses) is required. However, a sound correlation between environmental conditions and the physiological responses they induce in workers is an essential prerequisite for any heat stress index.

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 projects, not only in terms of viability, but also in terms of minimising 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.*, 1986).

The five most important aspects of the environment that influence the rate of heat transfer from the surface of the human body, and thus determine the heat stress experienced by workers, are: air temperature, water vapour partial pressure, air velocity, mean radiant temperature (MRT) and barometric pressure.

In order to understand the limitations of the various heat stress indices used internationally, it is important to consider each in turn. What follows is an explanation and description for each of the major indices and, where applicable, comparisons of the metabolic rate criteria associated with them.

5.2.1. Aim of heat stress indices

In mines, as in other industries, the exposure of workers to excessively hot, humid conditions is unhealthy and counterproductive. The major concern with excessive heat and humidity underground relates to the unfavourable physiological, psychological and behavioural (i.e. work performance) responses of workers exposed to such conditions. These aspects have considerable potential for negative influences on health, accident rate and productivity, all of which ultimately affect profitability. The question then raised is what constitutes an

acceptable level for thermal parameters of the environment, in terms of sustaining workers' well-being and productivity?

A controversy that has continued throughout this century is the question of how to accurately quantify the ability of an air stream to remove metabolic heat from the human body. A fundamental obstacle to this is the number of environmental variables involved, including wet-bulb, dry-bulb and radiant temperatures, as well as air velocity and density. In addition, there are a number of important human factors not amenable to direct measurement, such as the health, fitness, body mass, surface area and degree of acclimatisation of exposed individuals.

It can therefore be said that heat strain is the body's response to heat stress, and thus, control of heat stress will, in turn, control heat strain. Heat stress control is costly. Thermal control measures are affected by numerous factors such as the layout of the working areas, the number of heat sources and the types of heat they produce, as well as the nature of the job and the resources available. Mine planning, ventilation and air conditioning, modification of production methods or work practices, acclimatisation and education are possible ways of avoiding the detrimental effects of heat in mines. The goal of such actions, as mentioned above, is to reduce the heat strain experienced by miners and to maintain high efficiency and safety standards in hot mines.

Environmental heat strain in workers is the result of the heat stress imposed by the environment through its air and radiant temperatures, relative humidity and air velocity. The effects of these stresses are materially influenced by factors such as clothing, physical activity, and the individual's level of acclimatisation to heat, and these combine to exert an upward influence on body temperature. The body's thermo-regulatory response can, depending on the individual's level of acclimatisation to heat, be swift and effective but can also impose considerable strain on the cardiovascular system. This can lead, firstly, to discomfort with concomitant reductions in work performance and cognitive ability, and, with continued exposure, to heat illness and possible permanent disability or death (ILO, 1998). It is these potential effects of heat stress that indicate the essential need to assess hot work environments in order to ensure the performance and, more importantly, the health and safety of workers.

Heat stress indices generally provide a single value which indicates the total level of heat stress imposed by the environment. The value integrates the effects of the various thermal parameters on workers and can be used as a basis either for designing the work environment or for adapting work practices to suit it. Considerable research effort has been devoted to the development and evaluation of heat stress indices, often in an attempt to produce the definitive index. However, it may well be that no single index can fully satisfy the various needs of all work situations, hence the proliferation of heat stress indices over the years, most of which succeed in satisfying the needs of the specific application for which they were devised. In fact, several indices, particularly those that fail to address all six thermal parameters and work variables, are theoretically inadequate or even flawed, but have still proved useful within the specific context for which they were developed (ILO, 1998).

The common aim of all heat stress indices is 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, where the use of one index indicates that two environments impose equivalent levels of heat stress, use of another can indicate a considerably different level of stress. Most commonly used indices yield reasonably consistent and accurate results when applied within the range of environmental conditions for which they were devised, but none is completely suitable for the full range of conditions currently found in South African gold mines or those anticipated for ultra-deep mining.

5.2.2. 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 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. Most mines in South Africa use wet-bulb temperature as the principal means of assessing thermal acceptability, with 27,5°C regarded as the action level at which formal heat stress management procedures are required and 32,5°C as the limit for routine work. These levels compare favourably with recommendations made by MacPherson (1984) in respect of unacclimatised workers. A psychrometric (aspirated) wet-bulb temperature of 27°C or 28°C was suggested as a criterion above which work rates or shift hours should be reduced, while 32,5°C was suggested as the upper limit of acceptability. In the sections that follow all the relevant heat stress indices will be dealt with in detail.

5.2.2.1 Single measurements

In hot and humid environments (as also expected in ultra-deep mining), where the predominant mode of heat transfer is evaporation, the wet-bulb temperature of the ambient air is the most powerful variable affecting body cooling. At this stage almost all mines in South Africa retain the wet-bulb temperature as the sole indicator of climatic acceptability. A psychrometric (aspirated) wet-bulb temperature of 27°C or 28°C may be employed as a criterion above which work rates or shift hours are reduced, while 32,5°C may be regarded as the upper limit of acceptability (MacPherson, 1984).

5.2.2.1.1 Wet-bulb temperature

The introduction of heat acclimatisation in the South African mining industry was prompted by the unacceptably high incidence of heat stroke. Since its occurrence was most strongly associated with the hot, humid conditions typical of underground gold mines, an analysis of heat stroke incidents was performed to establish the critical wet-bulb temperature beyond which the risk of heat stroke becomes unacceptable, independent of work rate, air velocity, etc. Given the relative uniformity of conditions underground in terms of air velocity and relative humidity, wet-bulb temperature serves as an adequate descriptor for environmental heat stress in mines, which, in terms of WBGT, averages approximately 30°C (Schutte *et al.*, 1986).

As early as 1905, Haldane identified the wet-bulb temperature as the best single indicator of environmental heat stress. Of all the parameters amenable to simple and direct measurement, wet-bulb temperature remains the most important in assessing thermal conditions in hot environments, particularly in underground workplaces. Heat transfer from the body surface of a worker to the surrounding air takes place by convection, radiation and the evaporation of perspiration. Of these, the latter is by far the most effective means of body cooling. If the dry-bulb and radiant temperatures exceed those of the skin, convection and radiation will result in heat transfer to the body. Evaporative cooling must counter this effect, as well as that of metabolic heat production, in order for the individual to maintain thermal equilibrium. The skin temperature of a healthy individual is normally about 35°C, but may increase by 2 or 3°C without detriment in the case of acclimatised people working in a hot environment.

As the wet-bulb temperature of the air approaches that of the wetted skin, evaporative potential (which is dependent on the vapour pressure gradient between the skin and the air) decreases rapidly, reducing evaporative cooling of the body surface and hence the individual's ability to maintain thermal equilibrium. Although it is not uncommon for underground wet-bulb temperatures to exceed 32°C, a range of 27°C to 28°C has been recommended as an acceptable limit for design purposes (Parsons, 1995) with an upper limit of 32,5°C for routine work (Schutte *et al.*, 1986).

The environment's ability to remove metabolic heat from workers' bodies depends primarily on wet-bulb temperature and air velocity. The two most important ventilation parameters are therefore wet-bulb temperature and air velocity, but knowledge of dry-bulb temperature is required in order to allow calculation of the density and moisture content of the air to assess evaporative potential. The direct effect of dry-bulb temperature on workers is minimal, provided it does not exceed 37°C (Schutte *et al.*, 1986). Strydom (1980) stated that physiologists tend to ignore relative humidity (RH) in conditions where the wet-bulb temperature is below 24°C, and rightly so. Conditions where RH is as high as 100% with a dry-bulb temperature of 30°C are well tolerated by unacclimatised men working moderately hard, provided that these two conditions do not coincide with a wet-bulb temperature higher than 24°C. Where T_{wb} exceeds 24°C, tolerance to such levels of humidity and dry-bulb temperature would be contingent on adequate acclimatisation to heat.

Where the wet- and dry-bulb temperatures are both at a level of 30°C (100% RH), all three avenues of heat loss (convection, radiation and evaporation) would be sufficiently available to the acclimatised man (albeit with some constraints on metabolic work rate) to maintain thermal equilibrium. This is so because a healthy man working under these conditions would have a skin temperature of approximately 35°C, thus providing the necessary temperature gradient for heat loss by convection and radiation. Evaporative heat loss would be possible by virtue of the sweat on the skin's surface being at a temperature of approximately 35°C, i.e. 5°C higher than the air temperature (30°C in the example being considered) and sweat would be evaporated by heat drawn from the skin. The fact that evaporation would be immediately followed by condensation in the air is immaterial, as the cooling benefit would already have been provided and normal ventilation arrangements would maintain the wet-bulb temperature at 30°C.

However, should the differential between T_{wb} and T_{db} be increased by the value of the latter being raised to 35°C (68% RH), heat loss by radiation and convection would become

impossible. The only benefit from such a condition, that of better evaporation of sweat, would be insufficient to compensate for the total elimination of radiation and convection as means of heat loss. Increasing the dry-bulb temperature above the level of the skin temperature to 40°C would actually result in heat gain by radiation and convection. Even without considering the need to shed metabolic heat, it would be detrimental to allow skin temperature to increase beyond 35°C, as the gradient between body core and skin temperatures would become too small for effective heat transfer and, hence, for body temperature regulation. From the above it is obvious that for the conditions of still air and high RH that prevailed in Cornish tin mines, wet-bulb temperature was a good measure of environmental stress. However, it is of limited value for conditions of high air velocity and radiant temperature (Wyndham, undated).

5.2.2.1.2 Air velocity

The second most important variable in assessing workplace thermal conditions is air velocity. Although this parameter alone provides little indication of climatic acceptability, it can be readily considered in conjunction with wet-bulb temperature. This may be achieved by measuring the natural wet-bulb temperature, i.e. the temperature indicated by a non-aspirated wet-bulb thermometer held stationary within the prevailing air-stream or by determining the aspirated wet-bulb using a whirling hygrometer.

5.2.2.1.3 Dry-bulb temperature

Dry-bulb temperature alone has a limited impact on the acceptability of hot mining environments, and it is generally accepted that 37°C is the upper limit for dry-bulb temperature where physical work is to be performed. It has been stated that a 5°C rise in dry-bulb temperature has the same physiological effect as a 1°C increase in wet-bulb temperature at saturation (Strydom, 1980), indicating that a T_{wb}/T_d condition of 30/40°C would be equivalent to a saturated temperature of 32°C.

5.2.2.1.4 Metabolic rate

Based on underground determinations of metabolic work rate for various mining tasks and on workers' body temperature responses to those tasks and the thermal conditions under which they performed them, T_{wb} limits have been recommended with respect to various ranges of metabolic rate (Schutte *et al.*, 1986). These limits are presented in Table 5.2.2.1.4.

Table 5.2.2.1.4

Metabolic rates and associated limits for wet-bulb temperature

| Work rate | Range of metabolic rate | T_{wb} limit (°C) |
|-----------|----------------------------|---------------------|
| Low | 65 – 130 W/m ² | 33,0 |
| Moderate | 130 - 200 W/m ² | 30,4 |
| High | 200 - 260 W/m ² | 28,2 |

Experimental findings and experience have indicated that the classification of an individual as “potentially heat tolerant” during the screening test currently applied at many South African gold and platinum mines does not necessarily indicate an ability to work safely at the temperature limits applicable for (previously) formally acclimatised men. At higher metabolic rates, the wet-bulb temperature limit for a screened but unacclimatised population becomes progressively lower than that applicable to a formally acclimatised group. The

screened population should, however, be able to perform moderate work (<170 W/m²) in environments of up to 29°C wet-bulb temperature (Schutte *et al.*, 1991).

5.2.2.2 Empirical heat stress indices

Empirical indices of heat stress either have been derived from the statistical treatment of responses among volunteers in a controlled work environment, or are based on simplified relationships that utilise measurable parameters but have not been derived through rational or theoretical analysis. Some refer to a single psychrometric parameter, while others consider multiple parameters. These are discussed below.

5.2.2.2.1 Wet-bulb Globe Temperature index (WBGT)

WBGT is certainly the most widely used index. Its origin is in US Navy research undertaken as a result of heat casualties among trainees (Yaglou and Minard, 1957). The intention was to replace, in an approximate manner, the more cumbersome Corrected Effective Temperature index (CET), as well as to account for the absorption of solar heat by military clothing. Demonstrated benefits of its application, in comparison with the previous use of air temperature alone, included reductions in the incidence of heat illnesses and in time lost as a result of training interruptions. WBGT was adopted by NIOSH in 1972, by ISO in 1989 and by the ACGIH in 1990. The method of application specified in ISO 7243 provides rapid assessments of hot environments, specifications for required instrumentation, as well as limits for acclimatised and unacclimatised workers.

Measurements used to calculate the WBGT index are made by means of a 150-mm black globe thermometer, a dry-bulb thermometer and a naturally ventilated wet-bulb thermometer. The natural wet-bulb thermometer (as distinguished from a psychrometric wet-bulb thermometer) consists of a mercury-in-glass thermometer accurate to 0,5°C, with a wet cotton wick sock surrounding the thermometer bulb. The wick is placed in a small Erlenmeyer flask containing distilled water, with 12 mm of exposed wet sock between the thermometer bulb and the flask. For outdoor measurements, a dry-bulb thermometer reading is also considered (Dumka, 1988). The American Conference of Governmental Industrial Hygienists recommend the use of WBGT (ACGIH, 1997), as defined by the two relations (one for indoor use, the other for outdoor applications) that follow:

$$\text{WBGT (indoor)} = 0,7 T_{\text{nw}} + 0,3 T_{\text{g}}$$

$$\text{WBGT (outdoor)} = 0,7 T_{\text{nw}} + 0,2 T_{\text{g}} + 0,1 T_{\text{db}}$$

$$\text{WBGT} = 1,044 \text{ WGT} - 0,187$$

where: T_{wb} = the temperature indicated by a stationary wet-bulb thermometer in the prevailing air stream

T_{g} = the globe thermometer reading

T_{db} = the dry-bulb temperature, and

WGT = the wet globe temperature.

A WBGT threshold limit value of 26°C over an eight-hour shift is recommended for US mines. However, the WBGT index was designed as a means of assessing environmentally imposed thermal stress on workers from an unscreened population, in order to control the risk of unacceptably high body temperatures. In this regard, the worker selection and acclimatisation procedures presently employed in the South African mining industry are designed to identify heat-intolerant individuals who are susceptible to developing heat illnesses and to exclude them from hot workplaces underground. Where such procedures are employed and they are appropriate for workplace thermal conditions, selected individuals can safely work at higher temperatures than would be acceptable for a general or unscreened population (MacPherson, 1984). This lends support to the practice of exposing screened individuals to conditions that exceed the preceding WBGT-based criterion.

The advantages of the WBGT index can be summarised as:

- ❖ WBGT is simple to use in determining levels of heat stress.
- ❖ Discrete measurement of thermal parameters (i.e. air and radiant temperatures and relative humidity) to determine WBGT provides information useful in evaluating the efficacy of environmental control measures, provided appropriate conversion factors between aspirated and natural wet-bulb temperatures are applied (Ramsey and Chai, 1983).
- ❖ Discrete measurement of air velocity, which is difficult to do accurately at low levels, is not required as T_{nwb} takes air velocity into account.
- ❖ WBGT is a reliable indicator of environmentally imposed heat stress and provides a reasonable level of accuracy within its applicable range.
- ❖ Electronic instruments available for measuring WBGT are small in size, require short stabilisation periods and are simple to use.
- ❖ There is a high correlation (0,8 - 0,9) between WBGT and physiological responses in humid environments.

The disadvantages of WBGT as a heat stress index are:

- ❖ WBGT estimates of heat stress become progressively less accurate under conditions of low humidity (Azer and Hsu, 1977), but this would not be a disadvantage in deep-level mining.
- ❖ Although WBGT does allow consistent predictions of physiological responses to different environments, higher air temperatures and work rate and lower humidity levels tend to result in inconsistent assessments (Azer and Hsu, 1977).
- ❖ WBGT does not consider the metabolic workload.
- ❖ Initial costs for instrumentation to determine WBGT are relatively high.

The National Institute for Occupational Safety and Health in the US recommend WBGT as a criterion for heat stress (NIOSH, 1986), with the exposure limits represented in Figure 5.2.2.2.1. Heat stress levels based on the WBGT index have also been the basis of other national and international standards.

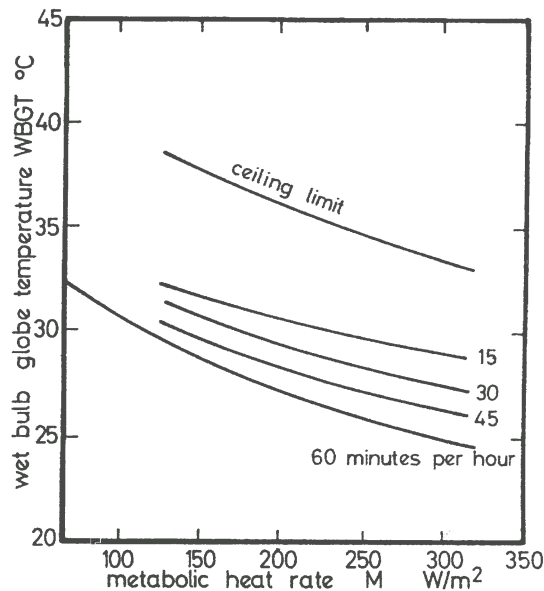


Figure 5.2.2.2.1 *Permissible exposure periods for acclimatised workers with respect to WBGT and metabolic work rate*

5.2.2.2.2 Wet Globe Temperature index (WGT)

The temperature of a wetted black globe of appropriate size can be used as an indicator of heat stress. The underlying principle is that the globe is affected by both dry and evaporative heat transfer in a manner similar to a sweating man, and the value of the temperature so indicated can be used as an indication of heat stress. Olesen (1985) described the WGT as the temperature within a 63,5-mm-diameter black copper globe covered with saturated black cloth. The temperature is read when equilibrium is reached, normally after 10 to 15 minutes of exposure. NIOSH (1986) describe the Botsball (Botsford, 1971) as the simplest, most easily used instrument for assessing human heat stress. It is a 76,2-mm copper sphere covered with a black cloth wetted by a self-feeding water reservoir. The thermal transducer is located at the centre of the sphere and the temperature is read on a (colour-coded) dial.

A simple equation relating WGT to WBGT for conditions of moderate radiant heat and humidity (NIOSH, 1986) is expressed as:

$$\text{WBGT} = \text{WGT} + 2^{\circ}\text{C}$$

This relationship cannot hold over a wide range of conditions and such a simplistic conversion would not be valid for the entire range of thermal conditions likely to prevail in ultra-deep mining.

5.2.2.2.3 (Basic) Effective Temperature and Corrected Effective Temperature indices

Effective Temperature (ET) is an index of relative comfort determined experimentally by successive comparisons of subjective responses to various combinations of temperature, humidity and air movement, immediately upon entering a particular environment. The ET index was suggested by Yaglou (1927) and the Corrected Effective Temperature (CET) index by Bedford (1940). The numerical value for ET is equated with the temperature at which still and saturated air immediately induces a similar sensation of warmth or coolness in the

exposed person as the environment being considered. In practice, ET is determined by reference to purpose-designed charts in which the measured parameters of wet- and dry-bulb temperatures, air velocity and humidity are considered.

Experimentation has indicated that an approximation can be made of ET, in the absence of a chart, by summing 90 % of the wet-bulb value and 10 % of the dry-bulb value. By way of example, the ET (or temperature of saturated air) having the same cooling effect on a person as air at 27/32°C would be 27,5°C. This ET approximation takes no cognizance of air velocity and, accordingly, can only be used for approximate ET determinations. There are, however, modified ET scales that do consider air movement (Dumka, 1988).

The evaluation of ET by physiologists has revealed some shortcomings that limit its valid use in predicting the physiological strain imposed by a particular environment. These include:

- ❖ Insufficient consideration of the deleterious effects of air velocities below 0,5 m/s
- ❖ Overemphasis on high dry-bulb temperatures where air movement is in the range 0,5 to 1,5 m/s
- ❖ Insufficient consideration of the harmful effects of combining high air velocity (greater than 1,5 m/s) and air temperatures exceeding 49°C (hot, humid conditions)
- ❖ Environments that induce similar levels of physiological strain, as assessed by observing workers' rectal temperature, heart rate, sweat rate and tolerance time, often yield different effective temperatures when actual measurements for environmental parameters are evaluated, particularly under conditions of severe heat stress.

Another shortcoming of ET is that it only assesses environmental heat stress, a direct result of the fact that it was developed on the basis of subjective assessments of thermal environments as provided by sedentary people. Where physical work and resultant metabolic heat load combine with environmentally imposed heat stress, it is essential to consider both sources of stress in determining thermal limits. To address this shortcoming would require either a specific ET limit for each work rate or category of occupation/task or, alternatively, modifications of the ET index to account adequately for metabolic heat load.

A number of empirically derived nomograms have been developed for ET since the concept was first proposed. These devices variously utilise wet-bulb temperature, dry-bulb and/or globe temperature. ET nomograms vary in the type of clothing considered, the manner in which wet-bulb temperature is measured and whether consideration is given to dry-bulb temperature, globe temperature or both. Use of ET for certain environmental conditions has been shown to provide misleading indications of the environment's cooling power. This parameter is best regarded as a "comfort index" for sedentary people attired in accordance with the specific variant of ET being employed. It cannot be seen as a heat stress index suitable for hot conditions where physical work is performed and, accordingly, most mining industries have abandoned ET as a means of determining heat stress. It is still used in the UK and Germany where a suggested maximum of 28°C is applied. The Germans also progressively reduce shift duration where ET exceeds 28°C (MacPherson, 1984). ET's continued acceptance in these countries would appear to be at least partially related to lower levels of humidity and higher levels of mechanisation.

ET's overemphasis of the effect of humidity at low temperatures and its underestimation of humidity effects at high temperatures (when compared with steady-state responses) resulted in the need to introduce black globe temperature in place of dry-bulb temperature in the ET nomograms for the CET (Bedford, 1940). Research by MacPherson and Ellis (1960) suggested that the CET index accurately predicts the physiological effects of increased mean radiant temperature.

The advantages of the CET index are:

- ❖ Ability to integrate the four main climatic factors into a single value (Goelzer, 1977)
- ❖ Simplicity and ease of use (WHO, 1969)
- ❖ Usefulness as a design tool for environmental engineers (Fuller and Smith, 1981).

The disadvantages of CET as a heat stress index are:

- ❖ CET has a limited capacity for considering the effects of clothing and metabolic heat generation.
- ❖ Different environments with the same CET value do not necessarily result in the same level of heat strain, particularly where relative humidity is below 40 % (Goelzer, 1977).
- ❖ CET underestimates the adverse effects of high humidity and low air velocity.
- ❖ Updated findings cannot be assimilated into the index to extend its scope or improve its accuracy, as a result of the manner in which it was derived and documented (WHO, 1969).

ET and CET are rarely used as comfort indices nor, as indicated previously for ET, as means for assessing heat stress. Bedford (1940) proposed CET as an index of warmth, with upper limits of 34°C for reasonable efficiency and 38,6°C for physiological tolerance. Subsequent investigations, however, demonstrated serious shortcomings in the ET heat stress index, which led to development of the Predicted Four-hour Sweat Rate index, considered in the subsection on rational heat stress indices.

5.2.2.2.4 Wet-kata thermometer

The wet-kata thermometer was devised as a means of quantifying total heat loss from the skin or the cooling power of the environment under various climatic conditions by representing heat transfer from the skin to the environment. The kata thermometer is an improvement over the wet-bulb thermometer as a means of assessing heat stress as it considers the combined effects of convection, radiation and evaporation. Despite its apparent advantages, little research has been done to quantify the relationships between the heat stress of the environment, as determined by kata-derived cooling power, and the physiological responses of exposed people.

Orenstein introduced the wet-kata thermometer into the South African gold mining industry in 1919 and summarised the relationship between kata cooling powers and workers' responses as indicated in Table 5.2.2.2.4 (Orenstein and Ireland, 1922).

Table 5.2.2.2.4

Relative effect of various levels of environmental cooling power

| Cooling power determined by: | | Assessment of conditions for workers stripped to waist |
|------------------------------|----------|--|
| Wet-kata | Dry-kata | |
| 5 | 1,5 | Extremely oppressive, profuse sweating, rise in body temperature and heat rate, especially during physical work |
| 10 | 3,5 | Distinctly oppressive, normal body temperature maintained only through profuse sweating. Skin flushed and wet, pulse rate high |
| 15 | 5,5 | Lower limit for comfort |
| 20 | 8,0 | Quite comfortable for work |
| 25 | 10,0 | Cool and refreshing for work |

Orenstein and Ireland (1922) determined the endurable lower limit for kata cooling power to be 5. It was also determined that as workers became acclimatised, they could sustain work in moist and still air at wet-bulb temperatures up to 32°C, as compared with the limit of 25°C determined by Haldane (1905). Researchers were apparently aware that the relationship between heat stress from the environment, as measured with the wet-kata thermometer, and human responses to that stress is not a simple one. Despite the environment's cooling effect on the wet-kata thermometer depending primarily on wet-bulb temperature and air velocity, it could not be convincingly demonstrated that wet-kata cooling power offered a convenient and reliable index of comfort under moist conditions. Nevertheless, it was not until 1936 that the kata thermometer appears to have been finally dismissed in the United Kingdom as a means of measuring environmental cooling power and determining heat stress for accurately predicting human responses to work in heat. The major reason for the discrepancy between wet-kata predictions and human responses to environmental heat stress was thought to be that the kata thermometer, being much smaller than a person, is more sensitive in its response to low levels of air velocity.

Use of the wet-kata thermometer has continued in South African gold mines as a means of measuring the cooling power and determining environmental heat stress in workplaces. Readings from a kata thermometer indicate the cooling power of the air by measuring the time to cool a fully wetted thermometer bulb 20 mm in diameter by 2,0°C from an initial temperature of 36,5°C. The wet-kata provides a good indication of the cooling power experienced by acclimatised men working in hot and humid conditions, but is likely to yield unreliable indications of cooling power in dry atmospheres or where workers' skin surfaces are not fully wetted. The wet-kata index is normally stated as a dimensionless value but the underlying unit is, in fact, mcal/cm²/s, as expressed by the following relation (Stewart, 1989a):

$$K_{cp} = (0,7 + V^{0,5}) (36,5 - T_w)$$

where: V = the air velocity in m/s, and
 T_w = the unventilated wet-bulb temperature in °C.

5.2.2.3 Rational heat stress indices

A rational index of heat stress is one that has been established on the basis of the following equation for physiological heat balance (Stewart, 1989a):

$$M = Br + Rad + Con + Evap$$

where:

- M = metabolic heat generation
- Br = respiratory heat exchange (breathing)
- Con = convection
- Rad = radiation, and
- Evap = evaporation.

A model for thermo-regulation can be used for detailed computer-based investigations of existing or proposed facilities. However, for rapid manual assessments or where predictions of average cooling power for a given work area are required, a model for thermo-regulation can be simplified into charts or tables. This involves establishing specific values for the weaker parameters or, alternatively, defining fixed relationships between those parameters and the more dominant variables. A choice must then be made from among the various physiological response parameters that provide an indication of heat strain and climatic acceptability, i.e. body core temperature, skin temperature or sweat rate (MacPherson, 1984). Various rational heat stress indices are considered below.

5.2.2.3.1 Predicted Four-hour Sweat Rate index (P4SR)

The Predicted Four-hour Sweat Rate index was developed by McArdle *et al.* (1947) and evaluated through seven years of work by MacPherson (MacPherson and Ellis, 1960). The index value derived is the amount of sweat secreted by fit, acclimatised young men during four hours of loading naval artillery weapons. The index considers the effects of the six principal environmental parameters. The actual amount of sweat indicated relates to the specific population on which the index is based and should be used only as an index value, not to predict actual sweat rate for workers in a given environment.

It was acknowledged that for sweat rates greater than 5 l per 4 h, P4SR is not a good indicator of heat strain. The P4SR nomograms were adjusted in an attempt to account for this shortcoming, but the index remains inadequate for conditions other than those for which it was derived. In addition, the index oversimplifies the effects of clothing and it appears more useful as a heat storage indicator than as a heat stress index. Accordingly, McArdle *et al.* (1947) proposed a P4SR of 4,5 l as a limit for fit and acclimatised young men.

5.2.2.3.2 Cooling power (CP)

Neglecting respiratory heat exchange and heat transfer by conduction, the cooling power (CP) of any given environment can be calculated as follows (Stewart, 1989a):

$$CP = f_r h_r (T_s - T_r) + h_c (T_s - T_a) + w h_e (p_s - p_a)$$

where:

- f_r = view factor for radiant heat exchange from humans
- h_r = radiant heat transfer coefficient ($W/m^2 \cdot ^\circ C$)
- T_s = average temperature of the body skin surface ($^\circ C$)
- T_a = ambient dry-bulb temperature ($^\circ C$)

T_r = mean radiant temperature of the surroundings ($^{\circ}\text{C}$)
 h_c = convective heat transfer coefficient ($\text{W}/\text{m}^2 \cdot ^{\circ}\text{C}$)
 w = portion of the skin surface which is wet with sweat
 h_e = evaporative heat transfer coefficient ($\text{W}/\text{m}^2 \cdot ^{\circ}\text{C}$)
 p_s = saturated water vapour pressure at T_s (kPa)
 p_a = water vapour pressure in ambient air (kPa).

If the values used for T_s and w in the above equation are linked to a safe rectal temperature as discussed previously, it follows that workers would be able to maintain a safe body core temperature where cooling power equals or exceeds the rate at which metabolic heat is being generated. Two environments with differing thermal characteristics but equal cooling powers can be regarded as imposing the same level of heat stress, in that they will induce the same body core temperature for a given rate of metabolic heat production (Stewart, 1989a).

The cooling power of underground mining environments can be determined from measurements of wet-bulb temperature and air velocity or from wet-kata readings. Cooling power values can be determined from wet-bulb temperature and air velocity by referring to the appropriate cooling power scale (Scale-A for acclimatised workers or Scale-B for unacclimatised individuals) quantified in W/m^2 , using a purpose-designed table. Cooling power can also be determined by relating wet-kata measurements to cooling power from a nomogram for cooling power and wet-bulb temperature (Stewart, 1989b). Cooling power, therefore, simply embodies the principle that a given environment has a quantifiable capacity to cool workers expressed in W/m^2 , the denominator being the individual's skin surface area.

5.2.2.3.3 Air Cooling Power (ACP)

The Chamber of Mines Research Organisation conducted the most comprehensive investigations of heat stress in mining. This resulted in a concept which is fundamentally sound, from both an engineering and a physiological perspective, and defines the balance between metabolic heat (M) and the collective cooling effects of radiation (R), convection (C), and evaporation (E), as expressed in the following relation (Stewart, 1989a):

$$M = R + C + E$$

The units of these parameters are normalised to watts of heat transferred per square metre of skin surface area. Respiratory cooling, conductive heat transfer and mechanical work output are assumed to be negligible. The summation of $R + C + E$ can be regarded as a measure of ACP. Provided this value remains equal to or greater than M, workers will maintain thermal equilibrium. If, on the other hand, metabolic heat production exceeds ACP, the skin temperature of the worker will rise. This may be sufficient to increase ACP until a heat balance is achieved, otherwise the worker's body core temperature will increase. If the latter situation develops and is not alleviated, the worker will exhibit progressive symptoms of heat strain.

The terms of ACP may be computed from the following relations (Stewart, 1989a):

$$\begin{aligned}
 R &= 4,93 (T_{sk} - T_r) \\
 C &= 0,608 P^{0,6} u^{0,6} (T_{sk} - T_{db}) \\
 E &= 965 [P^{1,6} u^{0,6}] / (P - e) (e_{sk} - e)w
 \end{aligned}$$

where:

| | | |
|----------|---|--|
| T_{sk} | = | average skin temperature |
| T_r | = | average radiant temperature of the surroundings |
| P | = | barometric pressure |
| u | = | air velocity |
| T_{db} | = | dry-bulb temperature |
| e | = | actual vapour pressure |
| e_{sk} | = | saturated vapour pressure at skin temperature, and |
| w | = | wetted fraction of body surface. |

The equations that lead to the calculation of ACP are convenient for incorporating into computer programs but cumbersome for manual calculations. For this reason, nomograms and tables are available (Stewart, 1989b) for specified values of T_{wb} (wet-bulb), which are necessary to determine e_{sk} and e where it is assumed that:

$$T_r = T_{db} = T_{wb} + 2$$

An inspection of Figure 5.2.2.3.3 (Stewart, 1989a) indicates that air velocities of approximately 0,5 and 1,5 m/s are required to achieve an ACP of 300 W/m² at wet-bulb temperatures of 27 and 29°C, respectively. It is important to note that increasing air velocity from 0,5 to 1,5 m/s at a constant wet-bulb temperature will increase ACP by approximately 20%. In contrast, decreasing wet-bulb temperature from 31 to 25°C for a constant air velocity of 0,5 m/s will increase ACP by nearly 60%, and would provide an even greater increase in ACP for a velocity of 1,5 m/s.

When designing an environmental control system, ACP can be used to determine the required reject wet-bulb temperature for areas with high air velocities. However, ACP does not lend itself to subsequent monitoring and control in the underground work situation, as it cannot be measured with a single instrument. Non-environmental co-determinants of ACP, such as skin temperature, sweat rate, work rate, etc. are difficult to measure and, thus, reduce the practicability of ACP for monitoring and control purposes. Accordingly, the use of ACP should be limited to design applications, with wet-bulb temperature and air velocity (both of which are readily measured with reasonable accuracy) being used for monitoring specific areas and workplaces.

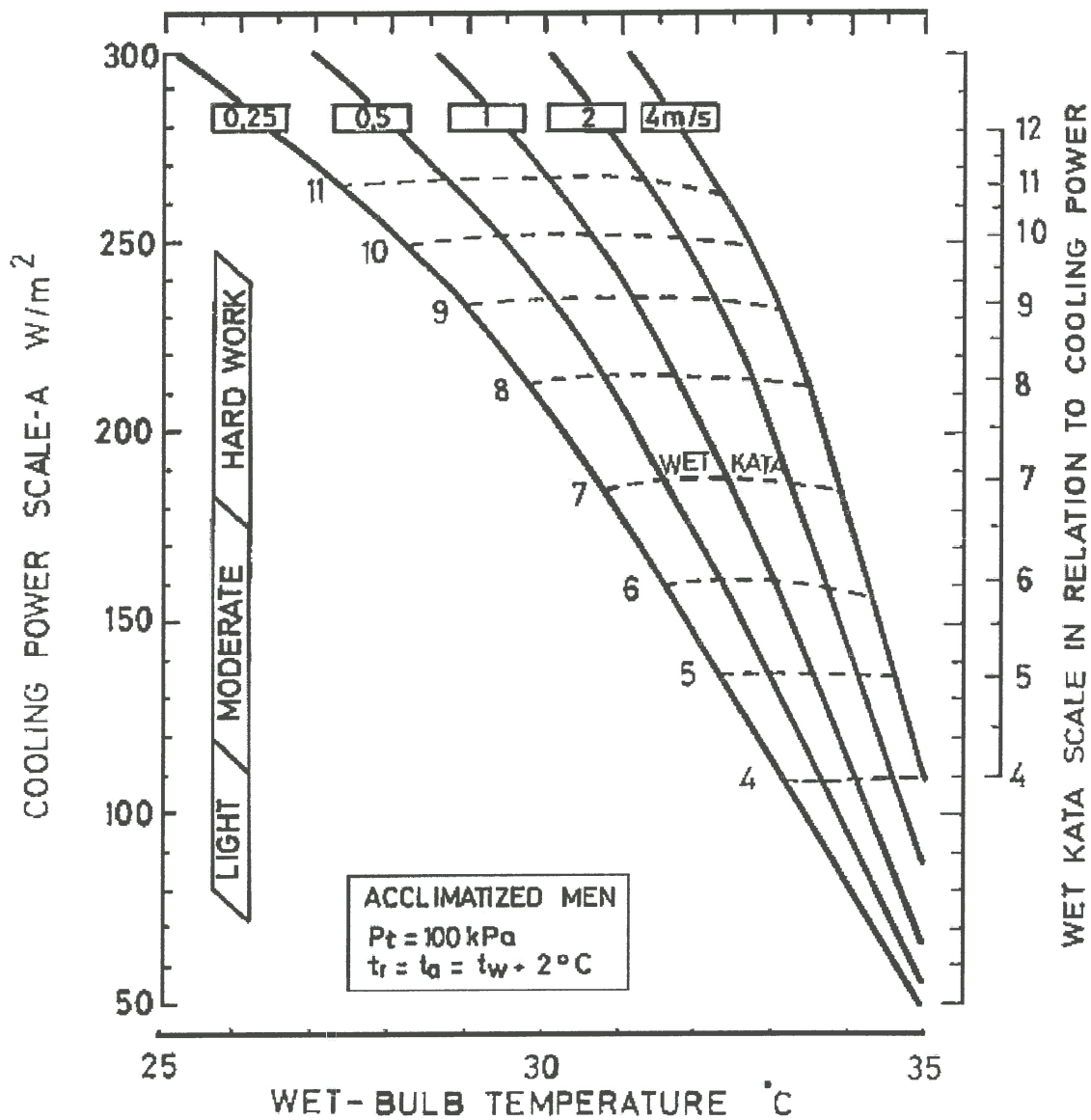


Figure 5.2.2.3.3 Environmental design parameters in relation to Air Cooling Power (ACP)

This more limited definition is sometimes termed the Specific Cooling Power (SCP) or A-Scale cooling power, to distinguish it from general ACP. For design purposes, it has been recommended that ACP should not be less than 300 W/m^2 (MacPherson, 1984). Although lower design and control limits for ACP are in use, most notably in Australia, these are within the context of high levels of mechanisation and air-conditioned operator cabins.

5.2.2.3.4 Specific Cooling Power (SCP)

The ventilation engineer can use calculations of SCP to determine those combinations of temperature and air velocity that most economically provide the required cooling power or rate of cooling. Values for SCP can also be used in conjunction with estimates of metabolic rate to determine the environmental conditions necessary to maintain thermal equilibrium for

a person performing a specific task. Ignoring the negligible amount of energy leaving the body in forms other than heat, a person working in a particular environment will be able to maintain equilibrium for as long as the cooling power of that environment equals or exceeds the metabolic rate associated with the task being performed. An acclimatised worker will be able to maintain equilibrium with a skin temperature of 35°C and experience only mild heat strain if the SCP equals or exceeds the metabolic rate. The metabolic rates typical of light, moderate and hard work are 90, 180 and 270 W/m², respectively.

An analysis of past environmental performance in various GENMIN mines indicated that the average SCP in their deeper and hotter mines was 293 W/m², with values ranging from 241 to 318 W/m² (Dumka, 1988). These related to stopes with air velocities ranging from 0,73 to 1,24 m/s around a mean of 0,93 m/s. The author made the following recommendations for the design of workplace thermal environments:

- ❖ A minimum SCP of 300 W/m²
- ❖ A range of average stope velocities from 0,5 to 1,2 m/s
- ❖ New mine designs should be based on the combinations of wet-bulb temperature and air velocity indicated in Table 5.2.2.3.4.
- ❖ Consideration should be given to the fact that the combined conditions of 0,5 m/s for air velocity and 27°C for wet-bulb temperature provide the greatest safety factor, in terms of catering for ventilation breakdowns or interruptions.

Table 5.2.2.3.4

Recommended combinations of wet-bulb temperature and air velocity

| | | | | | | | | |
|--------------------------------------|------|------|------|------|------|------|------|------|
| Stope face air velocity (m/s) | 0,5 | 0,6 | 0,7 | 0,8 | 0,9 | 1,0 | 1,1 | 1,2 |
| Wet-bulb temperature (°C) | 27,0 | 27,5 | 27,8 | 28,1 | 28,4 | 28,6 | 28,8 | 29,0 |

5.2.2.3.5 The Heat Stress Index (HSI)

The Heat Stress Index is the ratio of evaporation required for maintaining heat balance (E_{req}) to the maximum evaporation that could be achieved in the environment (E_{max}), expressed as a percentage (Belding and Hatch, 1955). Accordingly, HSI is related to heat strain in terms of body sweating and quantified as relative values between 0 and 100. At an HSI of 100, the evaporation required for heat balance or thermal equilibrium would be the maximum achievable in the given environment and, thus, represents the upper limit of the prescriptive zone. At an HSI > 100, body heat storage necessarily occurs, and allowable exposure times are calculated based on a 1,8°C rise in body core temperature (heat storage of 264 kJ). For an HSI < 100, there is a mild cold strain, for example, when workers are recovering from heat strain. The upper limit of 390 W/m² is assigned to E_{max} (sweat rate of 1 ℓ/h, taken to be the maximum sweat rate that can maintained over eight hours, assuming adequate rehydration). Simple assumptions are made about the effects of clothing (long-sleeved shirts and trousers), and the skin temperature is assumed to be constant at 35°C (ILO, 1998).

The advantages of the HSI are that it:

- ❖ Permits the estimation of tolerance periods and required rest intervals (Goelzer, 1977)
- ❖ Is useful in designing and evaluating the efficiency of environmental control systems (Goelzer, 1977)

- ❖ Can be continuously expanded in scope and accuracy as new information on heat exchange is acquired (WHO, 1969)
- ❖ Differentiates between thermal parameters with due consideration to the level of physiological strain they impose.

The disadvantages of the HSI are that it:

- ❖ Is difficult to apply for variable or intermittent heat exposure (Goelzer, 1977)
- ❖ Has been validated only for young acclimatised men (Goelzer, 1977)
- ❖ Involves difficult calculations and requires more instruments than other indices
- ❖ Underestimates the adverse effect of low air velocities in hot, humid environments
- ❖ Does not differentiate correctly between heat generated by physical work and that gained by convection or radiation (Ramsey and Beshir, 1985).

5.2.2.3.6 Index of Thermal Stress (ITS)

Givoni (1963) introduced the Index of Thermal Stress, which was an improved version of the HSI. Its most notable advantage was its provision for the fact that not all sweat secreted evaporates, achieved by appropriately reducing estimates of evaporative cooling (ILO, 1998).

5.2.2.3.7 Required Sweat Rate index (SW_{req})

A further theoretical and practical development of the HSI and ITS was the Required Sweat Rate index (Vogt *et al.*, 1981). It indicates the amount of sweat secretion and evaporation required for maintaining thermal equilibrium by using an improved heat balance equation. More importantly, SW_{req} also provides a practical method for interpreting the results by comparing the amount of sweat required with what is physiologically possible and acceptable. This index was incorporated into ISO 7933 (1989) but with cautionary notes when circulated as a proposed European standard. These concerned methods for assessing dehydration and evaporative heat transfer through clothing as a result of differences between predicted and observed responses among workers.

SW_{req} is based on a less critical aspect of heat strain in that excessive depletion of body water and salt as a result of sweating can be prevented. The values of the P4SR index do not demonstrate such a clear relation between the sweat loss and the more critical parameters of heat strain, such as body core temperature and heart rate.

Reference values for acceptable or practicably achievable sweat rates are used to provide a practical interpretation of calculated values (ILO, 1998). Firstly, predictions of skin wetness (W_p), sweat rate (SW_p) and sweat evaporation rate (E_p) are made. Essentially, if what is calculated as required can be physically achieved, then these become the predicted values (e.g. $SW_p = SW_{req}$). If the required response cannot be achieved, the maximum achievable values can be applied (e.g. $SW_p = SW_{max}$). Where the required sweat rate can be achieved without unacceptable fluid loss, no limit is implied for heat exposure over an eight-hour shift. If, however, the required sweat rate is unachievable or can be achieved only through unacceptable fluid loss, the duration-limited exposure (DLE) is calculated as follows:

where: $E_p = E_{req}$ and $SW_p = DLE_{max}$ (over an eight-hour shift), then

$DLE = 480$ min and SW_{req} can be used as a heat stress index.

If the above conditions are not satisfied, then:

$$DLE_1 = 60 E_{\max} / (E_{\text{req}} - E_p)$$

$$DLE_2 = 60 DLE_{\max} / (E_{\text{req}} - E_p)$$

The duration-limited exposure is determined as the lower of DLE_1 and DLE_2 , measured in minutes.

5.2.2.3.8 Predicted Heart Rate index (T+p)

Fuller and Brouha proposed a simple index based on the prediction of heart or pulse rate (p) in beats per minute (bpm) (ILO, 1998). The relationship, originally formulated for metabolic rate in BTU/h and partial vapour pressure in mmHg, provides a simple prediction of heat stress based on the sum of body temperature and heart rate, hence, the T+p index. Givoni and Goldman (1973) also provided equations for changing heart rate over time, with corrections for the level of workers' acclimatisation to heat (ILO, 1998).

A method of work and recovery heat rate is described by NIOSH (1986), largely based on the work of Brouha (ILO, 1998) and that of Fuller and Smith (1981). Body temperature and pulse rate are measured during recovery from a work cycle or, alternatively, at specified time intervals during the working shift. At the end of the work cycle or at the prescribed time interval, as appropriate, the worker is seated and his oral temperature is recorded along with the following three pulse rates:

| | | |
|-------|---|--|
| p_1 | = | pulse rate measured from 30 seconds to 1 minute |
| p_2 | = | pulse rate measured from 1,5 minutes to 2 minutes |
| p_3 | = | pulse rate measured from 2,5 minutes to 3 minutes. |

The fundamental criterion of the T+p index for determining absence of heat strain is an oral temperature $\leq 37,5^\circ\text{C}$, but the following criteria are also considered:

- ❖ If p_3 is < 90 bpm and/or $(p_3 - p_1) \geq 10$ bpm, this indicates that the work level is high, but there will be little increase in body temperature.
- ❖ If $p_3 > 90$ and/or $(p_3 - p_1) < 10$ bpm, the heat stress is too high and action is needed to redesign the work or reduce the environmental heat stress.

Vogt *et al.* (1981) and ISO 9886 (1992) provide a model using heart rate to assess thermal environments. The component of thermal strain HR_T as a possible heat stress index can be calculated from the following:

$$HR_T = HR_r - HR_0$$

where: HR_r = heart rate after recovery, and
 HR_0 = resting heart rate in a thermally neutral environment.

An acceptable average heart rate for prolonged work in hot environments is 120 to 130 beats per minute, not to be exceeded during any hour, while a rate of 180 beats per minute is generally regarded as a safe limit for fit people over limited periods.

5.2.2.3.9 Index of Physiological Effect (IPE)

Sweat rate and skin temperature are secondary indicators of heat strain in comparison with the fundamental parameters of body core temperature and heart rate. The Index of Physiological Effect (IPE) was design to reflect both fundamental and secondary responses by including all four of the following criteria:

- ❖ Body core temperature
- ❖ Heart rate
- ❖ Sweat rate
- ❖ Skin temperature.

Despite the IPE's incorporation of multiple physiological responses as criteria of heat stress, the index did not gain widespread acceptance, mainly because the effects of radiant heat and air velocity were not incorporated into the empirical charts developed for the index.

5.3. Comparison of relevant heat stress indices

A heat stress index 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 cognizance 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 NIOSH emphasise the requirement that measurements and calculations must be simple and predictive of workers' physiological strain. The 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.*, 1980).

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.

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, WGT, ACP, SCP, wet-bulb temperature and wet-kata indices. All of these provide an accurate indication of heat stress for typical underground gold mining environments. They are compared by means of an example constructed from a specific set of underground conditions as indicated in Table 5.3.

Table 5.3

Underground thermal conditions for comparison of 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 |
| Barometric pressure | 87,1 kPa |
| Air velocity | 0,25 m/s |
| Metabolic heat load for light work rate | 100,0 W (assumed) |

5.3.1. Empirical heat stress indices

The thermal conditions tabulated above are assessed by means of the four empirical heat stress indices identified as potentially relevant to ultra-deep mining, as indicated in Table 5.3.1a.

Table 5.3.1a

Assessment of given conditions by single measurement and empirical heat stress indices

| Heat stress index | Result |
|--|--|
| Psychrometric wet-bulb (T_{wb}) | 29°C (measured) |
| Wet-kata (K) | 9 (measured) |
| Wet globe temperature (WGT) | 31,8°C (measured) |
| Wet-bulb globe temperature (WBGT), no radiant heat load | $0,7 T_{nwb} + 0,3 T_g$ or $1,044 (WGT) - (0,187) = 33,0°C$ |

The assessment results in Table 5.3.1a indicate the level heat stress for the given set of environmental conditions, which are then characterised in Table 5.3.1b.

Table 5.3.1b

Characterisation of given thermal environment based on results from four empirical heat stress indices

| Heat stress index | Result | Characterisation of conditions |
|-------------------|--------|--|
| T_{wb} | 29,0°C | Only acceptable with formal heat stress management (1,6°C higher than non-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 |

5.3.2. 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.

5.3.2.1 Air Cooling Power

Reference is made to Figure 5.3.2.1 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 5.3) has a T_{db} 7°C higher than the T_{wb} . The relevant values for ACP (M scale), as read from Figure 5.3.2.1 are approximated in Table 5.3.2.1.

Table 5.3.2.1

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 |

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/m² 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 ($130\text{-}200 \text{ W/m}^2$). Furthermore, the only way for workers engaged in heavy work ($200\text{-}260 \text{ W/m}^2$) 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.

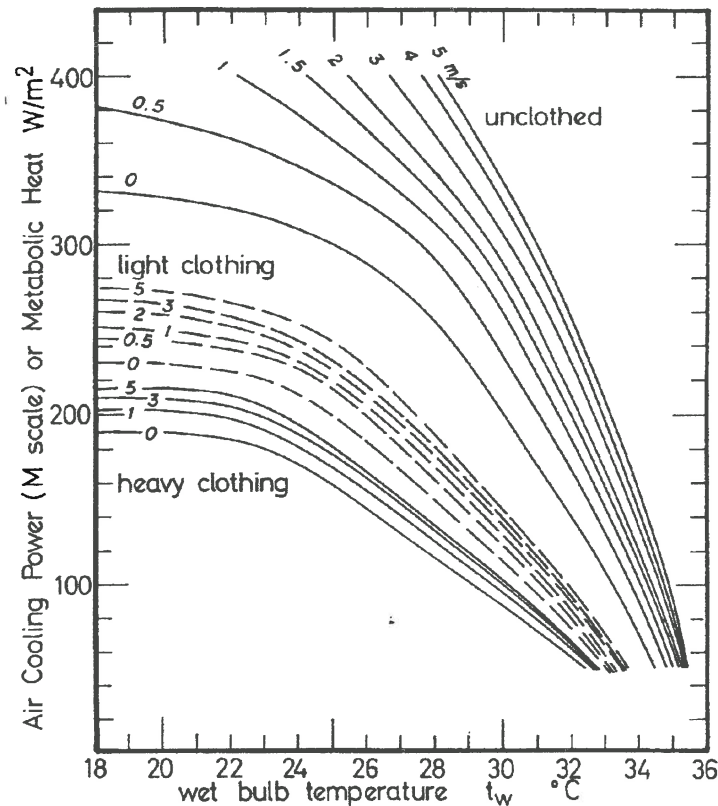


Figure 5.3.2.1 Air Cooling Power (M scale) or ACPM

5.3.2.2 Specific Cooling Power

Figure 5.3.2.2 can be used to determine the Specific Cooling Power (SCP) for the same conditions considered above (air velocity $0,25 \text{ m/s}$ and $T_{wb} 29^\circ\text{C}$). As was the case for the ACP nomogram, the figure below assumes T_{db} to be a function of T_{wb} ($T_{wb} + 2^\circ\text{C}$ 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. However, the given environment's SCP would be inadequate for mid-moderate and heavy work, which require approximately $160\text{-}200$ and $200\text{-}260 \text{ W/m}^2$, respectively.

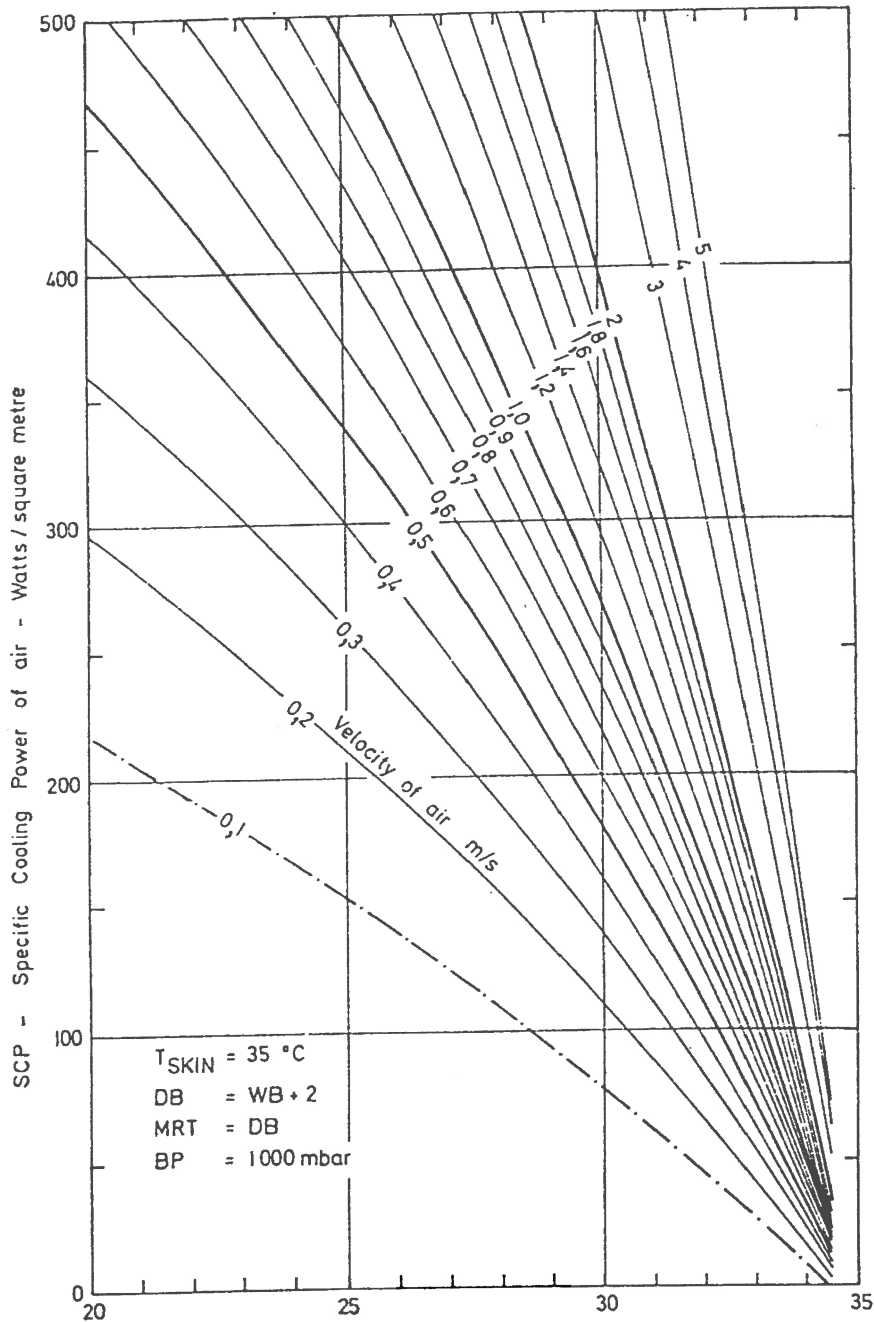


Figure 5.3.2.2 SCP values for various air velocities

5.4. Design of workplace air temperatures

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. Research and experience have

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 and this is prescribed in the legislation. 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, 1991). 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 minimise 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, 1996).

5.5. Heat stress limits for work in mines

The upper physiological limit for heat strain cannot be used as a criterion for hard work over an eight-hour shift on an ongoing or daily basis. Such work regimens upset the steady state of the human circulatory and heat regulatory systems, with long-term health implications for workers. A more immediate potential effect would be a negative impact on productivity and safety. As an example, using the P4SR index, 3 ℓ of sweat represents the upper tolerable limit for fit, unacclimatised men over an eight-hour shift (Leithead and Lind, 1964), and a P4SR value of 4,5 ℓ was characterised as beyond the endurance of fit, acclimatised men (MacPherson and Ellis, 1960). Similarly, young, fit, well-acclimatised and highly motivated individuals could hardly complete four continuous hours of moderately hard work above a CET of 33°C (Eichna *et al.*, 1947).

This illustration seems to imply that adherence to the present wet-bulb temperature limit of 32,5°C for routine work, while physiologically tolerable, would be likely to lead to reductions in work and safety performance, with ultimate impact on productivity and profitability. Accordingly, a thermal limit more conducive to safe and productive work is indicated for ultra-deep mining, which should consider the results of tests on cognitive ability.

6. International standards

6.1. Background

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.

Recognised national and international institutions that have produced such standards or guidelines include (Parsons, 1995):

- ❖ 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 Standardisation under the CEN
- ❖ The Hardcoal Industry of the Federal Republic of Germany
- ❖ The International Labour Organisation (ILO)
- ❖ The International Standards Organization (ISO)
- ❖ The Occupational Safety and Health Administration (OSHA) in the USA
- ❖ The Standards Advisory Committee on Heat Stress (SACHS)
- ❖ The World Health Organization (WHO)
- ❖ The National Institute for Occupational Safety and Health (NIOSH) in the USA
- ❖ Various national standards bodies and institutes.

Heat stress indices are included in or referred to by various standards to provide methods and limits for the design, assessment and control of hot environments. Such indices are described in the present report, with particular reference to those from the International Organization for Standardization (ISO) concerning the ergonomics of thermal environments.

6.2. International Labour Organisation

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 computerised software for solving ventilation network problems.

Recommendation 183, from the International Labour Organisation’s Conference on Safety and Health in Mines (ILO, 1998), 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.

6.3. 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, 1969). 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. Consultations with Dr Shasha at the World Health Organization offices in Pretoria aimed at determining whether any further recommendations have been made by that organisation yielded no useful information.

6.4. NIOSH and ACGIH standards

NIOSH (1972) 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 6.4 (ACGIH, 1997).

Table 6.4

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

| Work pattern | WBGT limit (°C) for given workload and 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 |

Higher exposures than those specified by the NIOSH and ACGIH 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.

6.5. OSHA standards

OSHA 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 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:

$$\text{WBGT} = (0,7 T_{\text{nw}}) + (0,3 T_{\text{g}})$$

where: T_{nw} = 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_{nw} .

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, 1977).

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 6.5.

Table 6.5
OSHA-recommended WBGT TLVs for various workloads

| Workload | Threshold limit WBGT values 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 |

6.6. Assessment of hot environment using ISO standards

A hypothetical example from Parsons (1995) 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 h in a hot radiant environment. They then rest for 1 h, after which they perform the same light work for 1 h 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.

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 unacclimatised 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 (1982) and ISO 9920 (1993) 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 (1993) provides guidance on medical supervision for such investigations (ILO, 1998).

6.7. Regulatory requirements

6.7.1. Introduction

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

6.7.1.1 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, undated). 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 $27,5^{\circ}\text{C}$, 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 (1998) 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.

6.7.1.2 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:

- a) Remove atmospheric contaminants resulting from blasting and other mining operations in the time allowed for that purpose, and
- b) 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

- 1) 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.
- 2) 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.
- 3) 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:
 - a) 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 6.7.1.2 ACP is also applied for design purposes. In considering the tabulated values, it must be appreciated that levels of mechanisation 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 mechanisation and on the micro-environments ultimately applied in ultra-deep mining, the ACP limits

indicated in Table 6.7.1.2 may not be sufficiently conservative for application to ultra-deep mining.

Table 6.7.1.2

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 | Acclimatise exposed workers |
| >220 W/m ² | Acceptable conditions |

6.7.1.3 United States

A report by Misaqi *et al.* (1975) 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.

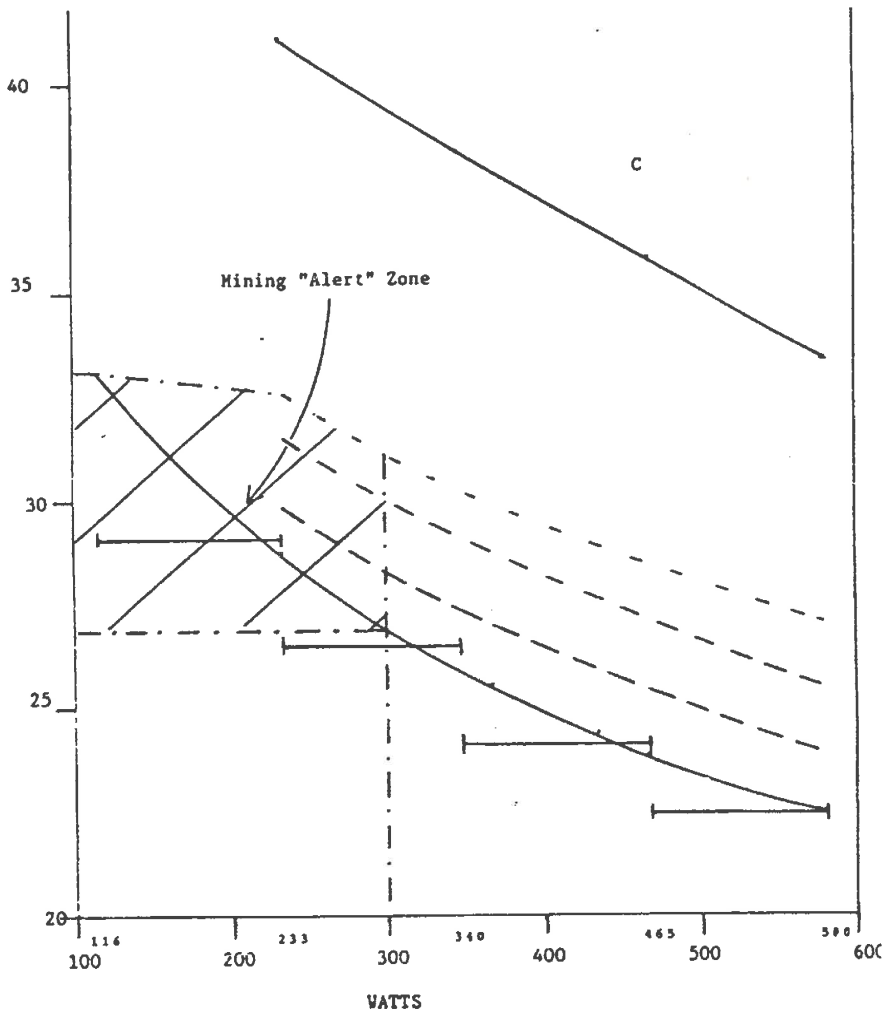
6.7.1.4 Other countries

Table 6.7.1.4 compares the heat stress indices and limits used internationally, as compiled by Graveling *et al.* (1988). 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.

Table 6.7.1.4
Comparison of heat stress criteria used in various countries

| Country | Source | Criteria | Comment |
|---------------|---|---|--|
| USA | ACGIH AIHA OSHA NIOSH (1986) | $T_r = 38,0^\circ\text{C}$ | 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 acclimatisation 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) | <p>Non-salt mining:</p> <ol style="list-style-type: none"> 1. for $T_{db} > 28^\circ\text{C}$ or $\text{BET} > 25^\circ$: <ol style="list-style-type: none"> a) 6-h max shift if ≥ 3 h at: <ol style="list-style-type: none"> i. $T_{db} > 28^\circ\text{C}$ (to max. BET of 29°C), or ii. $\text{BET } 25\text{-}29^\circ\text{C}$. b) 5-h max shift if $> 2,5$ h at BET of $29\text{-}30^\circ\text{C}$. 2. Personnel should not be exposed to $\text{BET} \geq 30^\circ\text{C}$, except for a 4-month max period directly followed by a 6-week break and <ol style="list-style-type: none"> i. if $\text{BET} = 30^\circ\text{C}$, a max 5-h daily exp. or ii. if $\text{BET} > 30^\circ\text{C}$, 2,5-h max. daily exp. 3. In face operations, only 1/3 of employees can be exposed to a $\text{BET} \geq 30^\circ\text{C}$. | <p>$\text{BET} = \text{Basic Effective Temperature}$</p> <p>Provisions made for rest breaks, period of acclimatisation, workers' age and work to be performed during emergencies, e.g. mine rescue operations</p> |
| | | <p>Salt mining:</p> <ol style="list-style-type: none"> 1. For $T_{db} > 28^\circ\text{C}$: <ol style="list-style-type: none"> a) 7-h max shift if: <ol style="list-style-type: none"> i. more than 5 h at T_{db} of $28\text{-}37^\circ\text{C}$, or ii. more than 4,5 hours at T_{db} of $37\text{-}46^\circ\text{C}$. b) 6,5-h max shift if 4 h at T_{db} of $46\text{-}52^\circ\text{C}$. 2. Personnel should not be exposed to $T_{db} > 30^\circ\text{C}$ or $T_{wb} > 27^\circ\text{C}$, 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 $\text{BET} < 30^\circ\text{C}$. |
| Great Britain | National Coal Board (1980) National Coal Board (1963) Lind (1963) WHO (1969) | <p>$\text{BET} > 28^\circ\text{C}$ for 1,5 hours during any shift incurs a heat allowance payment.</p> <p>$27,2^\circ\text{C}$ part. mechanised $28,3^\circ\text{C}$ fully mechanised</p> <p>$\text{BET } 30,2^\circ\text{C}$: 210 W $\text{BET } 27,4^\circ\text{C}$: 349 W $\text{BET } 26,9^\circ\text{C}$: 490 W</p> <p>$\text{BET } 30,0^\circ\text{C}$: light work $\text{BET } 28,0^\circ\text{C}$: mod. work $\text{BET } 26,5^\circ\text{C}$ hard work</p> | <p>Watts as the product of metabolic work rate and body surface area, typically $1,8 \text{ m}^2$</p> <p>Not highly acclimatised but well trained for work</p> <p>$\text{BET} = \text{Effective temperature, basic scale}$</p> |

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 acclimatised mineworkers, are graphically represented in Figures 6.7.1.4a and 6.7.1.4b, respectively.



(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 6.7.1.4a *US heat stress criteria in relation to Basic Effective Temperature (BET) and work rate*

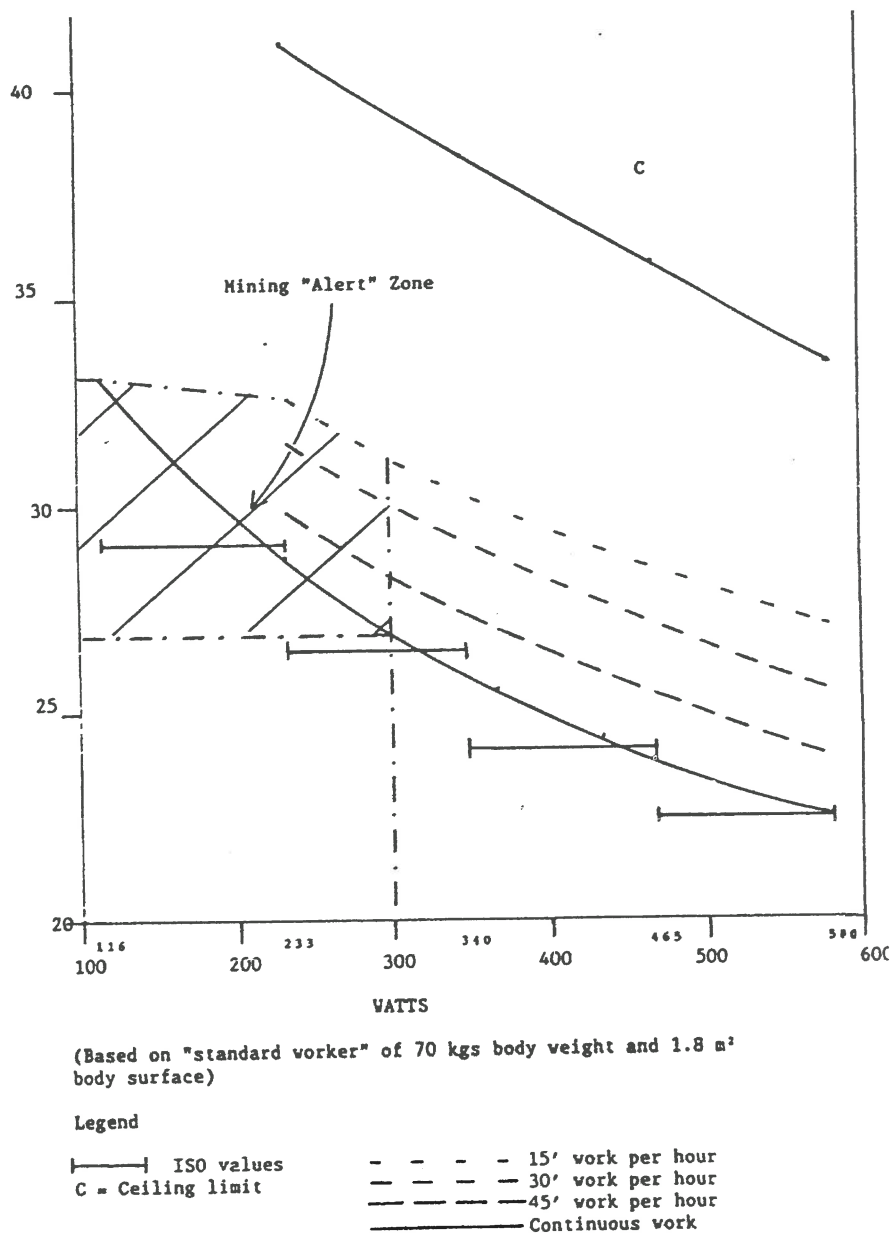


Figure 6.7.1.4b *NIOSH and ISO heat stress limits for acclimatized mineworkers in terms of WBGT and metabolic heat load*

6.7.2. Search for a standard index

As stated before in subsection 5.3, a heat stress index should satisfy the following criteria before it can be considered as a standard for industrial use:

- ❖ Be applicable to and accurate within the range of conditions for which it will be used
- ❖ Take cognizance 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.

The keywords in the above criteria are *applicable*, *simple* and *appropriate*. The problem then becomes one of incorporating the 20 or more factors contributing to heat strain into a simple, practicable and all-inclusive index, preferably in the form of a numerical scale. The ET, P4SR, HSI and WBGT indices satisfy most of these criteria and requirements.

Among the criteria given by NIOSH for selecting a suitable heat stress index to be used in an industrial environment are: (a) measurements and calculations should be simple and (b) index values should be predictive of the physiological strain resulting from workers' exposure. The WBGT meets the requirement for simple measurements and calculations. Other indices used extensively in industrial applications are: ET, CET, HSI and, less commonly, WGT (Chomposakdi *et al.*, 1980).

For most hot industrial situations, the objective is to choose the heat stress index that will indicate the overall stress imposed on workers most accurately, as well as being reliable and valid. In addition, it must be relatively easy to use and require minimal expenditure for manpower and instrumentation. When all of these factors are considered and appropriately weighted, the index or indices chosen for routine use in hot, humid environments may not be those that have the highest multiple correlation coefficients with overall physiological strain (Chomposakdi *et al.*, 1980).

Many investigators have already demonstrated that working in hot, humid conditions may result in greater physiological strain than working in hot, dry conditions, due to the limitations imposed on evaporative cooling. In future, the use of separate heat stress standards for hot, dry and for hot, humid conditions may be a useful alternative for controlling heat stress and strain. The same could be said for different workloads. Therefore, for ease of application, it is important to define distinctions based on environmental conditions and workloads in practical terms and for boundaries to be defined and indicated on psychrometric charts.

7. Results and discussion

7.1. Relevant environmental factors and dependence on depth

The findings of the investigation thus far indicated that cost-effective provision of acceptable thermal conditions in the workplace will be the greatest environmental control challenge in ultra-deep mining since the impact of most other environmental aspects is not expected to differ materially from what prevails at current mining depths. The influence of the cost aspect will be dealt with in detail in Section 8. The purpose of summarising the work done so far is to make it possible to use the results obtained in the various costing simulation models that follow.

It must be noted that barometric pressure (and its potential to cause baro-trauma and increase the toxicity of airborne pollutants) is a separate field of expertise and is being dealt with by CSIR Miningtek in detail. Since they are not dependent on depth, physical stresses such as noise, vibration, lighting/visibility, etc. should not differ materially from what prevails at current depths and, accordingly, the present standards and exposure limits for their control can be regarded as sufficiently protective for workers in ultra-deep mining environments.

7.2. Controlling the effects of heat stress on workers

The present findings on heat stress consider locally and internationally applied standards, exposure limits and indices and, to the extent that the information is available, include the bases for thermal limits in hot, humid underground mines. The limited information available from international sources that is relevant to underground mining appears to indicate that in fact more and better knowledge of human heat stress in a mining context has been developed locally. Accordingly, planning for cooling and ventilation requirements in ultra-deep mines should be based on a combination of best features of relevant heat stress indices and locally developed knowledge of human tolerance limits for safe and productive work.

Creating a suitable environment for removing metabolic heat from workers' bodies and thus limiting the negative impact on their health, safety and productivity, depends primarily on the wet-bulb temperature and air velocity, with the wet-bulb temperature having been proved to be the most useful single-measurement indicator of environmental heat stress. Although the wet-bulb temperature alone is of limited value under conditions of high air velocity and radiant temperature, such conditions would be relatively uncommon in ultra-deep mining. Where a high radiant temperature is possible, either as a result of rock being newly exposed or where diesel-powered equipment is used, this parameter must be taken into account in the assessment, either directly or by means of an appropriate heat stress index. Dry-bulb temperature has been shown to have a limited impact on the acceptability of workplace environments, with 37°C presently regarded as the upper limit for South African mines.

7.3. Heat stress indices and limits

Any heat stress index or indices ultimately adopted for ultra-deep mining should satisfy the following criteria:

- ❖ Be applicable to and accurate within the range of conditions being assessed
- ❖ Take cognizance of all relevant parameters of heat stress
- ❖ Be applicable through simple measurements and calculations, i.e. practicable
- ❖ Apply valid weighting to all factors considered, in direct relation to their contribution to total physiological strain and impact on work performance
- ❖ Provide an appropriate and practical basis for designing and enforcing regulatory standards and exposure limits.

7.4. Design and planning

A number of heat stress indices meet the above requirements to varying extents, 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, as it is a rational index combining all the determinants of environmental cooling capacity and relates directly to engineering design parameters. 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.

7.4.1. Workplace monitoring

Workplace monitoring should be performed on an ongoing basis and without undue reliance on specialised 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 specialised heat stress evaluation tool, not practicable for routine workplace monitoring by production personnel.

The wet-bulb temperature, as a single-measurement heat stress index, 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.

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 (Parsons, 1995), with the upper limit for routine work set at 32,5°C (Schutte *et al.*, 1986). There is nothing in the way of subsequent research findings to support an expansion of these upper limits. On the contrary, their basis on physiological tolerance criteria, together with the fact that work performance and safety would have a critical impact on the success of ultra-deep mining, may indicate a need for lower wet-bulb temperature limits than those currently applied. Accordingly, decisions relating to the thermal limits ultimately adopted for ultra-deep mining should consider the impact of heat stress on workers' performance and cognitive ability.

Given the ranges of relative humidity and air velocity presently prevailing underground and those anticipated for ultra-deep mining, wet-bulb temperature is likely to remain the most useful means of monitoring environmental heat stress. Where these parameters are likely to differ from current norms, ACP should prove to be the most useful basis for quantifying cooling requirements for ultra-deep mines, with its value being used for design purposes. If a combination of indices is adopted to provide for different applications (e.g. designing and planning vs. monitoring), cognizance must be taken of variations in their bases for assessing thermal environments to avoid discrepancies between design and workplace conditions.

7.5. Issues identified by industry practitioners

The input from environmental control practitioners indicates that the most critical interactions between environmental factors, most notably heat, and operational factors/contributors/constraints involve aspects that are closely related to the thermal environment. All the relevant factors and their dependence on depth have been fully covered in this section which gives a thorough summary of the aspects to consider in dealing with the environmental issues of ultra-deep mines.