Determining the Physical and Economic Impact of Environmental Design Criteria for Ultra-deep Mines

Mr RCW Webber

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ABSTRACT

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.

The purpose of this project was therefore to investigate the physical and economic impact of environmental design criteria to be used in ultra-deep-level mining. It was necessary to establish a new basis from which the cooling and ventilation requirements for ultra-deep mines could be simulated and evaluated. For this reason it was important to establish in what way these environmental design parameters would affect the productivity of the workforce (physiologically and psychologically) and what economic and environmental constraints would be involved.

Another purpose of this investigation was to establish the basis and application of workplace environmental criteria, standards and limits, both locally and internationally, to determine norms for occupational exposure to various environmental stressors and to evaluate standards for controlling them. The motivation was to ascertain the requirements for providing environmental conditions that would compare favourably and defensibly with those in other mining industries and to ensure the health, safety and productivity of workers, as well as the confidence of potential investors. A further aspect of the work was reviewing the relevant environmental factors in order to identify those that would become more critical at mining depths approaching 5 000 m, including their potential impact on workers and the extent to which they would affect mine designs and planning. The relevant standards and limits pertaining to the factors identified were then evaluated in terms of their

appropriateness and practicability for ultra-deep mining, and their cost implications were analyzed for the mining depths being contemplated.

The local and international use of heat stress limits, criteria and indices were also investigated. These are intended to ensure the health, safety and productivity of workers and, in the case of a heat stress index, to quantify the level of heat stress imposed by the environment. It was necessary to determine to what extent any other indices, limits or criteria would be applicable to South African deep mine conditions. In addition, it was necessary to establish whether there was a single heat stress index that could be used for South African deep mining conditions. Various practitioners from the industry were also consulted with regard to parameters that might influence ultra-deep mining.

Six heat stress indices that satisfied most of the important criteria were identified. The findings detailed in this report indicate that it is likely that an appropriate combination of heat stress indices will be required in planning for and ultimately controlling thermal conditions in ultra-deep mining. The depths being contemplated and the concomitant potential heat hazard present too great a risk for reliance on a single heat stress index, such as the wet-bulb temperature index at present in common use locally. Although this index is expected to be useful in ultra-deep mining, it is likely that it would be more beneficial when used in combination with others, such as wet-kata cooling power and specific or air cooling power (SCP and ACP, respectively). This would allow the use of the index most appropriate for a specific purpose, for example determining ventilation and cooling requirements, specifying minimal cooling power/maximal heat stress limits or monitoring workplace conditions. However, it would be essential to ensure that any inconsistencies among the indices adopted for these various purposes are quantified in order to avoid discrepancies between what is stipulated or planned and what is ultimately achieved. It was found that numerous heat stress indices are currently applied throughout the world's mining industries, and that some countries use a combination of indices as a means of specifying and quantifying heat stress limits.

The need to quantify the costs associated with various levels of wet-bulb temperature and air velocity (the two most important determinants and means of controlling heat stress) was *addressed through an analysis of a model mine operating at a depth of approximately 5 000 m. Several combinations of these two parameters were considered and the costs compared, enabling an assessment to be made of the relative costs involved in limiting environmental heat stress at various levels. It was also found that the ideal situation would be to provide a reject wet-bulb temperature of 25°C or, at least, lower than 27,5°C, to ensure productivity or, alternatively, to control the risk of heat disorders without resorting to formal heat stress management and all that it entails. The decision as to whether to provide a reject wet-bulb temperature of, say, 25°C or 27°C requires incremental quantifications of the decrement in performance and the difference in cost implications between such temperature levels. This would be particularly important for critical mining tasks and should clearly be considered in combination with the results of a detailed analysis of the costs of providing these various levels of wet-bulb temperature.*

From this investigation it was also found that it is possible that the provision of a given level of cooling power at a working depth near 5 000 m would be more cost-effective through increasing refrigeration and reducing the amount of ventilation air. This implies that lower wet-bulb temperatures may be more viable than had previously been expected.

The specific wet-bulb temperatures and stope face air velocities used in this study were adopted for the purpose of comparative cost analyses and should not be regarded as recommended levels. Such levels can only be determined through due consideration of the relevant physiological and work performance criteria, and within the specific design constraints for each mine. It is therefore imperative that the results of this investigation be interpreted with circumspection as the cost implications for environmental control in ultra-deep mining appear to differ significantly from those for current mining depths. However, the major conclusion, namely that reducing the design reject wet-bulb temperature, within limits, does not affect ventilation and cooling costs to the same extent as increasing the total air-flow quantity, appears to be valid for the mining depths being contemplated. In this regard, the simulation results indicate a cost increase of approximately 30% for reducing wet-bulb reject temperatures from 31°C to 25°C, as opposed to an increase of approximately 60% for increasing the stope face air velocity from 0,5 to 1,5 m/s.

Although it is recommended that the required level of environmental cooling power be provided at a minimum total air mass flow rate, it is recognised that practical constraints will dictate the minimum air flow quantity that can be used. Should existing mines be extended to ultra-deep levels, increasing refrigeration capacity may be preferable to increasing air quantities, given the relatively higher costs implied by the latter approach. To further contain the cost of providing a given air velocity at great depth, recommendations are provided on the implementation of controlled recirculation strategies. It must be noted, however, that such an approach could indicate the need to consider reducing emissions at source and/or introducing control measures for major contributors to air pollution in order to control air quality. In this regard, the potential benefits of controlled recirculation, together with the problems that could arise from its inappropriate implementation, formed an integral part of this investigation. An indication of the optimal use of controlled recirculation is also given.

From the various recirculation models for a longwall follow-behind mining layout that were investigated, it was found that global recirculation of air seemed to be the most cost-effective system in planning ventilation requirements at ultra depth. It was also found that a global recirculation percentage of return air of approximately 30% seemed to be the optimum for planning purposes with this type of mining layout. It appears that the application of recirculation strategies will be imperative in future if mining is to be done profitably. A saving of approximately 5% with recirculation was indicated in a comparison with a base-case ultra-deep-level simulation in which there was no recirculation of air. An expected cost figure of $38.9, in terms of dollar/ounce of gold produced, for the cooling and fan requirements for ultra-deep-level mining was calculated. The simulations done were based on conditions for a typical ultra-deep-level mine in the Carletonville area.

Finally, practitioners indicated the need for a multi-disciplinary approach to planning mine environmental control systems, for the establishment of a common virgin rock temperature database and for measures to control air pollutants based on health risk assessments. They also identified the need for research to resolve uncertainties regarding the significance of backfill as a heat source and regarding the control of heat transfer through the effective use of insulation. Practitioners' differing views on issues such as open-circuit vs. closed-circuit *pumping, surface vs. return airway heat rejection, and ice vs. chilled water as a cooling medium may be similarly indicative of additional research needs.*

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Nomenclature

°C	Degrees centigrade
ACGIH	American Conference of Governmental Industrial Hygienists
ACP	Air Cooling Power
AIHA	American Industrial Hygiene Association
ASHRAE	American Society for Heating, Refrigerating and Air Conditioning Engineers
BET	Basic Effective Temperature
BP	Barometric pressure
Bpm	Beats per minute
Capex	Capital expenditure
CET	Corrected Effective Temperature
CP	Cooling Power
CRA	Climatic room acclimatisation
DB	Dry bulb
DME	Department of Minerals and Energy
ET	Effective Temperature
FV	Face velocity
h	Hour
HSM	Heat stress management
HTS	Heat tolerance screening
HTT	Heat tolerance testing
ILO	International Labour Organisation
IPE	Index of Physiological Effect
ISO	International Standards Organisation
ITS	Index of Thermal Stress
J	Joule
km	Kilometre
kt	Kiloton
kW	Kilowatt
kWh	Kilowatt-hour
ℓ	Litre
L/M/H	Low/medium/high
M	Mega-
m	Metre
min	Minute
MRC	Medical Research Council
MRT	Mean radiant temperature
NIOSH	National Institute for Occupational Safety and Health
Opex	Operating expenditure
OHSA	Occupational Health and Safety Act
PV	Present value
R	Rand
RH	Relative humidity
RI	Relative importance
s	Second
SCP	Specific cooling power
SCSR	Self-contained self-rescuer

SW_{req}	Required Sweat Rate index
T_{db}	Dry-bulb temperature
T_g or T_r	Globe temperature/radiant temperature
T_{mr} or MRT	Mean radiant temperature
T_{nwb} or T_w	Natural or unventilated wet-bulb temperature
T_{wb}	Psychrometric or ventilated wet-bulb temperature
TLV	Threshold limit value
UDM	Ultra-deep mining
U/G	Underground
UN	United Nations
V or u	Air velocity
VRT	Virgin rock temperature
W	Watt
WB	Wet-bulb
WBGT	Wet-bulb globe temperature
WGT	Wet globe temperature
WHO	World Health Organization

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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**	**Radia-tion**	**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 recooled 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 recooled 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 *ad hoc* 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 emmissivity 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 27ºC or 28ºC may be employed as a criterion above which work rates or shift hours are reduced, while 32,5ºC 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/m^2) 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:

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

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

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

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.

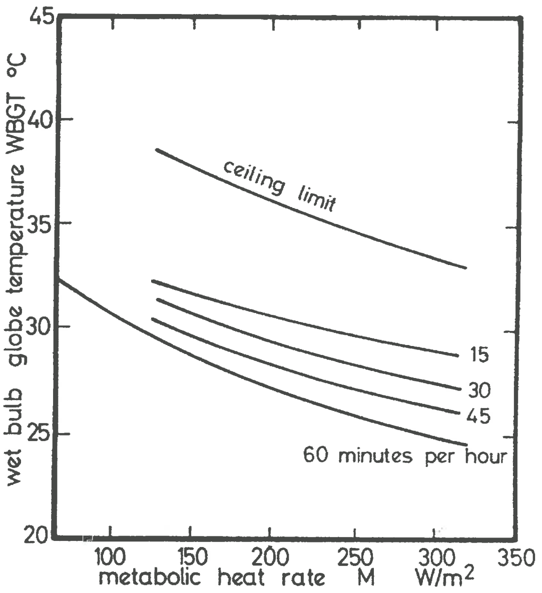


Figure 5.2.2.2.1 ***Permissible exposure periods for acclimatised workers with respect to WBGT and metabolic work rate***

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:

$$\text{WBGT} = \text{WGT} + 2°\text{C}$$

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 sub-section 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/cm^2/s, as expressed by the following relation (Stewart, 1989a):

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

where: V = the air velocity in m/s, and
$\mathrm{T_W}$ = 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):

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

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

T_r = mean radiant temperature of the surroundings (°C)
h_c = convective heat transfer coefficient ($W/m^2.°C$)
w = portion of the skin surface which is wet with sweat
h_e = evaporative heat transfer coefficient ($W/m^2.°C$)
p_s = saturated water vapour pressure at Ts (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):

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

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/m^2 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.

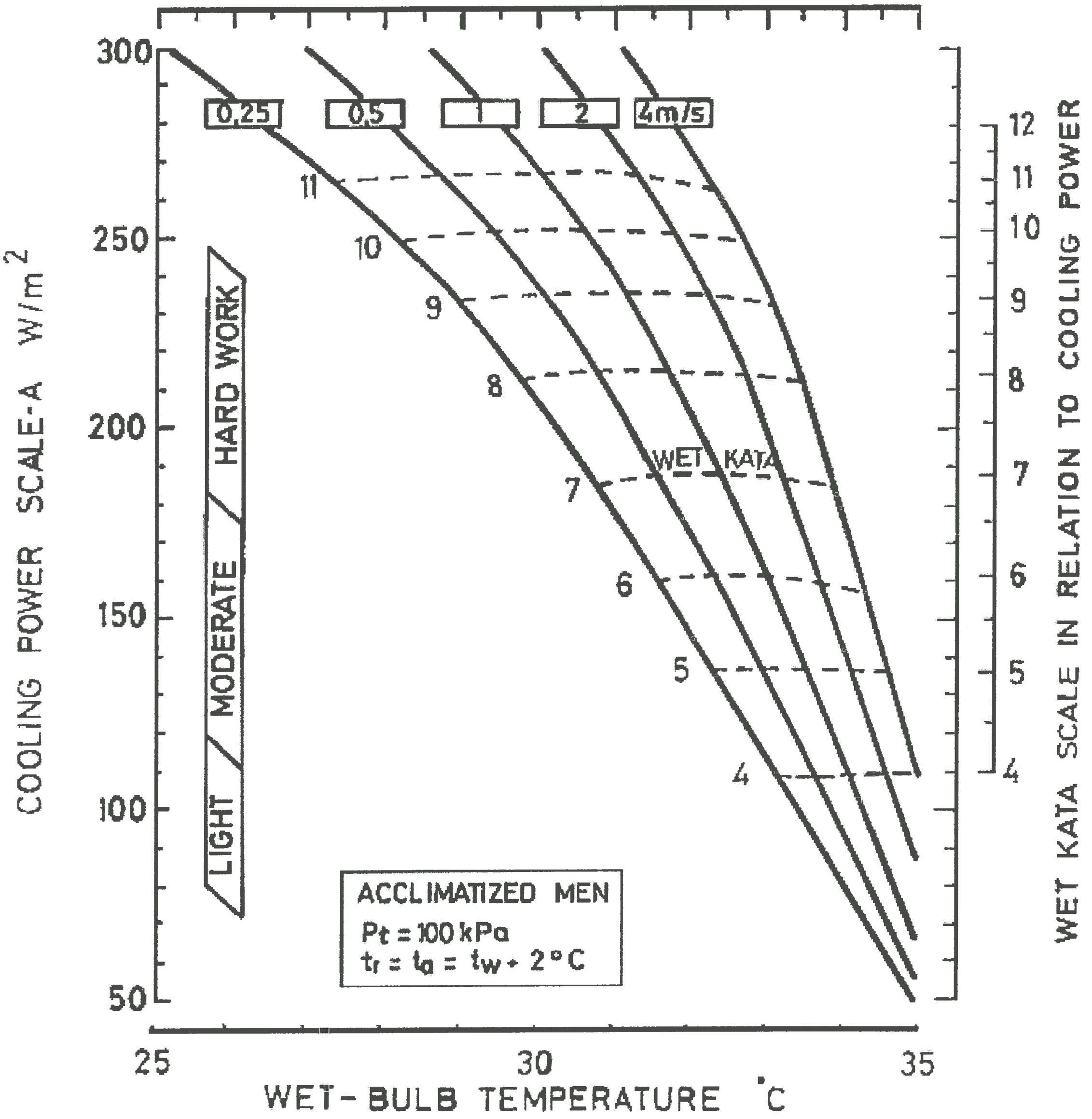


Figure 5.2.2.3.3 ***Environmental design parameters in relation to Air Cooling Power (ACP)***

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/m^2, 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/m^2, with values ranging from 241 to 318 W/m^2 (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/m^2
- 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/m^2 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:

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

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

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 ≤37,5°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:

$$HR_T = HR_r - HR_o$$

where:
HR_r = heart rate after recovery, and
HR_o = 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/m^2 would be marginally acceptable even for heavily clothed workers. However, lightly clothed workers ("normal underground attire") would be cooled at a rate of 135 W/m^2, making the given environment only marginally acceptable, even at the lower limit of the range for moderate work (130-200 W/m^2). Furthermore, the only way for workers engaged in heavy work (200-260 W/m^2) to be sufficiently cooled by the given environment would be to perform their duties without clothing (clearly an unreasonable requirement) and to avoid working at a rate that approaches the upper limit of the range.

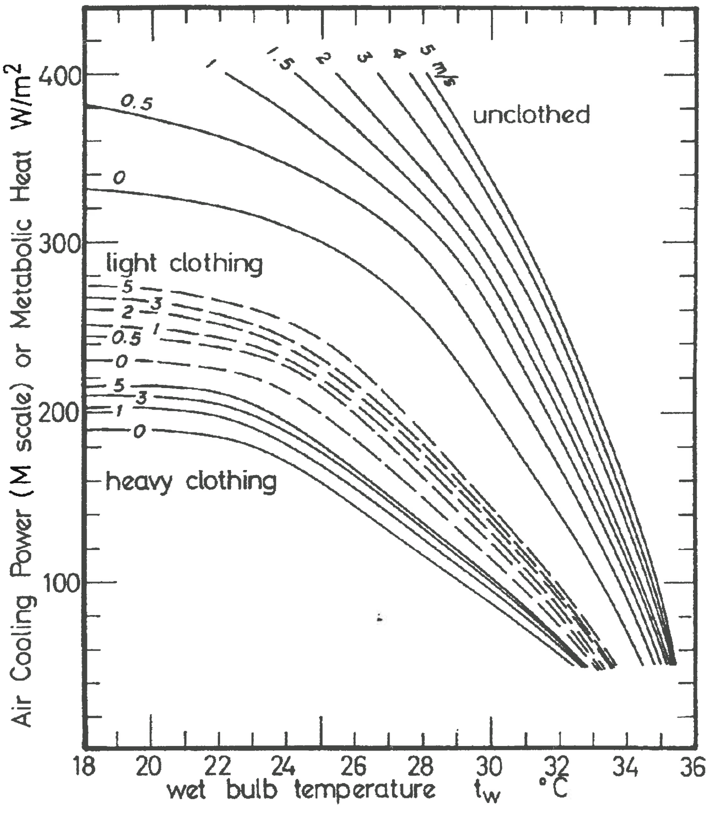


Figure 5.3.2.1 Air Cooling Power (M scale) or ACPM

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 m/s and T_{wb} 29°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°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 ate 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 160-200 and 200-260 W/m^2, respectively.

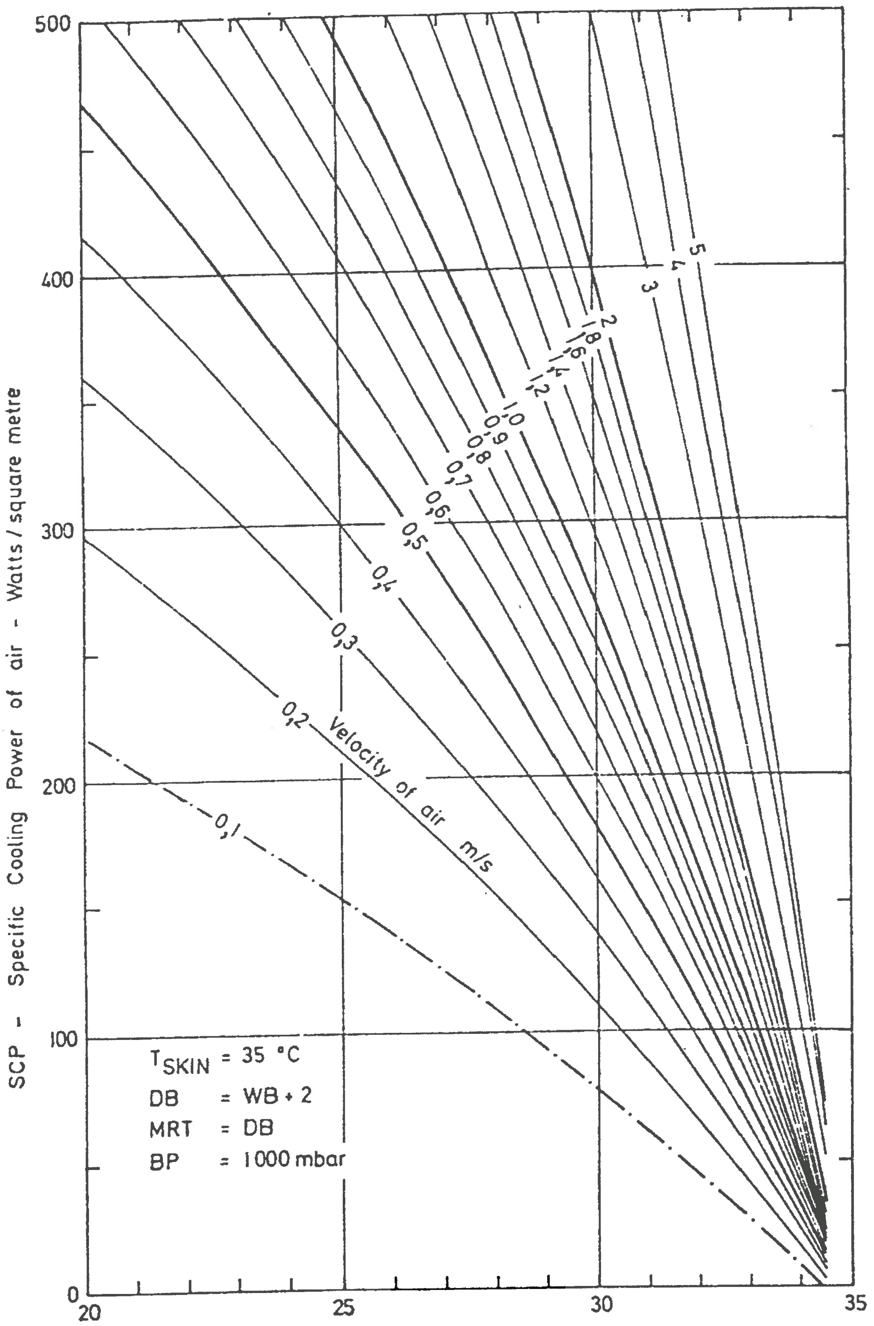


Figure 5.3.2.2 *SCP values for various air velocities*

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).

<u>Table 6.4</u>
ACGIH Wet-bulb Globe Temperature TLVs for various workloads in hot environments

	WBGT limit (°C) for given workload and work pattern		
Work pattern	**Light**	**Moderate**	**Heavy**
Continuous work	30,0	26,7	25,0
75% work and 25% rest each hour	30,6	28,0	25,9
50% work and 50% rest each hour	31,4	29,4	27,9
25% work and 75% rest each hour	32,2	31,1	30,0

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. OHSA standards

OHSA heat stress standards were developed in an attempt to establish work conditions that would ensure that workers' body temperatures do not exceed 38°C. This limit was based on recommendations by a panel of experts from the World Health Organization who considered the WBGT index as the most suitable means of specifying the work environment. They recommended threshold limit values in terms of a WBGT for three different workload ranges and two different ranges of air velocity. The WBGT index was chosen to specify the environment because it employs relatively simple measurements in its determination. It also consolidates into a single value the four environmental factors of dry-bulb temperature (T_{db}), vapour pressure or relative humidity (RH), mean radiant temperature (T_{mr}) and air velocity (V). For indoor environments with no solar load, the following relation for WBGT is applicable:

$$WBGT = (0,7\ T_{nwb}) + (0,3\ T_g)$$

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

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

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

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

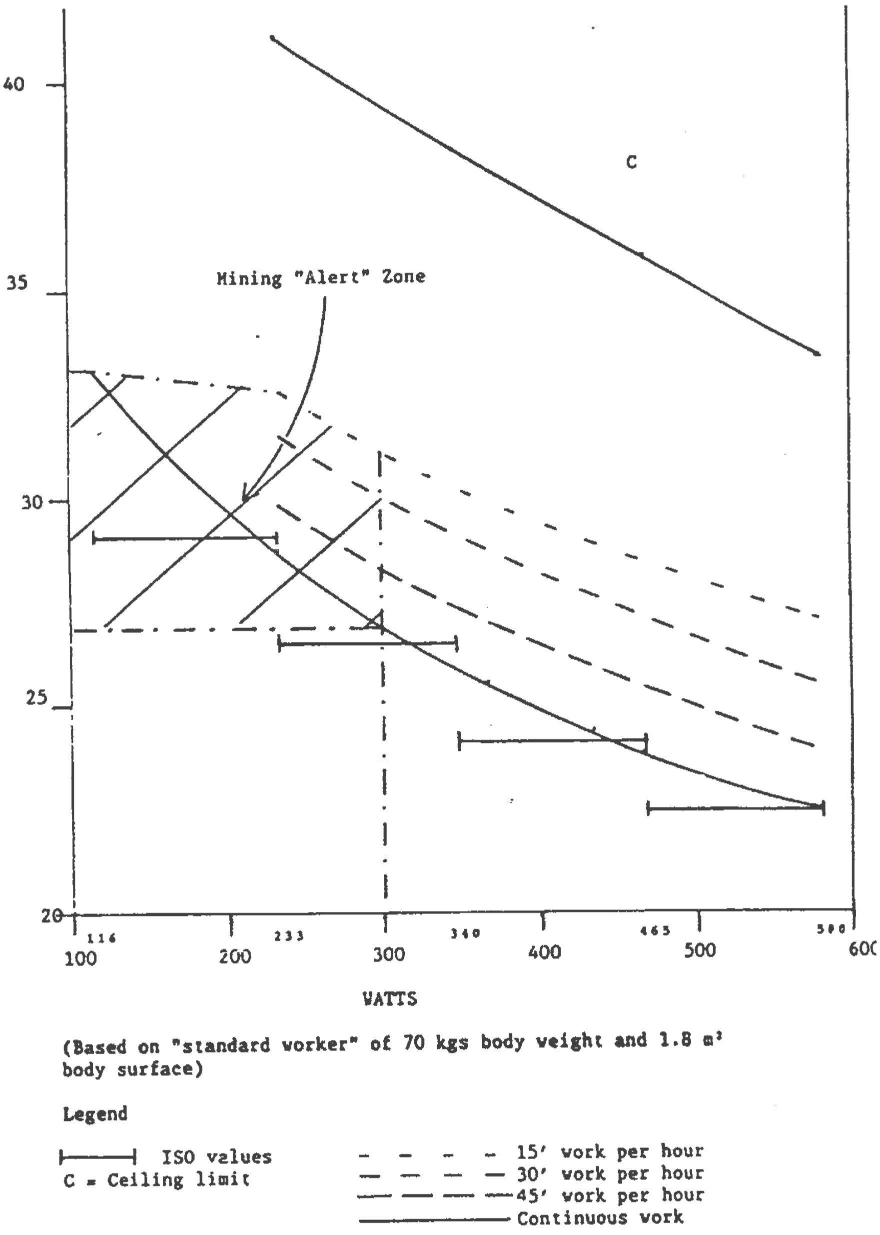
Table 6.7.1.4 compares the heat stress indices and limits used internationally, as compiled by Graveling *et al.* (1988). Although some of the information considered in the preceding sections is more recent than that in the table, no substantial differences are apparent in the specified criteria.

Table 6.7.1.4

Comparison of heat stress criteria used in various countries

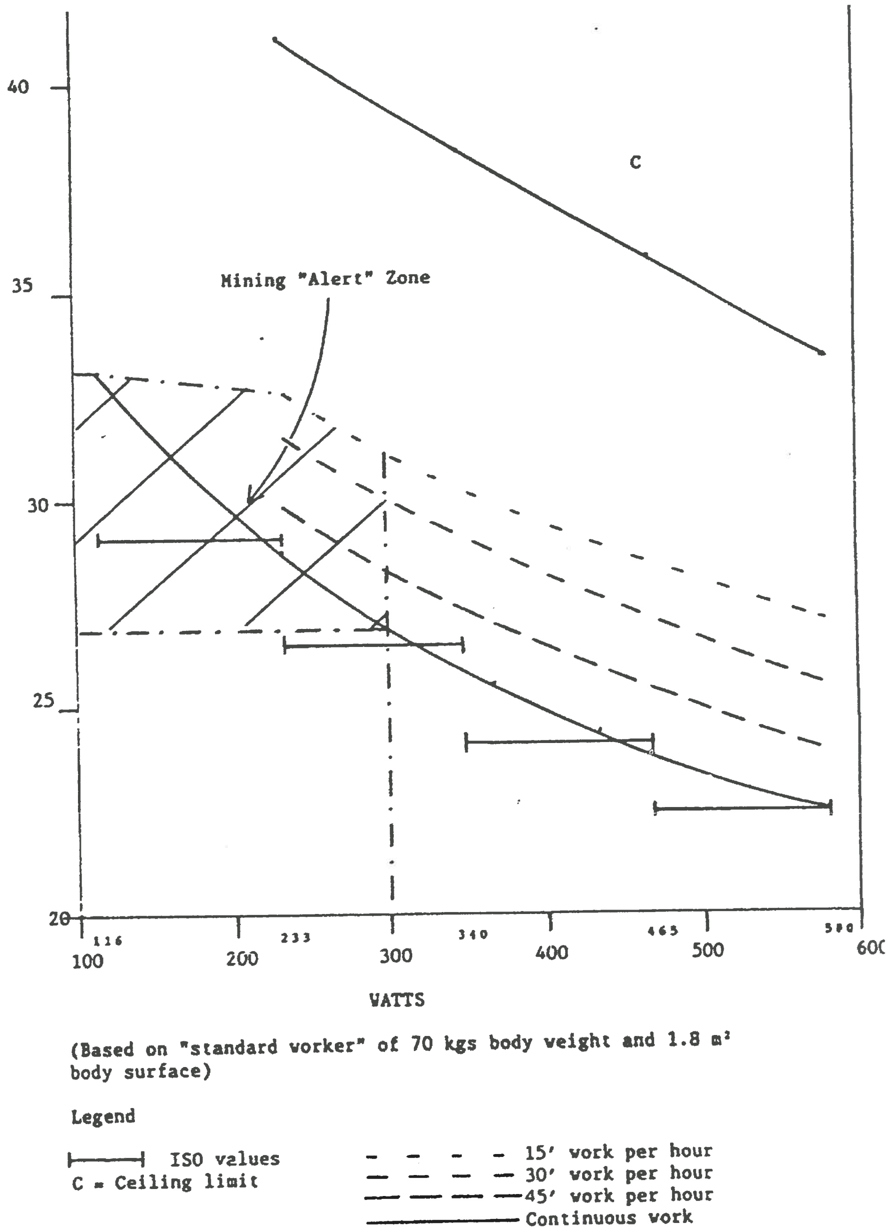
Country	Source	Criteria	Comment
USA	ACGIH AIHA OSHA NIOSH (1986)	T_r = 38,0°C	All sources provide comparable values, with some minor differences in their means of determination
Australia	Victoria Trade Council	ACGIH TLVs	Includes guidance on heat stress measurement, medical requirements, heat acclimatisation 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)	Non-salt mining: 1. for T_{db} >28°C or BET >25°: a) 6-h max shift if ≥3 h at: i. T_{db} >28°C (to max. BET of 29°C), **or** ii. BET 25-29°C. b) 5-h max shift if >2,5 h at BET of 29-30°C. 2. Personnel should not be exposed to BET ≥30°C, except for a 4-month max period directly followed by a 6-week break **and** i. if BET = 30°C, a max 5-h daily exp. **or** ii. if BET >30°C, 2,5-h max. daily exp. 3. In face operations, only 1/3 of employees can be exposed to a BET ≥30°C.	BET = Basic Effective Temperature Provisions made for rest breaks, period of acclimatisation, workers' age and work to be performed during emergencies, e.g. mine rescue operations
		Salt mining: 1. For T_{db} >28°C: a) 7-h max shift if: i. more than 5 h at T_{db} of 28-37°C, **or** ii. more than 4,5 hours at T_{db} of 37-46°C. b) 6,5-h max shift if 4 h at T_{db} of 46-52°C. 2. Personnel should not be exposed to T_{db} >30°C or T_{wb} >27°C, except where special means ensure that physiological effect is less than that of T_{db} 52°C or T_{wb} of 27°C.	Provision for special precautions to ensure that physiological effects of the work environment equate to a BET <30°C.
Great Britain	National Coal Board (1980)	BET >28°C for 1,5 hours during any shift incurs a heat allowance payment.	
	National Coal Board (1963)	27,2°C part. mechanised 28,3°C fully mechanised	
	Lind (1963)	BET 30,2°C: 210 W BET 27,4°C: 349 W BET 26,9°C: 490 W	Watts as the product of metabolic work rate and body surface area, typically 1,8 m^2
	WHO (1969)	BET 30,0°C: light work BET 28,0°C: mod. work BET 26,5°C hard work	Not highly acclimatised but well trained for work BET= Effective temperature, basic scale

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)

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



(Based on "standard vorker" of 70 kgs body veight and 1.8 m^2 body surface)

Figure 6.7.1.4b NIOSH and ISO heat stress limits for acclimatised 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/m^2 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.

8. Simulations - cost implications of identified parameters

8.1. Introduction

This section formed part of the scope of Task 6.1.1 of the Deepmine investigation. The main author was Mr. W Marx of CSIR Miningtek (Marx *et al.*, 2000). This section has been included with the permission of Mr. Marx and is given for the purpose of providing detailed background. The results of this investigation by Mr. Marx led to the investigation into the recirculation of air for deep mines, which was done by the author of this dissertation/report.

Based on the information previously gathered, it was necessary to use a simulation model that would include as many as possible of the parameters identified, so as to ensure that the expected working conditions and related costs could be accurately represented. The methodology that was followed to establish the simulation model, and other parameters related to it, was as follows:

- Determine design criteria and their applicable ranges
- Construct a representative mine layout to be modelled, stating all assumptions and taking into account the comparability of the model with other alternatives in ultra-deep-mine design
- Develop a simulation network using the program ENVIRON 2.5 in order to:
    - Establish the air flow and air thermodynamic properties to determine the cooling requirements
    - Determine the cooling requirements for different design criteria by varying the reject wet-bulb temperature and the stope face air-flow velocity
    - Apply the same process for various mining methods and cooling strategies to determine the effect of method on relative costs
    - Assess the results obtained and comment on the comparability of the modelled design with alternative designs for ultra-deep mines
    - Assess the results and comment on the effect of design criteria on mine ventilation and cooling costs
    - Formulate conclusions and recommendations.

8.2. Design criteria identified and range of values assessed

In all, ten different thermal design criteria applicable to ultra-deep mining have been identified and all of these govern either wet-bulb temperature or air velocity, or both to varying extents. From the investigations done, it became obvious that ACP is the most appropriate thermal design criterion for ultra-deep mines. It takes cognizance of most of the relevant thermal criteria and allows various combinations of wet-bulb temperature and air velocity to be applied in providing a specified level of environmental cooling power. This would, in general terms, make allowance for higher wet-bulb temperatures in areas with relatively high air velocities (e.g. main intake airways), creating opportunities to control costs through reducing the amount of air cooling.

The cost of providing a specific thermal environment is governed mainly by the capital and operating costs for the required cooling and ventilation systems. Design and performance specifications for ventilation and cooling systems are, in turn, determined mainly by the total cooling and air-flow volume required to achieve a specific wet-bulb temperature and air velocity.

Due to the specific layouts of underground mines and practical difficulties in controlling their ventilation, it is commonly accepted that actual wet-bulb temperatures over the extent of all working areas will vary by as much as 2°C above and below the design temperature. However, during the present study it was assumed that the design wet-bulb temperature is the maximum allowed and that the "real" design temperature will therefore be 2°C lower than the design value. The design wet-bulb temperatures considered were: 25, 27, 29 and 31°C (23, 25, 27 and 29 ±2°C, in practical terms), and the stope face air velocities assessed were: 0,5; 0,75; 1,0; 1,25 and 1,5 m/s. The model mine was assumed to be a green field operation, and the refrigeration plant and fan duties were adjusted to obtain the required design conditions.

8.2.1. Representative mine layout for simulation

In constructing the representative mine layout for modelling, all assumptions were carefully evaluated to ensure the comparability of the model with other design alternatives potentially applicable to ultra-deep mining. The comparability of the chosen simulation model will be discussed, together with the results for each simulation or set of simulations, as appropriate.

ENVIRON 2.5 was used to determine mine ventilation and cooling requirements, the details affecting those requirements, and the details of the ventilation and cooling systems themselves. In addition, electrical power requirements for various mine cooling and ventilation strategies were determined. The major design parameters used for the model mine were:

- Average mining depth of 4 900 m below surface
- Total monthly production of 100 000 tons reef and 15 000 tons waste
- Three production levels
- Summer ambient air intake conditions
- Geographical location in the Carletonville area.

The following are the more important assumptions and conditions applied to the simulation model:

- Refrigeration plants are all situated either on surface or underground, and are of the conventional type. Ice systems and water vapour refrigeration were not considered, and it was assumed that the same comparative results would have been obtained had these types of plants been used. Similarly, various combinations of surface and underground installations were not considered.

- The physical locations of underground bulk and spot air coolers in the simulation model were optimised to ensure that the design reject temperature was not exceeded anywhere in the intake airways or workings.

- Outlet air temperatures at underground coolers and service water temperatures/quantities applied during the simulations were determined to be as practicable and realistic as possible, based on practical knowledge and experience.

- The assumed efficiencies of the refrigeration plants, energy-recovery turbines, fans and pumps used to calculate operating costs were based on practical knowledge of such installations.

- The percentages for air leakage simulated in the intake airways and stopes were based on practical knowledge and experience and, hence, can be regarded as realistic.

- Intake airway sizes were optimised to ensure realistic air velocities and pressure losses.

- The ventilation system for the model mine did not include recirculation circuits.

- Other miscellaneous assumptions were based on knowledge of the mining methods currently being considered for ultra-deep operations, on practical experience and on measured data; they include stope face advance rate, stoping width, artificial heat loads and stope layouts.

Two mining methods were assessed to determine the comparability of the simulation model, viz. scattered and longwall mining. Table 8.2.1 summarises the cost value inputs used in the calculations for the categories of capital, maintenance and power costs. The cost calculations include all capital and operating costs for the ventilation and cooling systems, but exclude costs for the monitoring and control of ventilation and cooling. In other words, the costs associated with auxiliary ventilation systems and control measures such as doors, brattices and seals are not included. Electricity costs were based on a rate of R0,13 kWh, and capital costs were calculated on an annual basis at an interest rate of 12% over a 20-year period.

Table 8.2.1
Inputs to simulation model for estimated annual capital and operating costs of ventilation and cooling systems

Equipment	**Capital cost**	**Maintenance and operating cost**
Conventional surface refrigeration plant	R3 300/kW cooling	R100/kW cooling
Conventional U/G refrigeration plant	R4 500/kW cooling	R190/kW cooling
Main surface fans	R2 500/kW electricity	R80/kW electricity
Pelton energy recovery turbines	R2 300/kW electricity	R80/kW electricity
U/G bulk air coolers	R850/kW cooling	R10/kW cooling
U/G spot air coolers	R1 200/kW cooling	R15/kW cooling
Pumps	R2 500/kW electricity	R80/kW electricity
Pipes: 100 mm (Shaft / U/G reticulation)	R350 / R180/m	Included in refrigeration maintenance cost
Pipes: 200 mm (Shaft / U/G reticulation)	R940 / R242/m	
Pipes: 300 mm (Shaft / U/G reticulation)	R1 650 / R350/m	
Pipes: 400 mm (Shaft / U/G reticulation)	R2 100 / R500/m	
Pipes: 600 mm (Shaft / U/G reticulation)	R3 200 / R800/m	

8.3. Costs: Results and discussion

It was confirmed at an early stage of the investigation that heat would be the critical environmental factor in ultra-deep mining and that most other aspects of the environment would remain essentially unchanged in comparison with the situation prevailing at current mining depths. One obvious exception is barometric pressure, aspects of which did not form part of this investigation. It is therefore not considered further in this dissertation/report, except as a factor in the design of ventilation networks. The results from the findings of the various simulations are presented and discussed below.

8.3.1. Cost implications of thermal standards and limits

Analyses were performed to determine the financial impact of varying certain aspects of the thermal environment, including air velocity for a given wet-bulb temperature, wet-bulb temperature for a given air velocity, as well as the effect of various mining methods and cooling strategies.

8.3.1.1 Effect of design reject wet-bulb temperatures vs. constant stope face air velocity

Two sets of simulations were conducted during this part of the investigation. The purpose of the first simulation was to determine the impact of various design reject wet-bulb temperatures on environmental control costs, while that of the second was to confirm that the percentage variation in costs attributable to changes in wet-bulb temperature is approximately constant for different stope face air velocities. The costs for the model mine were calculated over the selected range of wet-bulb temperature (25 to 31°C) for air velocities of 1,0 and 1,5 m/s. It was assumed that refrigeration plants are situated on surface, that a Pelton wheel energy-recovery system (70 % efficiency) is in place and that a scattered mining method is used. Table 8.3.1.1 summarises the input parameter permutations and the simulation results obtained.

<u>Table 8.3.1.1</u>
Impact of reject wet-bulb temperature on annual costs for two different stope face air velocities

Stope face air flow velocity of 1 m/s						
Design T_{wb} (°C)	**Total cooling (kW)**	**Cooling Capex* (kR)**	**Ventilation Capex (kR)**	**Cooling Opex* (kR)**	**Ventilation Opex (kR)**	**Total cost (kR)**
25	53 967	45 815	5 385	55 803	19 630	126 633
27	48 850	42 284	5 385	50 510	19 630	117 809
29	43 699	38 729	5 385	45 181	19 630	108 925
31		38 251	34 970	5 385	39 545	19 630
Stope face air flow velocity of 1,5 m/s						
25	59 632	49 799	10 437	61 679	38 045	159 960
27	52 774	45 098	10 437	54 584	38 045	148 164
29	45 887	40 344	10 437	47 457	38 045	136 283
31	38 931	35 541	10 437	40 258	38 045	124 281

*Capex = capital expenditure, Opex = operating expenditure

In the comparison of the cost figures there was an indication that the ventilation and cooling costs for the mine modelled varied by approximately 30% for a 6°C change in wet-bulb temperature. This effect can be expected for any ultra-deep mine where stope face air velocities range from 0,5 to 1,5 m/s.

From the results it was also obvious that the absolute magnitude of additional heat flow caused by reducing the ventilation air temperature will be approximately constant at all depths. However, in terms of the proportional increase in total cooling requirements caused by that temperature reduction, the relative impact would be significantly less at greater depths. This can best be illustrated by means of the hypothetical example considered below.

The major contributor to heat load in deep mines is the rock mass, which adds heat to the ventilation air in direct proportion to the difference in temperature (ΔT) between the rock and the air. For a typical mine in the Carletonville area with an average working depth of 2 000 m, ΔT is 14°C (VRT of 40°C minus air temperature of 26°C). For a similar mine with the same air temperature, but having an average working depth of 4 900 m, ΔT would be 43°C, as a result of the VRT being 69°C. A reduction of 4°C in ventilation air temperature will result in a 30% increase in ΔT for an average working depth of 2 000 m, while at 4 900 m the same reduction in air temperature would increase ΔT by less than 10%. Accordingly, the cost of incremental reductions in air wet-bulb temperature at great depth, relative to that of maintaining it at the current limit for routine work (32,5°C) is of secondary significance.

8.3.1.2 Effect of various stope face air velocities for a constant wet-bulb temperature

Two sets of simulations were conducted during this part of the investigation. The purpose of the first simulation was to determine the impact of varying the design stope face air velocity, while that of the second was to confirm that the percentage variation in costs attributable to changes in air velocity is approximately constant for different reject air wet-bulb temperatures. The costs of environmental control were calculated for the selected stope face air velocities and at the maximum or reject wet-bulb temperatures of 27 and 31°C. It was again assumed that refrigeration plants are situated on surface, that an energy-recovery system is in place and that a scattered mining method is used. Table 8.3.1.2 summarises the input parameter permutations and the simulation results obtained.

Table 8.3.1.2

Impact of stope face air velocity on annual costs for two different reject wet-bulb temperatures

Reject air wet-bulb temperature of 27°C (25°C design)

Face velocity (m/s)	**Total cooling (kW)**	**Cooling Capex* (kR)**	**Ventilation Capex (kR)**	**Cooling Opex* (kR)**	**Ventilation Opex (kR)**	**Total cost (kR)**
0,5	43 855	39 009	1 656	45 367	6 038	92 070
0,75	46 241	40 404	3 617	47 806	13 186	105 013
1,0	48 850	42 284	5 385	50 510	19 630	117 809
1,25	50 845	43 723	8 021	52 580	29 240	133 564
1,5	52 774	45 098	10 437	54 584	38 045	148 164

Reject air wet-bulb temperature of 31°C (29°C design)

Face velocity (m/s)	**Total cooling (kW)**	**Cooling Capex* (kR)**	**Ventilation Capex (kR)**	**Cooling Opex* (kR)**	**Ventilation Opex (kR)**	**Total cost (kR)**
0,5	36 807	33 811	1 653	38 035	6 024	79 523
0,75	37 264	34 202	3 453	38 514	12 588	88 758
1,0	38 251	34 970	5 385	39 545	19 630	99 530
1,25	38 692	35 331	7 529	40 005	27 444	110 309
1,5	38 931	35 541	10 437	40 258	38 045	124 281

*Capex = Capital expenditure, Opex = Operating expenditure

The results highlighted the effects of auto-compression, air density and the increased resistance associated with higher stope face air velocities. The increased enthalpy of downcast air due to auto-compression is 9,8 kJ/kg per kilometre of depth. Therefore, the increase in cooling requirements attributable to auto-compression is directly related to the mass flow of air circulated through a mine and the depth of the workings. For the model mine under consideration, the air-flow volumes on surface required to yield stope face velocities of 0,5 and 1,5 m/s are 270 and 810 m^3/s, respectively. The increase in air density from approximately 1 kg/m^3 on surface to 1,5 kg/m^3 at the average working depth, combined with an increase in air leakage, is a significant factor in the greater air-flow requirement. The resultant increase in air mass flow contributes approximately 30 MW of additional heat from auto-compression that must be removed by the mine's cooling system.

However, an increased air mass flow rate in the intake airways will result in a smaller temperature difference across an air cooler. (1 kW or 1 kJ/s of cooling will yield a smaller difference if the total mass air flow across the cooler is increased.) This will reduce ΔT and, thus, cooling requirements. It is evident from the results, particularly for a reject temperature of 31°C, that the increased heat load from auto-compression is virtually cancelled out by the reduced heat load in the intake airways, as a result of the increased air mass flow rate. These effects explain the very significant increase in ventilation costs associated with a greater quantity of ventilation air and, ultimately, any increase in stope face air velocity.

From the results, it can also be deduced that the percentage increase in environmental costs due to changes in stope face air velocity is approximately constant for different reject wet-bulb temperatures, and that the percentage variation can be used as a general basis for environmental design studies. The findings are also indicative of the model's comparability.

8.3.1.3 Effect of various reject wet-bulb temperatures for different stoping methods

The simulations for this part of the study were conducted by means of a global heat load estimation program and not with ENVIRON 2.5. The main purpose was to confirm the comparability of the model and, thus, to determine whether the overall phenomenon identified during the study is applicable to different mining methods. No specific results are provided for this part of the study. However, it was found that a change in mining method does not have any significant influence on the cost trends demonstrated for variations in design reject wet-bulb temperature.

8.3.1.4 Varying design stope face air velocity for different cooling strategies

The simulations conducted during this part of the study were intended to confirm that the percentage variation in costs attributable to changes in reject air wet-bulb temperature is approximately constant for different refrigeration plant locations (surface or underground) and for various cooling strategies. Table 8.3.1.4 summarises the simulation results obtained when surface plant systems are compared with underground plant systems. It was assumed that sufficient heat-rejection capacity is available for underground plant, and the same assumptions as made previously were applied for energy-recovery systems and mining method.

__Table 8.3.1.4__
Impact of reject wet-bulb temperature on annual costs for various cooling strategies

Refrigeration plants located on surface (stope face velocity of 1 m/s)						
Design T_{wb} (°C)	**Total cooling (kW)**	**Cooling Capex* (kR)**	**Ventilation Capex (kR)**	**Cooling Opex* (kR)**	**Ventilation Opex (kR)**	**Total cost (kR)**
25	53 967	45 815	5 385	55 803	19 630	126 633
27	48 850	42 284	5 385	50 510	19 630	117 809
29	43 699	38 729	5 385	45 181	19 630	108 925
31	38 251	34 970	5 385	39 545	19 630	99 530
Refrigeration plants located underground (stope face velocity of 1 m/s)						
25	53 967	47 251	5 385	32 176	19 630	104 442
27	48 850	43 583	5 385	29 094	19 630	97 692
29	43 699	39 891	5 385	25 934	19 630	90 840
31	38 251	35 986	5 385	22 677	19 630	83 678

*Capex = Capital expenditure, Opex - Operating expenditure

An evaluation of the results indicated that the two cooling strategies considered do not differ significantly in their impact on relative cooling and ventilation cost trends for a given design reject wet-bulb temperature. It also indicated the comparability of the simulation model, and there is no reason to expect that cost trends for other cooling-generation systems would differ significantly from these results.

8.3.2. Conclusion on costing for thermal standards and limits

Although much of the knowledge gained in cooling and ventilating mines at depths approaching 4 000 m will certainly be applicable at 5 000 m, changes in the application of cooling and ventilation methods will inevitably be required. Current practice and conventional wisdom are necessarily based on previous research and practical experience in cooling and ventilating mines that are not as deep as those presently being contemplated. The industry's experience thus far has been that small improvements in thermal conditions have been achieved through large increases in ventilation and, particularly, cooling costs. In contrast, the results of the present study indicate that reducing the reject wet-bulb temperature would have less impact on the overall cost of ventilation and cooling than increasing the stope face air velocity. Over the range of reject wet-bulb temperatures considered (25 to 31°C), cooling and ventilation costs were shown to vary by up to 30% from the base case of 31°C. While it is acknowledged that reducing temperatures in ultra-deep mines would increase the absolute cost of environmental control, the increase in relative or percentage terms would be less significant than for current mining depths. In any case, a given level of ACP in an ultra-deep mine can be provided at far lower costs by reducing wet-bulb temperature than by increasing air velocity and air quantity. It follows then that, should health, safety and productivity-related requirements dictate a design reject wet-bulb temperature of, say, 25°C, it should be feasible (in terms of ventilation and cooling costs) to meet that criterion, provided a design temperature of 31°C was economically viable in the first place.

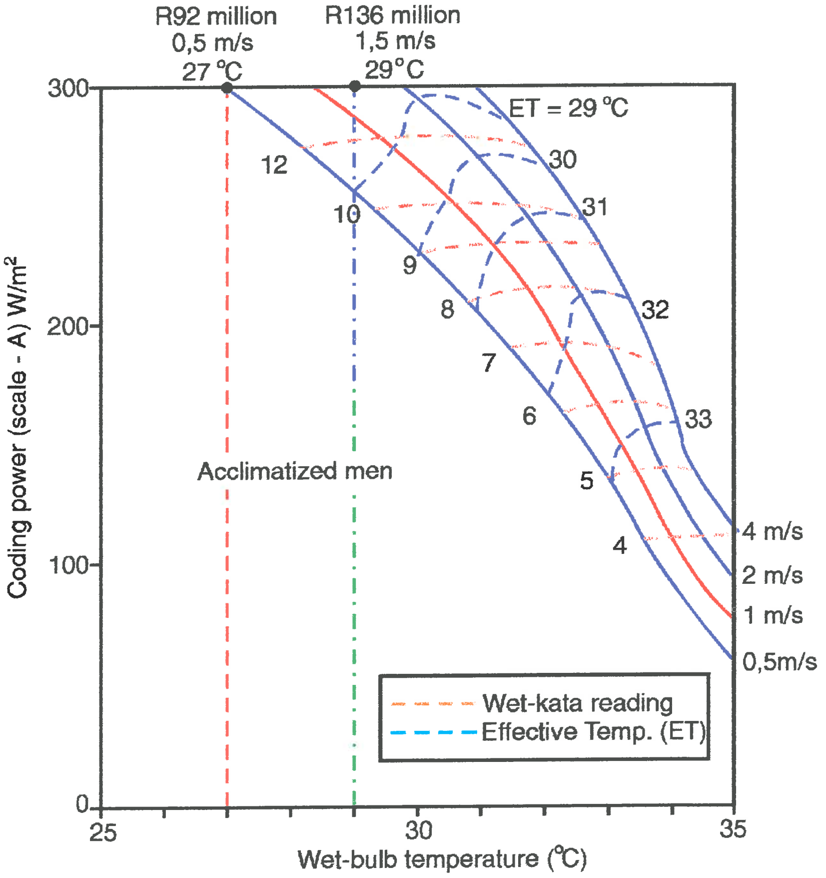


__Figure 8.3.2__ Annual costs for various combinations of wet-bulb temperature and air velocity that provide 300 W/m^2 of Air Cooling Power

Previous studies quantifying heat stress in terms of ACP have indicated that a level of 300 W/m^2 can be regarded as both safe and conducive to high productivity in nearly all instances. The projected costs for providing this level of ACP for air velocities of 0,5 and 1,5 m/s at wet-bulb temperatures of 27 and 29°C, as indicated in Figure 8.3.2, are based on the characteristics of the model mine considered. The significant cost increases associated with greater air velocities highlight the main conclusion of this analysis, namely that total air-flow quantity should be minimised and wet-bulb temperature reduced to achieve the required ACP in ultra-deep mines. Designing an environmental control system in accordance with these criteria would allow higher wet-bulb temperatures in areas that naturally have higher air velocities, e.g. intake airways, but the general approach indicated is to reduce wet-bulb temperatures through cooling, and not to increase air velocity.

The practicability of thermal design limits, including those for air velocity and wet-bulb temperature, and the physiologically/psychologically related requirements of the work force will be principal determinants of the design criteria ultimately adopted for ultra-deep mines. The investigation of worker-related factors should also receive attention.

These cost simulations demonstrated the significant impact of higher stope face air velocities on both cooling and ventilation costs. The results therefore form the basis for the recommendation that environmental control systems in ultra-deep mines should be designed to provide the required thermal environment (in accordance with the many and various criteria relevant to this critical decision) at a minimal total air mass flow rate. With possible cost variations as demonstrated by the current findings being as great as 60% (relative to the base case of 0,5 m/s), minimising the air mass flow rate should certainly be an integral part of an ultra-deep mine's ventilation strategy.

A logical extension of minimising air mass flow rate would be the inclusion of controlled air recirculation techniques into ultra-deep ventilation and cooling strategies. Recirculation can enable reductions in fan power requirements of up to 60% to be made, according to previous research (Willis *et al.*, 1997). Furthermore, recirculation could greatly reduce the impact of auto-compression on total heat load. However, caution should be exercised in reducing the overall quantity of air supplied, as a reduction may introduce practical difficulties in providing the required cooling, as well as impose constraints or requirements for additional control measures where certain types of equipment are used, e.g. diesel-powered machinery. The beneficial effects of recirculation on environmental control costs, together with the potential risks that its inappropriate implementation could impose, indicated the need for a separate investigation, which is dealt with in the following section.

It must again be emphasised that the cost analysis conducted during the present investigation was of a comparative and relatively simplistic nature, as a result of the need to use a single simulation model. Accordingly, these findings should be interpreted and applied with circumspection but, more importantly, also validated for specific mine designs as they are developed.

In a similar vein and to underscore previous comments, the heat stress limits ultimately adopted for ultra-deep mining should include criteria for work performance, in order to ensure that productivity levels contribute to the profitability of such mining projects.

9. Recirculation of mine air

9.1. Introduction

The provision of acceptable environmental conditions is an important aspect of all underground mining activities. As mines have (and will still) extended deeper and working areas have become more remote, the costs and practical problems of ensuring adequate supplies of ventilation air at the appropriate places have become a matter of serious concern. The potential benefits of recirculating air underground are great, but this practice has hardly been used in South Africa in the past, largely because of concerns of safety. Work carried out in the early 1980s indicated that recirculation of air can in fact be regarded as a safe, reliable and effective procedure, provided that certain precautions are taken (Burton, October 1984).

In South African gold mines in the past very little use has been made of controlled recirculation. A trial was conducted at East Rand Propriety Mines in 1948, when a portion of the upcast air was cooled and then mixed with the downcast air (Gorges, 1952). In 1973, Holding reported on a recirculation scheme in a single stope (Holding, 1973). An intensive investigation into the use of controlled recirculation was pursued, which resulted in a trial conducted at Loraine Gold Mines Ltd (Burton *et al.*, 1984; Fleetwood *et al.*, 1984). A great deal of success was achieved with this trial and other subsequent studies followed.

Although there are a considerable number of technical papers available concerned with the use of controlled recirculation in mines, they suffer from two main disadvantages. First, the majority of the papers are concerned with small-scale recirculation systems in British collieries and secondly, each paper tends to deal only with individual aspects of recirculation. Burton in his report covered all the relevant aspects of recirculation of air for deep gold mines in full detail (Burton, October 1984).

9.2. The role of controlled recirculation

9.2.1. Background

Control of the underground environment relies on the use of ventilation air to perform a wide variety of functions. An understanding of the role of controlled recirculation can therefore only be gained if these functions are clearly defined. There are four major reasons for which air is required in mines. First, an adequate supply of oxygen is needed to support the necessary complement of workers and also to supply any diesel locomotives or other diesel trackless equipment that may be operating. The amount of air required for this reason, although vital, is small compared with that demanded for any of the other reasons and does not require special consideration.

Secondly, sufficient air is required to dilute and remove noxious and inflammable gases so that gas layering is minimised and acceptable concentration limits are not exceeded. An adequate supply of air is also needed to remove blasting fumes timeously.

Thirdly, air is essential for the dilution and removal of respirable dust since the measures used to suppress dust at its source are not always completely successful. A large number of dust filters are used underground, particularly at tipping and transfer points, and air is also required to convey the dust to these filters.

Finally, although chilled water can be used to absorb some of the heat load in working areas, most of this heat load will be absorbed by air. In shallow mines the effects of auto-compression and heat transfer from the rock are small, and downcast ventilation air, without any refrigeration, is capable of absorbing the underground heat load, while maintaining reject temperatures at an acceptable level.

As depths increase, this capability is progressively reduced. In summer at a depth of about 2°500 m below surface, downcast ventilation air reaches a wet bulb temperature of 28°C. Clearly, if the desired reject temperature is also 28°C, the downcast air has lost all its capacity for cooling. Therefore, below this depth, all the heat produced underground must be removed by refrigeration. However, although the usefulness of downcast ventilation air decreases with increasing depth, air is still required for two important cooling purposes: as a medium for distributing the necessary amount of refrigeration, and also as a means of removing heat from any underground refrigeration plant.

9.3. The use of controlled recirculation

Controlled recirculation of ventilation air can be defined as the reintroduction of a portion of the return air from an area into the intake of that same area. The term 'area' is used in a general sense and can mean a development end, a single stope or a whole section of a mine. For illustration purposes a simplified 'controlled recirculation system' is shown in Figure 9.3.

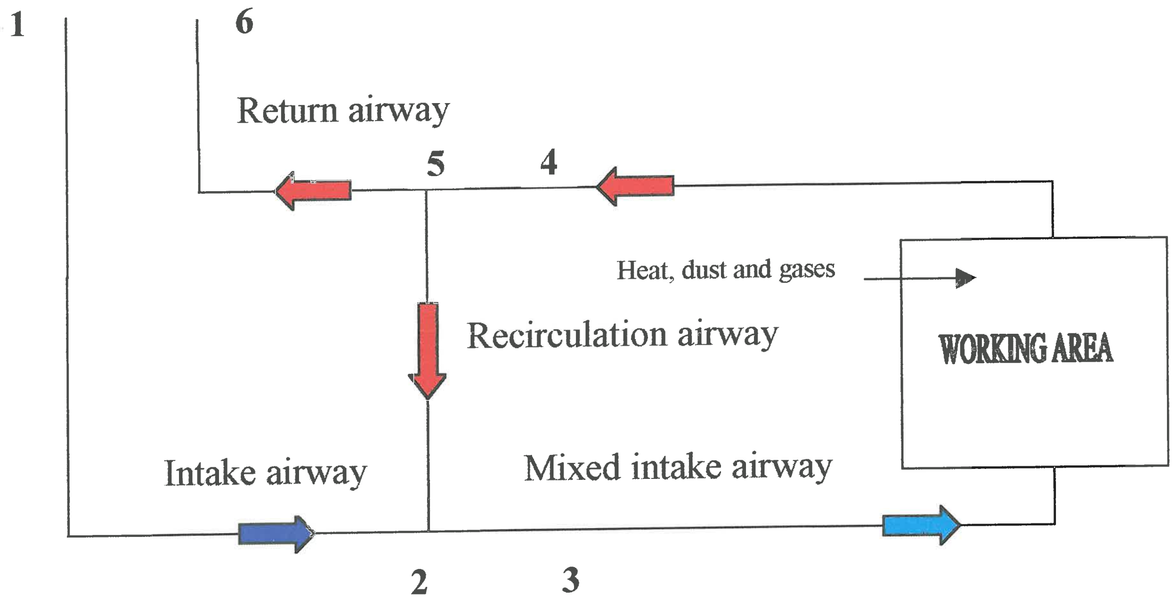


Figure 9.3 ***Simplified section of a controlled recirculation system for a mine***

In the figure 'fresh' intake air flows along the path from point 1, passes through the working area and is finally rejected at point 6. Meanwhile recirculation takes place along the route 2-3-4-5-2. It can be observed that the rate at which air is recirculated is dependent on the quantity of the intake air; essentially, recirculation is merely the enforced circulation of the fixed volume of air contained in the area 2-3-4-5-2, and this can be done with any quantity of intake air.

It will be apparent that the effect of superimposing recirculation onto the intake air flow is to increase the flow rate of air at point 3. Clearly, air velocities will also increase throughout the working area and this increase has two beneficial effects: increased values for cooling power without any changes in the actual air temperatures (Stewart, 1982) and increased air velocities which can also minimise gas layering (Bakke *et al.*, 1964).

However, the most important advantage of an increased air flow is that it provides a means of more conveniently distributing refrigeration within an area. When air flow is restricted, air temperatures will increase rapidly for a given heat load and repeated cooling using small air coolers becomes necessary. With an increased air flow created by recirculation, the rate of temperature rise decreases. The cooling needed for a specific area can then be achieved by means of a single bulk air cooler. It is important to recognise that controlled recirculation can only be used as a means of distribution and not as a source of refrigeration. The amount of refrigeration required in an area is virtually independent of any controlled recirculation that may take place.

Controlled recirculation on its own does not affect the return-air dust concentration. This concentration is largely dependent on the intake air quantity and on the amount of dust that is produced and becomes airborne within the working area. However, a situation could arise in which the intake quantity is insufficient to maintain the return air dust concentration at an acceptable level. Controlled recirculation, with bulk air dust filtration, could then be used as an alternative to increasing the intake air quantity.

So far, the beneficial effects of controlled recirculation, *per se*, and it's potential role in distributing refrigeration and controlling dust levels have been described. It is now necessary to identify those functions that controlled recirculation cannot perform.

Clearly, controlled recirculation cannot provide any oxygen that is required. The intake air must supply the oxygen. It is also important to note that the return air concentrations of any noxious or inflammable gases that are produced in a working area (excluding those produced by the blast) are not affected by controlled recirculation. Such concentrations are largely dependent on the intake air quantity and the amount of gas produced within the area. Furthermore, although blasting fumes are a special case for consideration, controlled recirculation has little or no effect on the rate of removal of such fumes; again, the overriding influence is that of the intake air quantity. Some practical considerations regarding the continuation of recirculation during and after a blast will be discussed later.

Finally, since controlled recirculation has no effect on the quantity of return air (at point 6, Figure 9.3), it can be of no assistance in rejecting heat from any refrigeration plant. This could have an important influence on the future use of recirculation. This aspect will also be discussed in detail later.

9.4. Effects of controlled recirculation on the environment

9.4.1. Background

There are a number of mathematical models that can predict the effects of controlled recirculation on gas and dust concentrations and on the rate of removal of blasting fumes. A simple model was also developed by Burton which showed the effect of combining controlled recirculation and bulk air cooling on the temperature levels within an area. In the models, reference is made to three air quantities. By referring to Figure 9.3 they are defined as follows: 'Fresh intake air' flows from points 1 to 2, 'recirculated air'" flows from points 5 to 2, and 'mixed intake air' flows from point 3, through the working area to point 4.

9.4.2. Recirculation model for gaseous contaminants

Burton made a conclusive statement in saying that the concentration of gaseous contaminants in the return air is not affected by recirculation. This concentration is determined by the intake air gas concentration, the intake air quantity, and the amount of gas produced in the working area. Controlled recirculation, at whatever rate, does not change the concentration at all.

However, it must be noted that the mixed intake concentration is dependent on recirculation and that the concentration increases as the recirculated fraction increases. For a given quantity of intake air, the recirculated fraction can vary only between zero and some value close to unity. If there is no recirculation, the mixed intake concentration is merely the intake concentration. As the quantity of recirculated air is increased, the recirculated fraction approaches unity and the mixed intake concentration will approach, but not exceed, the return air concentration.

In summary, the maximum or return air gas concentration is not affected by recirculation and all other concentrations in an area will remain below this level. Similar models have been developed previously, and the predictions have been confirmed on many occasions, particularly in regard to methane concentrations in United Kingdom collieries (Bakke *et al.*, 1964; Leach, 1966;Leach and Slack, 1969). In 1984 a major field trial of a controlled recirculation system was conducted at Loraine Gold Mines Ltd. (Burton *et al.*, 1984). In Figure 9.4.2 below, the predicted and measured values of carbon dioxide concentrations in the return and mixed intake air are presented. It can be seen that the predicted values are an accurate reflection of the measured values. Although they are not included here, similar results were obtained for other gases such as carbon monoxide and the nitrous fumes produced by diesel locomotives. A minor deviation from the values predicted may be obtained in the case of nitrous fumes, since nitric oxide is slowly oxidised to nitrogen dioxide.

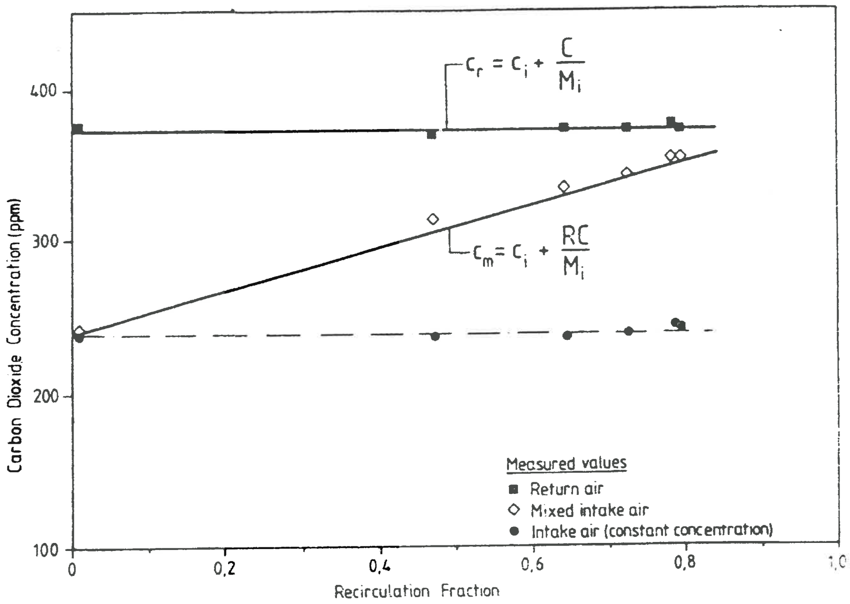


***Figure 9.4.2** Relationship between carbon dioxide concentration and recirculated fraction*

The equations as were used by Burton can also be used to predict the oxygen concentration in the return and mixed intake air. However, the value for the gas produced in the working area, C, would in this case be negative since oxygen is being consumed rather than produced. It can be seen that the minimum or return air oxygen concentration is not reduced by controlled recirculation.

Some important statements must be made regarding the effect of controlled recirculation on radon gas concentrations, and particularly on working level contamination. The equations presented in the paper by Burton can also be used to predict the return and mixed intake radon gas concentrations fairly accurately. In other words, radon gas behaves in much the same manner as the stable gases previously mentioned. A more comprehensive model was developed by Rolle (1982), which in fact showed that, due to the progressive decay of radon gas into its three daughters, return air radon gas concentrations are, in general, slightly lower with recirculation than without.

However, because of this decay, and also because controlled recirculation leads to increased residence times, working level contamination is increased by recirculation. Rolle showed that, for large quantities of recirculated air relative to intake air (R=0.8), the maximum or return air working level can be about 50% higher than the value existing when only the same quantity of intake air is supplied to an area. It should be emphasised, however, that at expected recirculated fractions of about 0,5 the increase is limited to about 25 to 30%. Clearly in uranium mines and those gold mines in which radon is present, consideration must be given to such effects. The quantity of intake air must be chosen to ensure that acceptable working levels are achieved. An increase could be largely prevented if dust filtration were to be carried out, since radon daughters become attached to dust particles.

9.4.3. Recirculation model for blasting fumes

In the paper presented by Burton, the conclusion was made that the rate of removal of blasting fumes depends largely on the quantity of intake air, and that the recirculation has either no effect or, because of better mixing, a slightly beneficial effect. In order to test the model, a series of measurements were made at the recirculation system installed at Loraine Gold Mines Ltd. An analysis was carried out on the return air, blast fume decay curves for both nitrous fumes and carbon monoxide for various quantities of intake and recirculated air. It was found that the decay curves were exponential in nature and a value for the time constant τ was determined in each case. In Figure 9.4.3 the relationship between the time constant and the intake air quantity is shown (note that the decay is inversely proportional to the time constant). It can be seen that the rate of decay and hence the removal of blasting fumes is closely correlated with the intake air quantity.

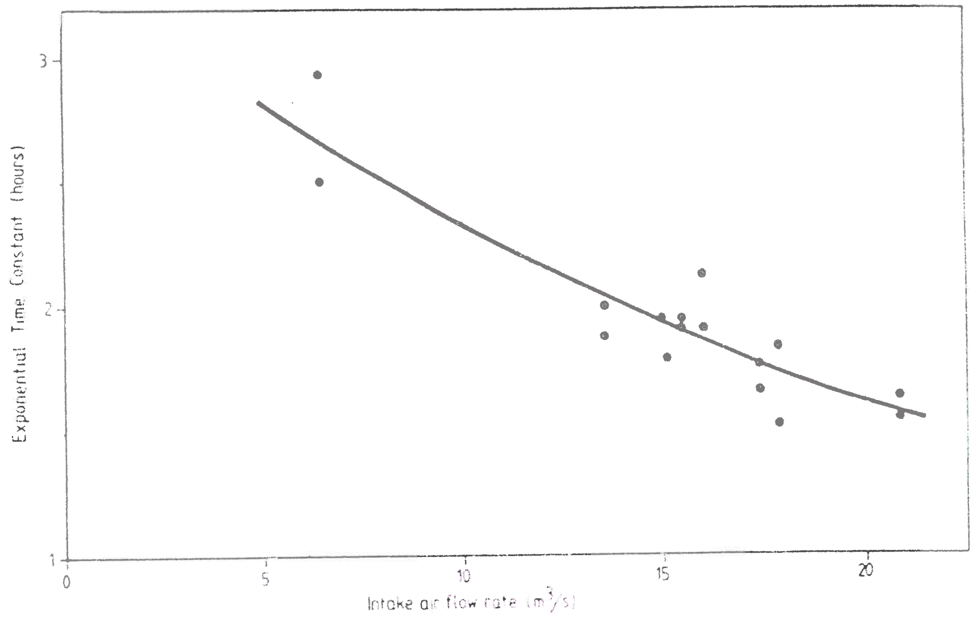


Figure 9.4.3 ***Relationship between the exponential time constant τ and the intake air quantity***

Each point in Figure 9.4.3 has a different value of recirculated air flow associated with it. The value varied from 49 m^3/s, with a corresponding variation in the recirculated fraction, R, of zero to 0,87. The figure therefore includes any effects that recirculation may also have on the blast contaminant decay. Clearly, it would have been desirable to isolate the two effects completely by independently varying the quantities of intake and recirculated air, but this was found to be difficult in practice. However, analysis shows that the quantity of recirculated air has very little effect on the value of the time constant and hence on the rate of decay. Burton also noted that considerably more data would be required to confirm the model.

Although the model has been shown to be a good representation of blast fume decay, the assumption made earlier that blasting results in a 'uniform' concentration of noxious contaminant may not be justified. In practice a dense 'plug' of fumes is usually formed and this travels along the return airway immediately following the blast. By stopping recirculation for a short period, this plug could be removed from the area completely, and the overall time for reducing noxious concentrations to acceptable levels may be decreased. This will be discussed in detail later.

9.4.4. Recirculation model for dust

The model developed for gaseous contaminants can also be applied, in general, to predict the effects of controlled recirculation on respirable (and total) dust levels. Briefly, if there is no dust filtration, the intake air quantity, the intake air dust concentration and the amount of dust produced that becomes airborne in the working area dictate the return air dust concentration. Controlled recirculation will not affect this concentration. Burton also suggested that as an alternative, air recirculation be used in combination with dust filtration.

Burton used a model to simulate various dust concentrations and concluded that the return air dust concentration would not change with recirculation and that the mixed intake air concentration would increase with recirculation. He also highlighted the aspect of dust collection efficiency and the results thereof are shown in Figure 9.4.4.

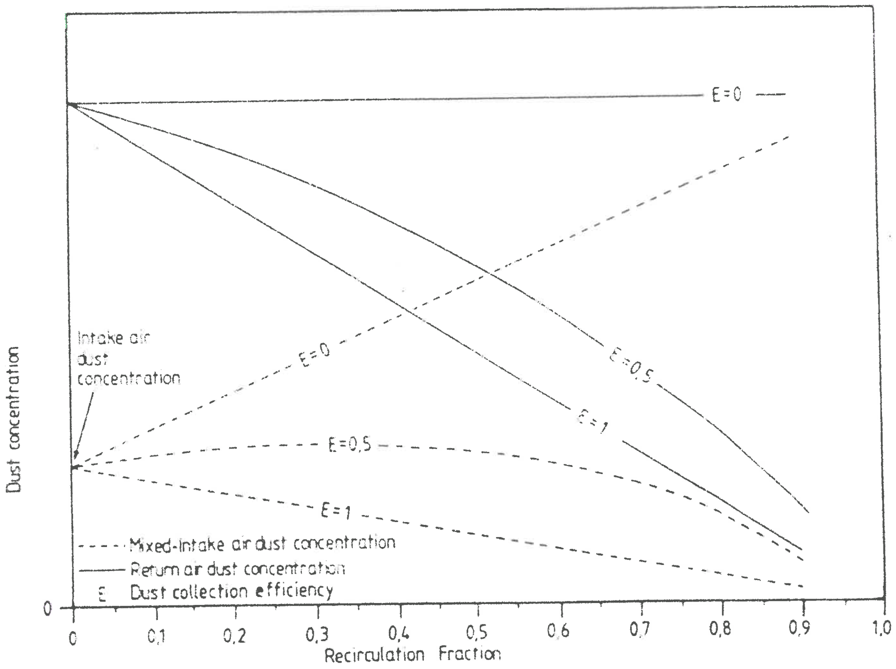


Figure 9.4.4 ***Effects of recirculation and dust filtration on the mixed intake and return air dust concentrations***

Controlled recirculation and dust filtration has been used in 'advance headings' in British collieries (Robinson, 1972; Pickering and Aldred, 1977). However, the filtration of respirable dust from large volumes of air, as envisaged in recirculation systems in gold mines, has still to be investigated (Burton, 1984).

9.4.5. Recirculation model for air cooling

The main motivation for installing recirculation systems in deep gold mines will be to provide acceptable temperatures in working areas as well as to reduce the load on the surface fans. Controlled recirculation, as mentioned before, should be regarded only as a means of more conveniently distributing the required amount of refrigeration in an area, since recirculation *per se* will not lead to lower temperatures. However, the higher air quantities that recirculation achieves can allow the use of a single bulk air cooler to maintain acceptable temperatures throughout the area.

When cooling is introduced, both the mixed intake and the return air enthalpies, and hence the temperatures, can be much reduced. At the Loraine field trial, the mixed intake wet-bulb temperature was reduced from 27,9°C to 22,3°C, and the return air wet-bulb temperature was reduced from 31,5°C to 28,4°C (Fleetwood *et al.*, 1984).

For the purpose of this investigation the various recirculation percentages, and the cooling associated with them, were calculated with the aid of the ENVIRON heat simulation program.

9.5. Summary of simulation models

Burton found that the various models that do predict the effects of controlled recirculation are in fact very reliable. The models have shown that, in general, the intake air and the recirculated air perform separate functions, and the respective air quantities that are used in a specific area must be chosen so that these functions can be achieved.

9.6. Factors affecting the introduction of controlled recirculation

9.6.1. Background

Controlled recirculation can be used as a substitute for downcast ventilation air, but there are certain issues that have to be kept in mind. One of the key aspects to consider is when recirculation of air should be prohibited and in what cases it will be beneficial to use it.

9.6.2. Reasons for using controlled recirculation

There are many factors that influence the ventilation and cooling arrangements required by a mine. An attempt is made in this study to provide a general recommendation on the introduction of controlled recirculation. There are, however, certain important factors that can indicate where controlled recirculation is likely to offer certain benefits, when compared with current ventilation practices. Burton investigated these issues and found that the minimum quantity of intake air that must be provided is that which is sufficient for:

- the provision of oxygen
- the dilution and the removal of gases during on-shift periods
- the timeous removal of blasting fumes.

This minimum value could be increased so that the intake air quantity is also sufficient for the dilution and removal of airborne dust. For shallow mines this figure can be 2,5 kg/s/kt of rock mined per month (Appelman and Schröder, 1984) and for deeper mines the figure can go as high as 6 kg/s/kt of rock mined per month. Extra air is sometimes needed to combat heat-related problems and it is this extra air that can be replaced by using controlled recirculation. The approach that Burton suggested was to limit the downcast air to not more than 2,5kg/s/kt per month, and to introduce controlled recirculation when extra quantities of air are required for distributing refrigeration.

In existing deep mines, there are already considerable practical difficulties in ensuring an adequate supply of ventilation air from surface. As depths and distances from the downcast shafts have been increased and will in future increase, so higher fan pressures are required. This results in large pressure differences between the intake and return airways, and large amounts of air are lost due to leakage. Such losses are difficult to control, but by limiting the volume of downcast air, these losses could be reduced. By using controlled recirculation, the larger mixed intake air quantities are only produced close to where the air is actually required, thus reducing the opportunities for leakage to occur. As mines are now deeper and distances from the downcast shaft have increased, the practical benefits associated with using controlled recirculation become more evident.

Although the practical benefits are considerable, the most important benefits are economic. Considerable savings in fan power could be realised for ultra-deep mines if the specific downcast air quantity could be limited to the suggested value of about 2,5 kg/s/kt per month. Limiting the downcast air quantity could also, in some circumstances, reduce the amount of refrigeration required to combat the effects of auto-compression. As mines become deeper, the combined effects of auto-compression and higher heat transfer from the rock may mean that the intake air has to be cooled.

A further consequence of not increasing the downcast air quantity is that this could delay the need for larger or multiple shafts and airways at greater depths. This is particularly relevant when considering the number of return airways and upcast ventilation shafts that are required. Although the benefits of introducing controlled recirculation in current mines can be considerable, there may be many constraints caused by established infrastructure. It is therefore important that when new ultra-deep mines are planned, the various advantages of controlled recirculation are realised by building recirculation into the design. An important aspect to remember is that controlled recirculation can be of no assistance in rejecting heat from any underground refrigeration plant. When the introduction of controlled recirculation is considered, careful thought must be given before introducing any new underground refrigeration plant into an area where recirculation is being proposed, particularly if the aim is to limit the intake air quantity.

From the work done in this study so far, it is obvious that the cost of providing air from surface becomes very expensive and that the recirculation of air almost becomes compulsory. Some of the objectives of this investigation are to determine to what extent and to what specifications recirculation should be used in ultra-deep mines..

9.6.3. Potential hazards of controlled recirculation

Underground fires are a major hazard in mines. This is particularly so in gold mines where explosives are employed and extensive use is made of wood for support. Controlled recirculation has certain implications regarding both the immediate and long-term effects of fires.

Depending on the position of the start of the fire, recirculation can have either no effect or may reintroduce the smoke generated by a fire into the stope. In the latter case, the recirculation fans will have to be stopped. In this way, an area can be immediately restored to a normal once-through ventilation system and standard fire procedures can be enforced. The controls for stopping the recirculation fans can be linked to the detecting devices and in that way they are made foolproof. These systems will, however, have to be tested on a regular basis.

It is therefore important that the available routes and associated risks be carefully considered for the various circumstances encountered. However, it is almost certain that recirculation of air will have to be stopped once a fire breaks out. Another important potential hazard associated with controlled recirculation is that of ensuring a continuous supply of intake air. If the intake air stops for any reason, there would be a gradual build-up of gases and dust within an area (Burton, 1984).

9.6.4. Prohibition of recirculation

It must be stated that there are certain instances where recirculation, whether controlled or uncontrolled, is specifically prohibited. In terms of the Mines and Works Act and Regulations, 1956, as amended, certain mines or part of mines are classified as fiery. In such circumstances recirculation is prohibited, unless an exemption from the Regulation is obtained.

It is interesting to note that although all British collieries would probably fall into this category, a total of 61 recirculation systems were operating in January 1983 (Allan, 1983). Indeed, it has also been suggested that recirculation of air could reduce methane layering in South African coal mines (Thorp, 1982; Greig 1982; Burton, 1984).

9.7. Design of a controlled recirculation system

9.7.1. Introduction

The variable circumstances encountered in mines preclude any rigid recommendation for the design of a recirculation system. However, a number of features will be common to all recirculation systems, namely the determination of the required quantities of intake and recirculated air, the arrangements for the establishment of these air flows, cooling arrangements and arrangements that will ensure that the recirculation system can be operated safely.

9.7.2. Determination of air quantities

Burton suggested that it would be inappropriate to give a recommendation on the quantity of air required. The actual value required in any area will depend on the specific circumstances encountered. There are recommended and statutory limits for certain contaminants and these must be observed. However, the final choice of the quantity of intake air for ensuring safe, acceptable conditions will rest heavily on the experience of the responsible environmental engineer. In making this choice, it can be noted that the quantity of recirculated air will not affect the maximum or return air contaminant levels. The major exception is working level contamination, which was discussed above.

9.7.3. Ventilation arrangements

For recirculation, the location of fans will to a large extent depend on specific circumstances. Such circumstances will include the availability of electrical power and the suitability of various locations with regard to tramming activities. The fans that are chosen must be capable of being adjusted to give higher air flows.

In the planning of a recirculation strategy for ultra-deep mines, one must keep in mind that the intake flow will be reduced because of an increased pressure drop in the recirculation circuit. Figure 9.7.3 below gives a simplified 3D recirculation layout of the possible ventilation arrangements as used at Loraine Gold Mines Ltd in 1984. An important issue that must be kept in mind is the total heat load of the fans, which can also have an effect on the amount of cooling required. Within the area itself, regulators or even extra fans may be necessary to direct the required quantities of mixed intake air to the individual working areas.

Burton in his paper discussed two major reasons why it may possibly be desirable to stop recirculation at the time of each blast. First, the plug of fumes that normally occurs at each blast may be passed directly to the return airway. Furthermore, the dust and corrosive fumes caused by the blast would not pass through the recirculation fans or cooling sprays. Secondly, if recirculation is continued at the blast, the entire mixed intake airway must be included in the re-entry zone (for the safety of essential personnel).

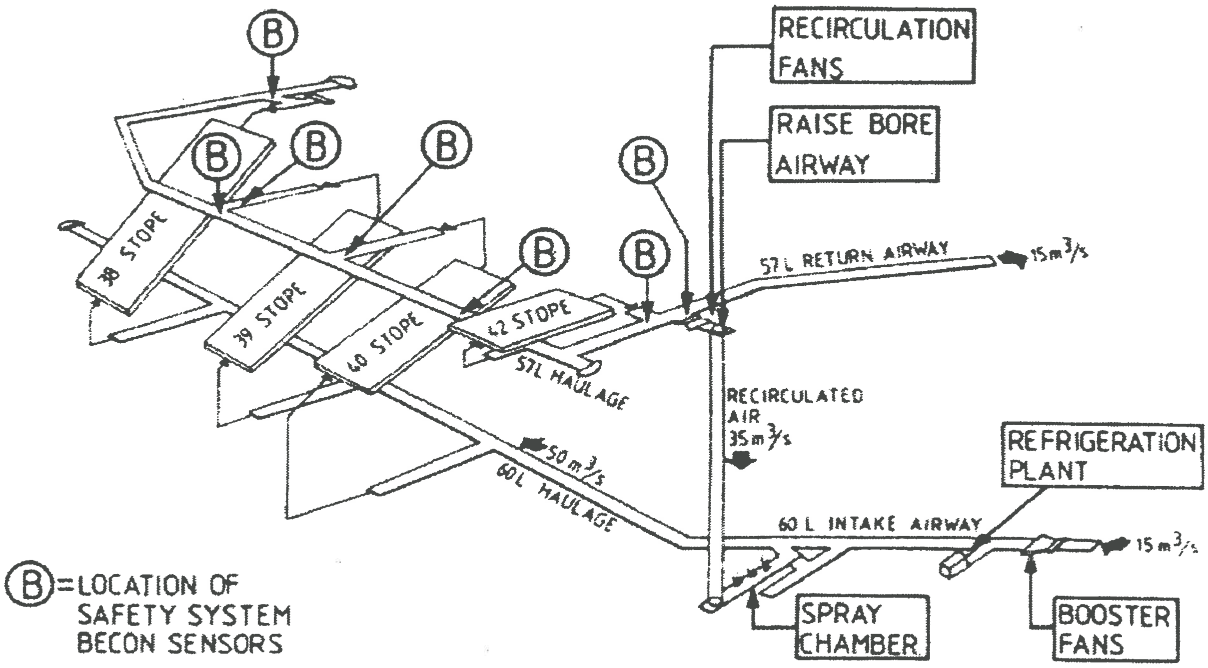


Figure 9.7.3 Simplified 3D drawing of a recirculation of air layout

9.7.4. Cooling arrangements

One of the main objectives in providing a recirculation system is to allow more bulk air spray cooling to be employed, rather than the troublesome cooling coil networks currently used. If the recirculation of air stops for blasts, it would be better to locate the coolers in the mixed intake air. Burton stated that this would offer two advantages, namely the intake air would continue to be cooled and that this cooling load may be sufficient to keep the refrigeration plant running.

An important aspect to consider is the heat-rejection facilities that may be required. If the chilled water required by the bulk air cooler is provided by a refrigeration plant located elsewhere in the mine or on surface, then no special provision need be made. It is therefore quite important to keep this aspect in mind in the initial design for ultra-deep mines. If a refrigeration plant is planned in the recirculation area, the proposed quantity of intake air and hence return air may not be sufficient if the introduction of recirculation implies a reduction in return air quantity.

In the event of there being no other return airways nearby which could be used for heat rejection, the condenser water could be piped away for recooling, but this might be impractical. It is therefore important to keep this aspect in mind in planning a recirculation system for ultra-deep mines. The quantity of return air must remain sufficient for heat rejection.

9.7.5. Safety arrangements

If a fire were to start within the area served by the recirculation system, hazardous fumes would be introduced into the intake. There are automatic safety systems and they have been used successfully in the past. The objectives of such a system would be:

- To detect reliably and quickly the occurrence and, preferably, the location of a fire
- To stop the recirculation fans immediately and restore the area to a once-through ventilation system
- To raise an alarm with the responsible personnel so that normal fire procedures can be followed.

These objectives must be achieved, either by using trained personnel or by installing a fire detection system or a combination of both. It must be emphasized that controlled recirculation should not be contemplated without the use of a suitable system (Middleton *et al.*, 1985).

Another important hazard that can occur is the gradual build-up of contaminants if the intake air is interrupted. If this happens, the contaminants would build up in virtually the same way as if there had been no controlled recirculation in the first place. Controlled recirculation would merely 'spread' the contaminants within the area and would not add to them.

In a normal once-through ventilation system, all the air supplied to an area is, of course, the intake air and workers would soon be aware of it if the fans stopped. However, if the recirculation fans were to continue to run, workers might not be aware that the intake air was no longer being supplied. Although some effects would not constitute an emergency, mines normally consider interlocking the recirculation fans with the intake booster fans so that recirculation cannot take place on its own (Burton, 1984).

9.8. Operation of controlled recirculation systems

Burton suggested that the use of controlled recirculation may require some changes to standard procedures in existing mines. In the design for a new mine, the various parameters related to the recirculation of air can be included beforehand so as to eliminate unnecessary problems. The quantity of intake air, however, should be sufficient for controlling return air contaminant levels and it should be ensured that controlled recirculation does not, in general, affect such levels. Once a recirculation system is established, a careful check must be made as to whether the intake quantity is actually sufficient. This will require monitoring in the return air during on-shift periods. In addition, measurements must be made to check that blasting fumes are removed at a sufficient rate from the area. The quantity of intake air may need to be increased if contaminant levels exceed acceptable values (Burton, 1984).

9.9. Aspects relevant to controlled recirculation

Controlled recirculation of air can and will play an important role in the provision of an acceptable underground environment for ultra-deep-level mining. More specifically, the following can be stated:

- Controlled recirculation provides a means of distributing the required amount of refrigeration in underground workings. This is achieved by increasing the air flow in an area without any increase in downcast air quantity.

- Controlled recirculation does not, in general, lead to an increase in return air contaminant levels, nor does it lead to a gradual build-up of contaminants over time.

- In all recirculation systems a quantity of 'fresh' intake air must be supplied to maintain acceptable gas levels and to remove blasting fumes timeously. This air must also be sufficient to control dust levels if no dust filtration is practised.

- Controlled recirculation will offer considerable practical and financial benefits in ultra-deep gold mines and the extent of the financial benefits will be investigated in following sections. In planning new mines, many of the recirculation constraints experienced by existing mines can be eliminated so as to optimise the benefits possible.

- The most important hazard associated with the use of controlled recirculation is fire. A reliable means of identifying, as soon as possible, the occurrence and location of a fire and of stopping recirculation is an essential requirement of all recirculation systems (Burton, 1984).

9.10. Simulation models and ENVIRON modelling parameters

9.10.1. Introduction

The representativeness and prediction capability of environmental software such as ENVIRON depends heavily on the accuracy of the mining layout and other operational considerations. For the base-case simulation model, the following applied:

The mine was assumed to be in the Carletonville area and all weather data, rock and geothermal properties used were taken from the MVS Data Book. The depth of the block of ground to be mined was between 3 800 m and 5 000 m. The peak stoping production was limited to 45 000 m^2 per month. This value corresponded to a nominal tonnage of 192 954 tons per month at a stoping width of 1,5 m. The development advance rate was taken at 60 m per month, which gave an approximate additional tonnage of 45 804 tons per month. The total tonnage mined for the simulation model was 238 758 tons. The mining method that was chosen for this simulation was the longwall, follow-behind system.

In essence this mining method means that the development is always behind the mined-out stope faces so as to ensure that the development always takes place in a destressed area. This mining method was used in setting up the simulation model and the various terms used, such as lower follow-behind (LFB) and upper follow-behind (UFB) relate to the position of the development in relation to the actual stoping. The main intake air per raise line, as indicated in Figures 9.10.1a and 9.10.1b, is on the lower level through an airway leading to the stope, and the return air passes through a ventilation boxhole down to the upper follow-behind airway, back to the main return airway.

For the base-case simulation model, a fixed mass flow was used to satisfy the design criteria chosen for the model. For the base case, no recirculation of air was considered and the air mass flow rate down the shaft was 934 kg/s. This meant a planned air requirement of approximately 3,9 kg/s/kt mined. The base case was then used as a reference in setting up the global and recirculation simulation models. For both the global and localised recirculation models, controlled recirculation percentages of 20, 30, 40, 50 and 60% were assumed and these different percentages of re-circulated air were built into the base-case simulation model by using fixed mass flows for that specific area. Figures 9.10.1a and Figure 9.10.1b are simplified drawings to explain the difference between global and local recirculation as it was incorporated into the base-case model.

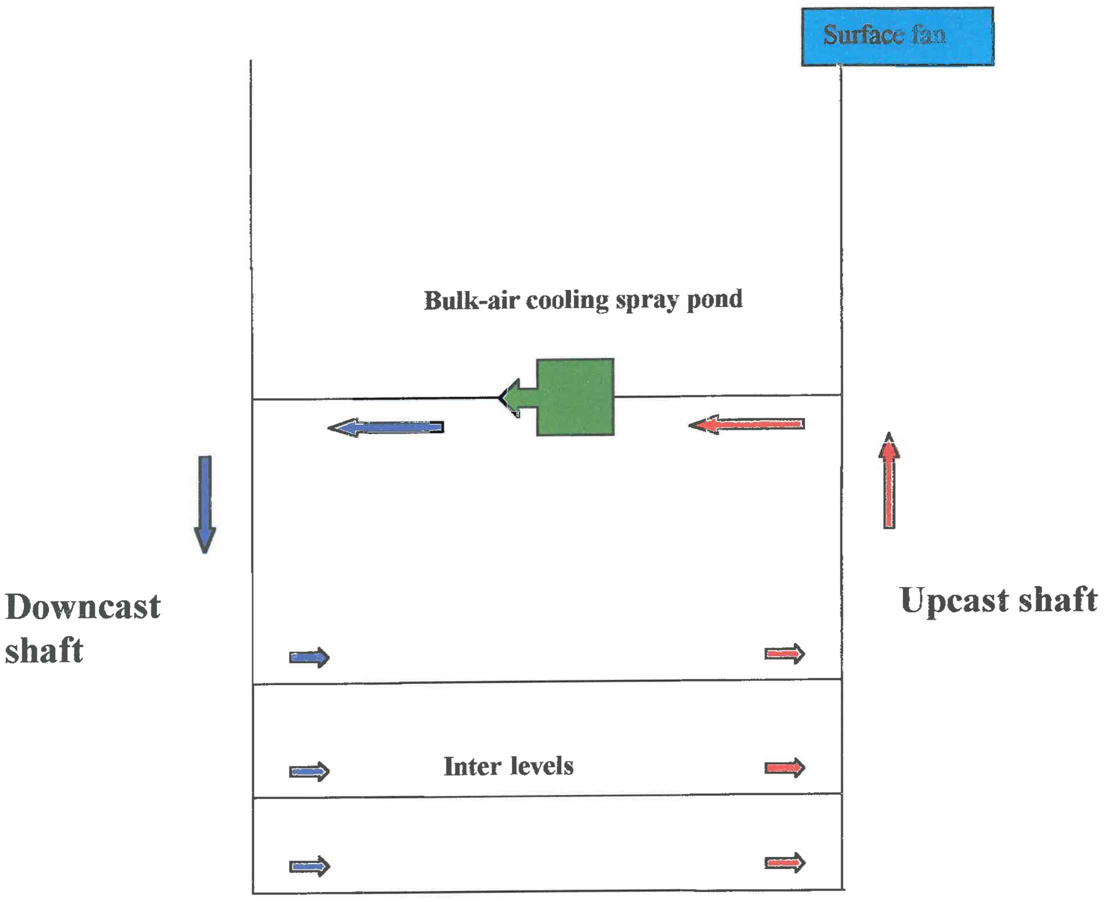


Figure 9.10.1.a *Simplified drawing of a global recirculation layout*

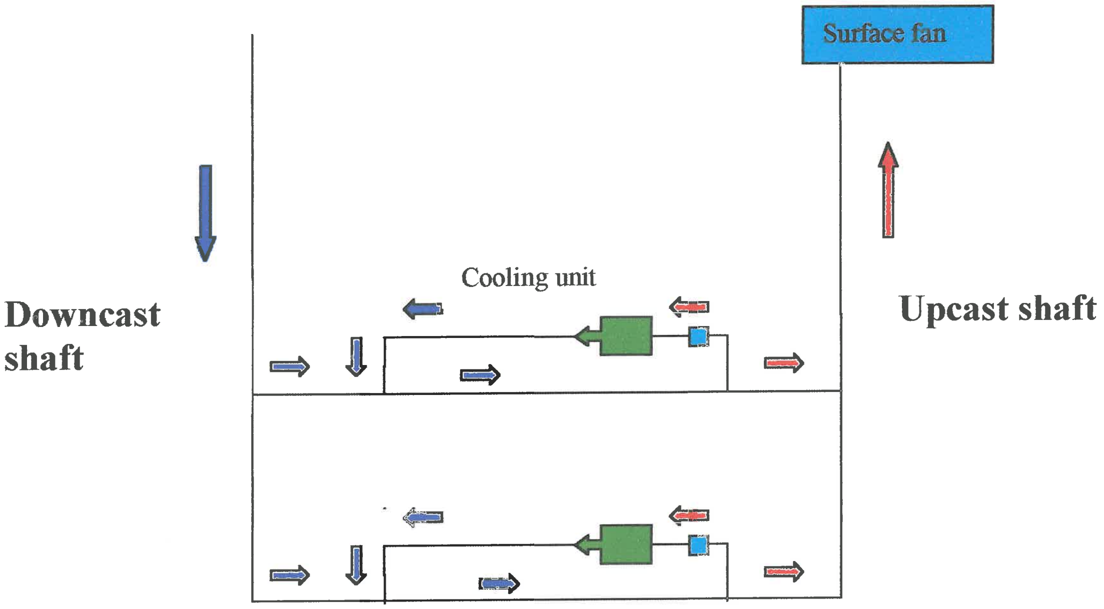


Figure 9.10.1.b ***Simplified drawing of a localised recirculation layout***

For the simulation of the global recirculation model, the amount of air to be recirculated was drawn off on level 3 500 m as a percentage of the main upcast return air mass flow and this meant a reduction in the total amount of downcast air from surface. The amount of air that was drawn off was then reintroduced to the main downcast shaft where it was mixed with the now reduced amount of fresh downcast air and was sent through the bulk air cooler, which was also situated on level 3 500 m. For the base-case scenario, the full 934 kg/s coming from surface was sent through the bulk air cooler. In the case of the localised recirculation model, only the reduced amount of downcast air was sent through the bulk air cooling system on 3 500 m. The amount of air recirculated on each level was cooled by coolers introduced for each of these recirculated circuits.

With controlled localised recirculation of return air, an amount of air equal to a set percentage of the return air was drawn off at a specific point on every level where the return air coming from a raise and incline connection rejoined. This was indicated by the longwall follow-behind mining method. This air was then cooled and reintroduced into the main intake air feeding that specific raise line and incline. This meant a reduction in the total air required per level and hence a reduction in the total air required from surface. This recirculation of return air was repeated for all levels at different recirculation percentages in order to bring about an overall reduction in the total air needed from surface.

9.10.2. Other ENVIRON modelling parameters

9.10.2.1 General parameters

The design reject wet-bulb temperature from all stopes was limited to 27°C ± 1°C. This temperature range rendered a value for specific cooling power of at least 300 W/m^2 at a velocity of 0,5 m/s as was proposed in the initial stages of this investigation. Air quantities entering the stopes were planned to ensure that face velocities remained between 0,5 and 1,0 m/s. The minimum face velocity as required by South African regulations is 0,25m/s, which would mean an over-design and well within limits. The same velocity was used for all the simulation models and it was therefore a constant factor throughout the investigation. The face zone width was assumed at 5 m (as a normal standard used for ventilation control). The average face advance was taken as 12 m/month.

Maximum design wet-bulb temperatures in all intake airways, development ends and travelling ways were limited to 29°C±1°C. Ventilation for development ends was based on a minimum requirement of 0,3 m^3/s per m^2 of face (double the amount required by South African regulations) and the minimum air quantity for intake airways was 10 m^3/s. In all instances a leakage percentage of 30% was assumed.

The main vertical downcast shaft was limited to a depth of 3 500 m. For purposes of evaluating main fan power, the shaft diameter was calculated on the assumption that the nominal air velocity would be about 11 m/s. For the purpose of comparison, the shaft diameter was not changed for the various simulation models, but it could become a major cost-saving issue needing investigation once the optimum recirculation percentage has been determined.

A sub-vertical downcast shaft was modelled from a depth of 3 500 m to 5 000 m and the diameter was based on an air velocity of about 11 m/s. Upcast shafts were sized to ensure that air velocities remained at about 20 m/s and avoided the critical velocity zone.

The temperature of the service water arriving at stopes was assumed to be 12°C for all workings up to 800 m from shaft; thereafter it was modelled to be proportionally warmer due to the additional pipe losses. The addition of linear heat in the intake airways in which chilled water pipes were installed was set to a negative value of 150 W/m (net) and for the remaining intake airways a net value of 50 W/m was used. Intake airways were not insulated and the haulages were considered to be 'wet' but without drains. It was assumed that the drain water was collected and returned via pipes from the working areas back to the return-water dams. The chilled service water consumption used was 1 ton of water per ton of rock mined. The overall fissure water inflow was 0,4 tons per ton of rock mined.

The wet-and dry-bulb temperatures of the ambient air entering the shaft system on surface were set to 17°C and 27°C respectively. The primary air cooler was situated at the top of the sub-vertical shaft at 3 500 m and cooled the mixed downcast and recirculating air to 18°C wet-bulb. Secondary air coolers were located in intake airways and travelling ways. Chilled service water was provided in all cases and in-stope air cooling when needed. The temperature of the air leaving the coolers was set at 20°C wet-bulb.

For layouts using backfill, the temperature of the backfill arriving at the stopes was assumed to be 27°C and thus, in terms of the simulation modelling, created neither a heating nor a cooling load in the stopes. In layouts where backfill was used, placement corresponded to an effective area of 70%.

The Atkinson method was used in determining pressure losses due to friction. The following values were based on past experiences and reference material for the various network components:

Downcast shafts	0,025 Ns^2/m^4
Upcast shafts	0,007 Ns^2/m^4
Intake airways	0,010 Ns^2/m^4
Upcast shafts	0,004 Ns^2/m^4

In-stope ventilation, air pressure loss was assumed to be 20 Pa per 10kg/s for a single-sided stope measured over six panels. This figure was based on past experience and on analyses of measured data collected during stope heat flow studies in similar settings.

The linear heat loads modelled in tunnels and cross-cuts were set to 50W/m. This figure was considered to be reliable and is typical of linear heat loads encountered in a deep-level mine. It was also assumed that electric locos would be predominantly used, thereby minimising the heat load. Additional heat generated by other types of locos, such as diesel, was catered for in the assumed overall average linear heat figure.

The total heat load depends to an appreciable extent on the age of the excavations. Based on anticipated mining rates, the average age used in this simulation model was four years. This figure is typical for the mining area, and thus for the rock surfaces, at various times over its life. No spot heat loads were added in these models.

9.10.2.2 Diagrammatic layout for base-case and air recirculation models

In the base-case model each level and its various subsections were subdivided into sections and were marked accordingly from A to S. This numbering was also later used in identifying the various recirculation sections in the comparison with the localised recirculation section. The important issue was therefore to find out to what extent the cooling and fan requirements would change with various changes in the amount of air being recirculated globally. The results would then be used in a costing model to determine the optimum recirculation of air (percentage). Figure 9.10.2.2 below shows a diagram of the simplified numbering of sections and the average depth for each level, as used in all the simulation models.

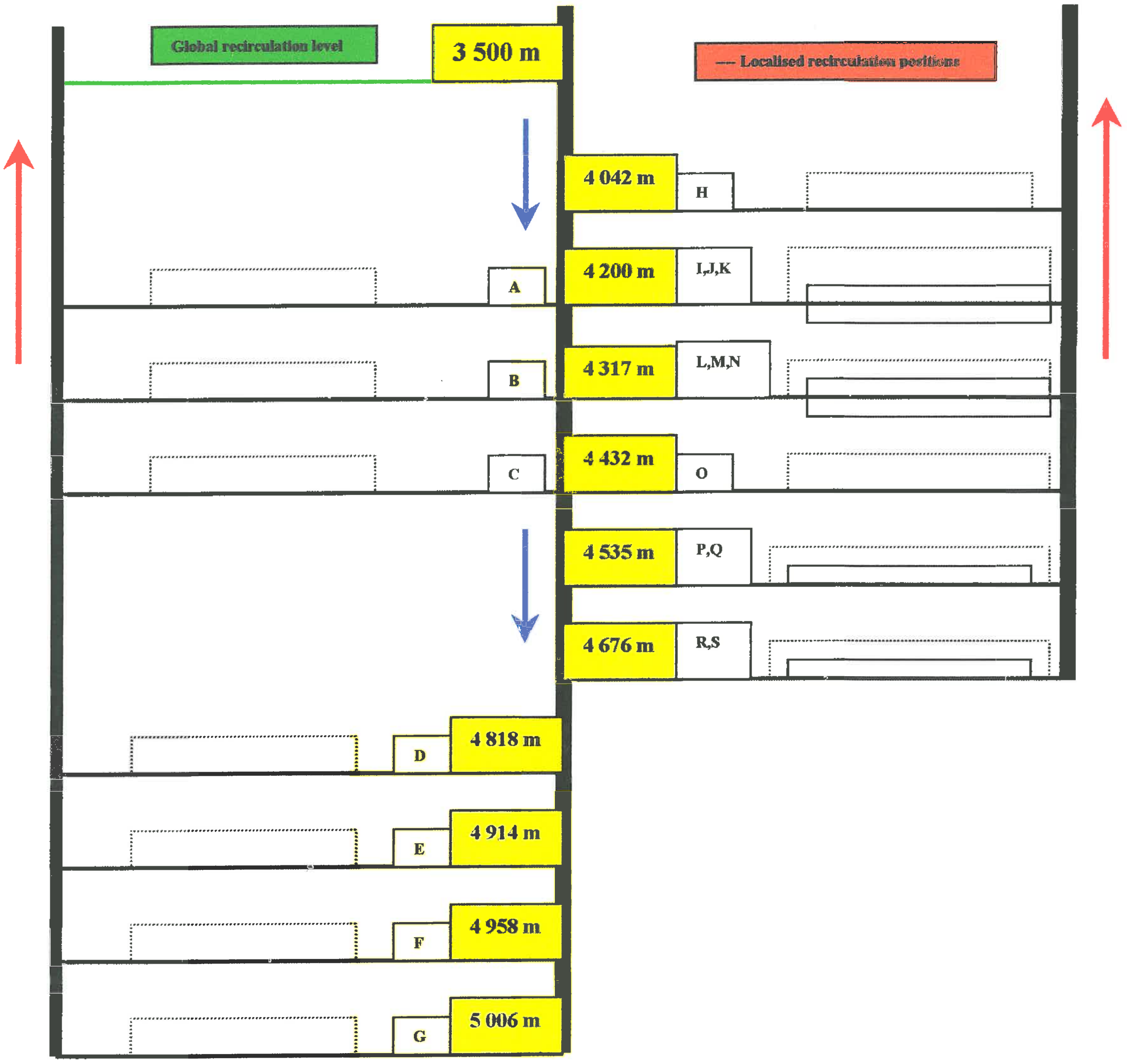


Figure 9.10.2.2 *Simplified numbering of sections and average depth*

9.10.2.3 Global features of base-case simulation model

In order to establish the base-case simulation model, a set of basic parameters as well as the assumptions mentioned before were used. Some of the other features of the base-case simulation model are listed in Table 9.10.2.3 below.

<u>Table 9.10.2.3</u>
Basic features of simulation model

Number of regulators	55
Number of fixed branches	1 for base case, 2 for the global recirculation model and 20 for the localised recirculation model
Number of fans (additional)	nil (fixed flow used as reference)
Number of hoists	1
Number of air coolers employed	74
Number of branches	456
Number of nodes	399
Number of working levels	10 (excluding bulk air cooling level)
Summary of tunnel results:	
Number of tunnels	193 (total length 98 021 m)
Summary of air cooler results:	
Number of air coolers employed	74
Number in operation	70
Summary of development results:	
Number of development ends	45
Summary of shaft results:	
Number of shafts	21 (including inclined shafts, and shaft split up into sections taken as additional shafts)
Summary of shaft station area results:	
Number of shaft station areas	11
Length of tunnels	11 km
Summary of stope results:	
Total number of stopes	54 (single and double-sided stopes)

10. Comparison of simulation model results

10.1. Introduction

The results achieved from the base-case simulation model (0% recirculated) were compared those obtained from the global and localised recirculation of return air models. These results were for various percentages of air recirculated, as specified before. In the comparison of all the results obtained, all aspects related to the costs for cooling and fan requirements were considered and evaluated. All the assumptions and calculations used for all comparisons will be discussed in detail.

10.2. Base-case simulation and global recirculation results

From the various global recirculation runs that were done on ENVIRON, a summary of each percentage global recirculation simulation was drawn up and compared with the results obtained from the base-case simulation. The results of the comparison of the physical parameters for the base-case and global recirculation models are summarised in Table 10.2 below.

<u>Table 10.2</u>
Summary of physical parameters for base-case and global recirculation models

	Base case	**20%**	**30%**	**40%**	**50%**	**60%**
Summary of global parameters:						
Number of shafts	21	22	22	22	22	22
Number of regulators	55	55	55	55	55	55
Number of fixed branches	1	2	2	2	2	2
Number of fans	0	0	0	0	0	0
Number of hoists	1	1	1	1	1	1
Number of air coolers	74	74	74	74	74	74
Number of dev. ends	45	45	45	45	45	45
Number of shaft stations	11	11	11	11	11	11
Number of stopes	54	54	54	54	54	54
Number of spot heat sources	0	0	0	0	0	0
Number of tunnels	193	193	193	193	193	193
Number of branches	456	457	457	457	457	457
Number of nodes	399	399	399	399	399	399
Summary of tunnel results:						
Number of tunnels	193	193	193	193	193	193
Total length (m)	98 021	98 021	98 021	98 021	98 021	98 021

Table 10.2 continued
Summary of physical parameters for base-case and global recirculation models

Summary of air cooler results:						
Total number of air coolers	74	74	74	74	74	74
Number in operation	70	70	70	70	70	70
Summary of development end results:						
Total number of development ends	45	45	45	45	45	45
Total production per month(tons/month)	45 804	45 804	45 804	45 804	45 804	45 804
Total service water used (tons/month)	32 063	32 063	32 063	32 063	32 063	32 063
Total fissure water (tons/month)	18	18	18	18	18	18
Summary of hoist results:						
Total number of hoists	1	1	1	1	1	1
Summary of shaft results:						
Total number of shafts	21	22	22	22	22	22
Total length (m)	10 012	10 012	10 012	10 012	10 012	10 012
Summary of shaft station area results:						
Total number of shaft station areas	11	11	11	11	11	11
Total length of tunnels (m)	11 000	11 000	11 000	11 000	11 000	11 000
Summary of stope results:						
Total number of stopes	54	54	54	54	54	54
Total production per month (kt/month)	193	193	193	193	193	193
Total service water used (kt/month) 193	193	193	193	193	193	
Total fissure water (t/month)	77 181	77 181	77 181	77 181	77 181	77 181
Summary of service water:						
Service water used in stopes (kt/month)	193	193	193	193	193	193
Service water dev. ends (kt/month)	32	32	32	32	32	32
Total service water used (kt/month)	225	225	225	225	225	225
Summary of production:						
Production stopes (kt/month)	193	193	193	193	193	193
Production dev. ends (kt/month)	45,8	45,8	45,8	45,8	45,8	45,8
Total production (kt/month)	239	239	239	239	239	239

From the table above it is obvious that the base-case model was kept almost the same for the global recirculation of air models, except for the fact that a recirculation circuit was introduced on level 3 500 m. This was done by introducing a fixed mass flow branch between the upcast and downcast shafts, as mentioned before. In terms of mining-related figures, all basic figures stayed the same so that a real comparison of results could be made eventually. The number of coolers in operation stayed the same, because all the air recirculated on the bulk air cooling level at 3 500 m underground went through the bulk air cooler as in the base case. The configuration of coolers and air-flow quantities for the lower levels therefore stayed the same.

10.2.1. Cooling and pumping requirements

In order to establish the cooling and pumping requirements, it was important to summarise the results achieved per level. By using the abovementioned method of subdividing the various levels, it was possible to summarise the cooling and pumping requirements for each level when global recirculation was considered. Table 10.2.1a gives a comparative summary of the results achieved for the cooling requirements for the base case and the percentages of air being recirculated globally.

Table 10.2.1a
Summary of cooling requirements for the base-case model and the models with various percentages for global recirculation of return air

Item description	**Average depth**	**Percentage of air re-circulated globally**					
		0%	**20%**	**30%**	**40%**	**50%**	**60%**
Bulk air cooling requirement (kW)	3 500	33 868	34 222	34 245	34 035	33 793	33 482
Cooling requirement per level (kW)	4 042	1 982	1 991	1 983	1 984	1 984	1 984
	4 200	6 482	6 526	6 511	6 519	6 526	6 531
	4 317	7 126	77 140	7 133	7 143	7 152	7 158
	4 432	5 438	5 404	5 147	5 387	5 384	5 381
	4 535	6 141	6 144	6 139	6 136	6 134	6 132
	4 676	3 650	3 698	3 696	3 701	3 703	3 705
	4 818	4 113	4 161	4 158	4 156	4 155	4 154
	4 914	4 638	4 689	4 681	4 679	4 677	4 675
	4 958	4 482	4 532	4 526	4 523	4 520	4 519
	5 006	3 861	3 920	3 912	3 909	3 908	3 906
Total cooling required (kW)		**81 781**	**82 428**	**82 130**	**82 171**	**81 935**	**81 628**

The table above is a summary of the results obtained from the detailed analysis for each level and each recirculation of return air (percentage).

In essence, the amount of bulk air cooling and cooling on the different levels basically stayed the same, as was expected. This is because of the fact that the amount of air flow down the sub-vertical shaft was kept constant. The only difference was that the hot return air from the upcast shaft was reintroduced into the main downcast air and cooled. This had the effect of slightly decreasing the amount of cooling required for each of the global recirculation of air models considered. This can be explained by the fact that the auto-decompression of air coming up from 5 006 m to 3 500 m below surface played a more significant role than the increase in temperature of the air coming from surface originally. Table 10.2.1b below gives a summary of the physical results for the comparison of the base-case simulation model and the various global recirculation percentages of return air.

Table 10.2.1b
Summary of total cooling requirements for global recirculation

	Base case	**20%**	**30%**	**40%**	**50%**	**60%**
Tunnels:						
Total heat load (kW)	41 467	41 309	41 166	41 141	41 088	41 043
Total heat from linear sources (kW)	-9 518	-9 518	-9 518	-9 518	-9 518	-9 518
Total heat load per metre (W/m)	423	421	420	420	419	419
Summary of air cooler results:						
Total cooling duty (reg. air coolers)(kW)	78 543	79 188	78 883	78 926	78 689	78 381
Summary of development end results:						
Total artificial heat load (kW)	707	707	707	707	707	707
Total heat load from service water (kW)	-596	-598	-604	-600	-601	-601
Total air heat load (kW)	5 100	5 074	5 036	5 053	5 046	5 040
Total heat load (kW)	5 695	5 672	5 640	5 653	5 646	5 641
Heat load/ton/month (W/ton/month)	124	124	123	123	123	123
Summary of hoist results:						
Total heat load (kW)	1 000	1 000	1 000	1 000	1 000	1 000
Summary of shaft results:						
Total heat from linear sources(kW)	-720	-720	-720	-720	-720	-720
Total heat load (kW)	1 761	1 769	1 768	1 777	1 778	1 777
Heat flow per metre (W/m)	176	177	177	177	178	178
Summary of shaft station area results:						
Total machine heat load (kW)	600	600	600	600	600	600
Total heat load (kW)	6 125	6 111	6 102	6 095	6 090	6 085

Table 10.2.1b continued
Summary of total cooling requirements and heat loads for global re-circulation

Summary of stope results:						
Total number of stopes	54	54	54	54	54	54
Total artificial heat (kW)	1 861	1 861	1 861	1 861	1 861	1 861
Total heat from service water (kW)	-2 642	-2 642	-2 644	-2 645	-2 645	-2 646
Total heat from fissure water (kW)	5 531	5 531	5 530	5 529	5 529	5 529
Total air heat load (kW)	22 026	22 006	21 987	21 980	21 974	21 969
Total heat load (kW)	24 667	24 648	24 631	24 624	24 619	24 615
Total heat load (W/t/month)	128	128	128	128	128	128
Summary of service water:						
Total heat load from service water (kW)	-3 238	-3 240	-3 248	-3 245	-3 246	-3 247
Summary of heat loads and cooling requirements:						
Total heat load (kW)	80 716	80 510	80 308	80 290	80 221	80 162
Heat load per ton (W/t/month)	338	337	336	336	336	336
Cooling: Service water (kW)	3 238	3 240	3 248	3 245	3 246	3 247
Cooling: Regular air coolers (kW)	78 543	79 188	78 883	78 926	78 689	78 381
Total cooling (kW)	81 781	82 428	82 130	82 171	81 935	81 628
Air-flow quantities:						
Downcast air main shaft (kg/s)	934	746	654	560	467	374
Total amount of air recirculated (kg/s)	0	188	280	268	374	560
Fan input power requirements:						
Surface main fans (kW)	18 482	8 140	5 865	4 107	2 771	1 789
Total recirculation fans underground (kW)	0	679	1 009	1 336	1 660	1 982
Total fan input power requirements (kW)	18 482	8 819	6 874	5 443	4 432	3 771

The table above also shows a comparison of the total amount of air being recirculated and how the amount of downcast air is reduced from 934 kg/s to 374 kg/s. The significant change in the fan input power requirements is also worth noting. The total reduction in input power required was due mainly to a substantial decrease in the pressure drop across the fixed flow branches from surface to underground. This gave further support to the opinion expressed earlier to the effect that the recirculation of air would become imperative in the design of the air-flow requirements for an ultra-deep mine. There was no great change in the amount of cooling required, as indicated, but a large difference in the input power required for fans. This immediately indicated that it would be more beneficial to make use of the recirculation of air.

10.2.2. Requirements for fans on surface and underground

In considering the requirements for the fans on surface and underground, the normal basic fan strategy of centrifugal fans was adopted. The same fans were assumed for all the simulation models and at no stage was the optimisation of any fans considered. For the base-case simulation model, 934 kg/s was used as the total amount of downcast air for comparative purposes. The amounts of air recirculated on level 3 500 m below surface were derived as a percentage of this total amount. As mentioned before, this amount of air was drawn off from the main upcast shaft and reintroduced into the main downcast shaft. After it had mixed with the total lower amount of downcast air, the full 934 kg/s was then bulk air-cooled. One would expect the required fan input power of the main fans on surface to decrease and the fan input power of the fans used in the global recirculation of return air to increase. Table 10.2.2 below gives a summary of the results obtained for the base-case and global simulation models.

<u>Table 10.2.2</u>
Summary of total air-flow and fan requirements for global recirculation

Item description	Average depth	Percentage of air recirculated globally					
		0%	20%	30%	40%	50%	60%
Air mass flow - downcast shaft		934	746	654	560	467	374
Mass flow of air recirculated	3 500	0	188	280	268	374	560
Main fans input power (kW)	0	18 482	8 140	5 865	4 107	2 771	1 789
Recirculation fans input power (kW)	3 500	0	679	1 009	1 336	1 660	1 982
Total input power surface and U/G (kW)		18 482	8 819	6 874	5 443	4 432	3 771

*Fan efficiency assumed as 76%.

It can be seen from the results obtained that there was a substantial reduction in the input power requirements for the base case compared with the recirculation models. This was expected due to the large decrease in the total volume and overall pressure required by the main fans on surface. There was a slight increase in the input power requirements for the recirculation fans as the amount of air recirculated was increased, but it was not as dramatic as the decrease in the input requirements for the surface main fans. The input power for the fans on surface was reduced by almost half for only 20% recirculation of air. For the purpose of this study an efficiency figure of 76% was assumed for all fans. However, the efficiency figure used here is a practical figure used for fans.

10.3. Base-case simulation and localised re-circulation results

From the various recirculation runs that were done on ENVIRON, a summary of each percentage localised recirculation simulation was obtained and compared with the results obtained from the base-case simulation. The results of the base-case and localised recirculation models and various other physical, related parameters are summarised and compared in Table 10.3 below.

<u>Table 10.3</u>

Summary of physical parameters for the base-case and localised recirculation models

	Base case	**20%**	**30%**	**40%**	**50%**	**60%**
Summary of global parameters:						
Number of shafts	21	21	21	21	21	21
Number of regulators	55	55	55	55	55	55
Number of fixed branches	1	20	20	20	20	20
Number of hoists	1	1	1	1	1	1
Number of air coolers	74	74	74	74	74	74
Number of dev. ends	45	45	45	45	45	45
Number of shaft stations	11	11	11	11	11	11
Number of stopes	54	54	54	54	54	54
Number of spot heat sources	0	0	0	0	0	0
Number of tunnels	194	194	194	194	194	194
Number of branches	456	481	481	481	481	481
Number of nodes	399	404	404	404	404	404
Summary of tunnel results:						
Number of tunnels	194	194	194	194	194	194
Total length (m)	98 021	98 021	98 021	98 021	98 021	98 021
Summary of air cooler results:						
Total number of air coolers	74	80	80	80	80	80
Number in operation	70	76	76	76	76	76
Summary of development end results:						
Total number of development ends	45	45	45	45	45	45
Total production per month (t/month)	45 804	45 804	45 804	45 804	45 804	45 804
Total service water used (t/month)	32 063	32 063	32 063	32 063	32 063	32 063
Total fissure water (t/month)	18	18	18	18	18	18
Summary of hoist results:						
Total number of hoists	1	1	1	1	1	1

Table 10.3 continued
Summary of physical parameters for base-case and localised recirculation models

Summary of shaft results:						
Total number of shafts	21	21	21	21	21	21
Total length (m)	10 012	10 012	10 012	10 012	10 012	10 012
Summary of shaft station area results:						
Total number of shaft station areas	11	11	11	11	11	11
Total length of tunnels (m)	11 000	11 000	11 000	11 000	11 000	11 000
Summary of stope results:						
Total number of stopes	54	54	54	54	54	54
Total production per month (kt/month)	193	193	193	193	193	193
Total service water used (kt/month)	193	193	193	193	193	193
Total fissure water (t/month)	77 181	77 181	77 181	77 181	77 181	77 181
Summary of service water:						
Service water used in stopes (kt/month)	193	193	193	193	193	193
Service water dev. ends (kt/month)	32	32	32	32	32	32
Total service water used (kt/month)	225	225	225	225	225	225
Summary of production:						
Production stopes (kt/month)	193	193	193	193	193	193
Production dev. ends (kt/month)	45,8	45,8	45,8	45,8	45,8	45,8
Total production (kt/month)	239	239	239	239	239	239

The table above also shows that the base-case design was not altered a lot. The only real difference was that 19 additional fixed flow branches were included on the ten working levels. This was done in order to simulate the total recirculation of return air per level. The strategy followed was that a percentage of the air coming from the boxhole airway connected to a stope and incline line on a specific level was recirculated. This process was repeated for every level and its effect was that the total amount of air that entered a specific level was now lower by the amount being recirculated. This led to a large reduction in the air in the downcast shaft. All other parameters were kept the same as in the base case.

10.3.1. Cooling and pumping requirements

As was the case with the global recirculation models, it was also necessary to summarise the results achieved per level for cooling and pumping requirements. By again using the method of subdividing the various levels as mentioned before, it was possible to summarise the cooling requirements for each level when localised recirculation on each level was considered. It was also obvious that the total amount of air in the sub-vertical shaft would now be less by the sum of the total amount of air that was recirculated on each level. In addition, the total amount of cooling required per level would increase due to the fact that the air being recirculated on each level had to be cooled. It was also one of the objectives to keep the total amount of air in each of the raise lines and inclines as close as possible to the base-case figures mentioned before. One would expect the fan input power of the main fans on surface to be reduced and the fan input power of the fans for localised recirculation of return air on each level to increase. Table 10.3.1a gives a summary of all the relevant cooling requirements for the base case, as well as the cooling requirements for the localised recirculation models using various percentages of return air.

Table 10.3.1a
Summary of cooling requirements for the base-case model and the models with various percentages of localised re-circulation of return air

Item description	**Average depth**	**Percentage of air recirculated locally**					
		0%	**20%**	**30%**	**40%**	**50%**	**60%**
Bulk air cooling requirement (kW)	3 500	33 868	29 606	27 368	25 070	22 757	20 365
Cooling requirement per level (kW)	4 042	1 982	3 000	3 124	3 248	3 367	3 474
	4 200	6 482	8 138	8 554	8 962	9 340	9 634
	4 317	7 126	8 298	8 568	8 813	9 023	9 201
	4 432	5 438	5 730	5 771	5 805	5 831	5 848
	4 535	6 141	6 360	6 457	6 544	6 623	6 693
	4 676	3 650	4 092	4 193	4 286	4 371	4 449
	4 818	4 113	4 241	4 217	4 195	4 174	4 153
	4 914	4 638	4 759	4 754	4 745	4 734	4 720
	4 958	4 482	4 598	4 594	4 585	4 576	4 564
	5 006	3 861	4 008	3 999	3 990	3 979	3 966
Total cooling required (kW)		81 781	82 830	81 599	80 244	78 775	77 067

The above table is a summary of the results obtained from the detailed analysis for each level and each percentage recirculation of return air.

A summary of the total cooling requirement results for localised recirculation is shown in Table 10.3.1b below.

Table 10.3.1b

Summary of total cooling requirements and heat loads for localised recirculation

	Base case	**20%**	**30%**	**40%**	**50%**	**60%**
Tunnels:						
Total heat load (kW)	41 467	43 497	43 118	42 654	42 079	41 294
Total heat from linear sources (kW)	-9 518	-9 518	-9 518	-9 518	-9 518	-9 518
Total heat load per metre (W/m)	423	443	439	434	428	420
Summary of air cooler results:						
Total cooling duty (reg. air coolers)(kW)	78 543	79 494	78 262	76 906	75 436	73 724
Summary of development end results:						
Total artificial heat load (kW)	707	707	707	707	707	707
Total heat load from service water (kW)	-596	-618	-619	-620	-621	-624
Total air heat load (kW)	5 100	4 985	4 975	4 965	4 954	4 939
Total heat load (kW)	5 695	5 603	5 594	5 584	5 575	5 562
Heat load/ton/month (W/t/month)	124	122	122	122	122	121
Summary of hoist results:						
Total heat load (kW)	1 000	1 000	1 000	1 000	1 000	1 000
Summary of shaft results:						
Total heat from linear sources(kW)	-720	-720	-720	-720	-720	-720
Total heat load (kW)	1 761	1 734	1 700	1 662	1 620	1 566
Heat flow per metre (W/m)	176	173	170	166	162	156
Summary of shaft station area results:						
Total machine heat load (kW)	600	600	600	600	600	600
Total heat load (kW)	6 125	6 049	6 004	5 956	5 903	5 847
Summary of stope results:						
Total number of stopes	54	54	54	54	54	54
Total artificial heat (kW)	1 861	1 861	1 861	1 861	1 861	1 861
Total heat from service water (kW)	-2 642	-2 718	-2 718	-2 718	-2 718	-2 720
Total heat from fissure water (kW)	5 531	5 500	5 500	5 500	5 500	5 500
Total air heat load (kW)	22 026	21 755	21 754	21 763	21 769	21 764
Total heat load (kW)	24 667	24 474	24 473	24 481	24 487	24 484
Total heat load (W/t/month)	128	127	127	127	127	127

Table 10.3.1b continued

Summary of total cooling requirements for localised recirculation

Summary of service water:						
Total heat load from service water (kW)	-3 238	-3 336	-3 337	-3 338	-3 339	-3 343
Summary of heat loads and cooling requirements:						
Total heat load (kW)	80 716	82 356	81 888	81 338	80 664	79 753
Heat load per ton (W/t/month)	338	345	3343	341	338	334
Cooling: Service water (kW)	3 238	3 336	3 337	3 338	3 339	3 343
Cooling: Regular air coolers (kW)	78 543	79 494	78 262	76 906	75 436	73 724
Total cooling (kW)	81 781	82 830	81 599	80 244	78 775	77 067

From these results it was also obvious that the base-case figures did not differ a lot from the results obtained for the various percentages of localised re-circulation of air. The most notable change was in the total amount of cooling required which decreased as the percentage recirculation of air on each level was increased. This could be explained by the fact that the bulk air cooling that was required on level 3 500 m below was much lower because the total amount of air that needed to be cooled was reduced according to the amount of air recirculated on the various levels. The detailed results showed that there was an increase in the amount of cooling needed per level. The temperature for air coming out of the coolers was set at 20°C saturated for all the coolers and no optimisation of cooler duty on the various levels was done. Since the nature of the study was comparative, this would not have changed the significance of the results obtained. In terms of the total cooling required, this will have to be considered in optimising the total cooling cost.

10.3.2. Requirements for fans on surface and underground

In considering the requirements for the fans on surface and underground for the localised re-circulation option, the normal basic fan strategy of centrifugal fans was adopted. As mentioned before, the same fans were assumed for all the simulation models and at no stage was the optimisation of any fans considered. In the case of the base-case simulation model, 934 kg/s was used as the total amount of downcast air for comparative purposes. No air was recirculated on level 3 500 m below surface anymore. The total amount of air sent through the bulk air cooler on level 3 500 m below surface decreased by the amount of the total sum of air recirculated per level. The reduced amount from surface was therefore the only air passing through the bulk air cooler. Additional coolers installed on each level cooled the recirculated air before it was reintroduced into the main stream on a level. One would expect the fan input power of the main fans on surface to decrease and fan input power of the fans recirculating the air on the various levels where recirculation of air took place to increase. Table 10.3.2 below gives a summary of the results obtained for the base-case and localised recirculation simulation models.

Table 10.3.2
Summary of total air-flow and fan requirements for localised recirculation of air

Item description	**Average depth**	**Percentage of air recirculated locally** **0%**	**20%**	**30%**	**40%**	**50%**	**60%**
Air mass flow		934	800	733	666	600	533
Mass flow of air recirculated	3 500	0	134	201	268	334	401
Main fans input power (kW)	0	18 482	10 440	7 563	5 325	3 598	2 249
Recirculation fans input power (kW)	4 042		1,4	1,6	1,7	1,6	1,3
	4 200		9,8	13,6	1,7	1,2	20,9
	4 317		9,0	14,0	19,4	25,1	31,1
	4 432		2,6	3,9	5,2	6,4	7,6
	4 535		3,0	4,5	6,0	7,6	9,1
	4 676		2,3	3,6	4,8	6,1	7,5
	4 818		1,1	1,6	2,1	2,5	2,9
	4 914		1,1	1,7	2,3	2,9	3,6
	4 958		1,1	1,8	2,4	3,0	3,8
	5 006		1,0	1,5	2,0	2,6	3,2
Total recirculation input power (kW)		0	32,4	47,7	62,6	77,2	91,1
Total input power surface & U/G (kW)		18 482	10 472	7 611	5 388	3 675	2 340

*Fan efficiency assumed as 76%.

10.4. Costing for base-case simulation model

10.4.1. Physical cooling and pumping parameters

To be able to set up a costing model for the cooling and pumping requirements, a basic strategy for cooling and pumping was applied. From this basic strategy all the various input parameters were obtained and considered in the actual costing applicable to an ultra-deep mine. The amount of cooling required from level to level was determined for each recirculation of air model. The amount of cooling also differed from one simulation model to another. This had an effect on the water flow requirements on each level and hence on the pumping requirements for each simulation model.

The physical parameters relating to the cooling and pumping required for the base-case simulation, as mentioned before, are specified in Tables 10.4.1c, d, e, f, g and h below. These tables show all the relevant parameters associated with the cooling of air and water underground, as well as the arrangements for pumping the water. They also give an indication of which parameters were included and which excluded for the purpose of setting up a base-case cooling and pumping model. The parameters specified below were used in the actual costing exercise that was done for all the simulation models. The program used was an in-house cooling simulation model developed by CSIR Miningtek and used in the Deepmine research projects.

Table 10.4.1c
Physical parameters for cooling and pumping

STRATEGY INPUT

Cooling generating systems:	
Surface refrigeration plants	Yes
No. of parallel plants	1
Availability	90%
Chilled water temperature	3,0°C
Intermediate temperature	10,0°C
Total chilled water flow	750,0 kg/s
Chiller configuration	Single units
Condenser configuration	Series

Cooling towers:	**Pre-cooling**	**Condenser**
Cooling towers exist	Yes	Yes
No. of parallel plants	1	1
Availability (%)	80	80
Approach temperature (°C)	3.0	5,0

Dams:	**Chilled water**	**Clean return**	**Dirty return**
Dams exist	Yes	Yes	Yes
No. of dams	1	1	1
Available (%)	90	90	90
Storage time (min)	480	480	480

Pumps:	**ChWD**	**CCT**	**PCT**	**CRW**	**DRW**	**WTP**
Pumps exist	Yes	Yes	Yes	Yes	Yes	No
No. of units	6	6	6	6	6	
Availability (%)	70	70	70	70	70	

Table 10.4.1c continued
Physical parameters for cooling and pumping

Surface ice plants	No	
U/G refrigeration plants (Cooling towers)	Yes	
U/G refrigeration plants (Return water)	No	
Energy-recovery systems:		
Pelton turbines	Yes	
Hydrolift devices	No	
Surface options:		
Pre-cooling towers	Yes	
Water treatment plants	No	
Chilled water dam	Yes	
Clean return water dam	Yes	
Dirty return water dam	Yes	
Level options:	**Turbine 1**	**Turbine2**
Depth (m)	1 750	3 500
Pelton turbines	Yes	Yes
Hydrolift devices	No	No
Throttle valve (OC)	No	No
Throttle valve (CC)	No	No
Refrig. plant (CT)	No	Yes
Refrig. plant (RW)	No	No
Chilled water dam	Yes	Yes
Ice mixing dam	No	No
Cool clean RW dam	Yes	Yes
Warm clean RW dam	Yes	Yes
Hot clean RW dam	No	No
Dirty RW dam	Yes	Yes
Settling dam	Yes	Yes
Water treatment plant	No	No

Several other inputs formed part of the simulation model for the pumping and cooling exercise. A very important aspect of the simulation in terms of cost-saving was the inclusion of a set of turbines on level 1 750 m below surface as well as on 3 500 m below surface. This was introduced as a basic strategy for all the simulations considered. The input figures relating to the turbines on 1 750 m and 3 500 m below surface are shown in Table 10.4.1d below.

Table 10.4.1d

Additional input figures for turbine on level 1 750 m underground

Pressure reduction:	**Pel. T**	**Hydro.**	**ThV(O)**	**ThV(C)**
Exist	Yes	No	No	No
No. of units	1			
Availability (%)	100			
Efficiency (%)	70			

Dams:	**ChW**	**Ice**	**CRWc**	**CRWw**	**CRWh**	**DRW**	**Sett**
Dams exist	Yes	No	Yes	Yes	No	Yes	Yes
No. of dams	1		1	1		1	1
Avail (%)	100		100	100		100	100
St. time(min)	480		480	0		0	0
L-to-W ratio	30		30	30		30	10

Pumps:	**HPCRW**	**LPCRW**	**HPDRW**	**LPDRW**	**UGCT**
Pumps exist	Yes	Yes	Yes	Yes	No
No. of units	6	6	6	6	
Availability (%)	100	100	100	100	
Efficiency (%)	70	70	70	70	

Pipes:	**HPChWo**	**HPChWc**	**LPIce**	**HPCRW**	**HPDRW**
Pipes exist	Yes	No	No	Yes	Yes
No. of units	2			1	1
Diameter (mm)	400			400	400

The input figures for the turbine on level 3 500 m below surface differed slightly from those used on 1 750 m and the differences are listed in Table 10.4.1e below. Figures for the dams, pipes and pumps were the same as those used on level 1 750 m. The amount of fissure water was taken as a constant figure for all levels and is therefore excluded from the figures for all simulation results.

Table 10.4.1e
Additional input figures for turbine on level 3 500 m underground

Cooling load				
Load (kW)	33 868			
To cooling load:				
Chilled water (from dam, l/s)	604,8			
Chilled water (from HP, l/s)	0,0			
Out of cooling load:				
Clean return water (cc, l/s)	0,0			
Clean return water (oc, l/s)	604,8			
Service return water (l/s)	0,0			
Water balance input:				
Water added to CC system (l/s)	983,3			
Ice added to mixing dam (kg/s)	0,0			
Estimated temp. RW to ice dam (°C)	30,0			
Pressure reduction:	**Pel. T**	**Hydro.**	**ThV(O)**	**ThV(C)**
Exist	Yes	No	No	No
No. of units	1			
Availability (%)	100			
Efficiency (%)	70			
Refrigeration plant (CT):				
No. of parallel plants	1			
Availability (%)	90			
Chilled water temperature (°C)	3,0			
Intermediate temperature (°C)	10,0			
Total chilled water flow	838,1 kg/s			
Chiller configuration	Single units			
Condenser configuration	Series			
Condenser cooling towers:				
No. of parallel plants	1			
Availability (%)	100			
WBT of return air (°C)	31,0			
Total return air (kg/s)	934,0			

The average depths for the levels at which the cooling and pumping equipment was situated, other than those already specified, were: 4 042, 4 200, 4 317, 4 432, 4 535, 4 676, 4 818, 4 914, 4 958, and 5 006 m. The pumping and cooling parameters used for all these levels are listed in Table 10.4.1f below.

Table 10.4.1.f
Input for pumping and cooling parameters for all other levels

Pelton turbines	No
Hydrolift devices	No
Throttle valve (OC)	Yes
Throttle valve (CC)	Yes
Refrig. plant (CT)	No
Refrig. plant (RW)	No
Chilled water dam	Yes
Ice mixing dam	No
Cool clean RW dam	Yes
Warm clean RW dam	Yes
Hot clean RW dam	No
Dirty RW dam	Yes
Settling dam	Yes
Water treatment plant	No

In the base-case simulation model, as well as for the other simulations, the cooling load and hence the water flow rates associated with the cooling varied from level to level. These are listed in Table 10.4.1g below

Table 10.4.1g
Changing cooling loads and water flow rates for each level

Cooling loads:

			To cooling load:	**Out of cooling load:**
	Average depth	**Load**	**Chilled water from HP (l/s)**	**Clean water return (cc, l/s)**
Levels	4 042	1 982	33,4	33,4
	4 200	6 482	121,6	121,6
	4 317	7 126	138,3	138,3
	4 432	5 438	108,1	108,1
	4 535	6 141	125,1	125,1
	4 676	3 650	76,0	76,0
	4 818	4 113	88,3	88,3
	4 914	4 638	102,7	102,7
	4 958	4 482	101,4	101,4
	5 006	3 861	88,3	88,3

Input parameters relating to dams, pumps and piping formed an integral part of the simulation program and the figures and parameters used are listed in Table 10.4.1h below.

Table 10.4.1h

Constant input parameter figures for dams, pumps and pipes for all levels

Pressure reduction	**Pel. T**	**Hydro.**	**ThV(O)**	**ThV(C)**
Exist	Yes	No	No	No
No. of units	1			
Availability (%)	100			
Efficiency (%)	70			

Dams:	**ChW**	**Ice**	**CRWc**	**CRWw**	**CRWh**	**DRW**	**Sett**
Dams exist	Yes	No	Yes	Yes	No	Yes	Yes
No. of dams	1		1	1		1	1
Avail (%)	100		100	100		100	100
St. time(min)	480		480	0		0	0
L-to-W ratio	30		30	30		30	10

Pumps:	**HPCRW**	**LPCRW**	**HPDRW**	**LPDRW**	**UGCT**
Pumps exist	Yes	Yes	Yes	Yes	No
No. of units	6	6	6	6	
Availability (%)	100	100	100	100	
Efficiency (%)	70	70	70	70	

Pipes:	**HPChWo**	**HPChWc**	**LPIce**	**HPCRW**	**HPDRW**
Pipes exist	Yes	No	No	Yes	Yes
No. of units	2			1	1
Diameter (mm)	400			400	400

Water temperatures:	
Temperature of service return water from working areas	28,0°C
Temperature of clean return water from coolers	18,0 °C
Quality of U/G insulation:	New

10.4.2. Unit costs for pumping and cooling requirements

In determining the total cost associated with cooling and pumping, certain unit costs had to be considered and used. In this section all the basic costs associated with cooling and pumping have been incorporated into all the simulation models. A summary of all the various constant figures used in the cost calculations for the base-case and global recirculation models is shown in Table 10.4.2.

Table 10.4.2
Unit cost figures as used in the Deepmine 6.4.1 cooling cost model

Basic cooling unit costs				
Cooling generating systems:				
Capital cost (R/l/s)		330 000		
Maintenance cost (R/l/s)		10 600		
Dams (surface):		**Chilled water**	**Clean return**	**Dirty return**
Capital cost (R/m^3)		500	500	500
Maintenance cost (R/R/m^3)		10	10	10
Energy-recovery systems:				
Capital cost (R/l/s)		18 000		
Maintenance cost (R/l/s)		2 000		
Pressure reduction:				
Capital cost (R/l/s)		18 000		
Maintenance cost (R/l/s)		2 000		
Dams (underground):		**CRWc**		
Capital cost (R/m^3)		725		
Maintenance cost (R/m^3)		80		
Pumps (U/G):	**HPCRW**	**LPCRW**	**HPDRW**	**LPDRW**
Capital cost (R/kW)	5 000	700	5000	700
Maint. cost (R/kW)	300	80	300	80
Pipes (U/G):	**HPChWo**	**HPCRW**	**HPDRW**	
Capital cost (R/m)	3 380	2 920	2 920	
Maint. cost (R/m)	50	80	80	

The cost that was assumed for electricity was R1 120 per kW per annum. This figure was used in the calculations for cooling, pumping and fan-related running costs. All these costs were related back to a present value (PV) cost and an interest rate of 15% over a period of 10 years was used. This made it possible to compare the costs of the various simulation models for cooling, pumping and fan requirements.

10.4.3. Unit costs for fan requirements

In order to evaluate the total PV costs relating to fans, certain unit costs in terms of R/kW had to be assumed to be able to obtain the running, maintenance and capital costs related to fans for surface and underground. A total PV cost for fans on surface and underground was calculated and will be discussed in detail in the sub-sections that follow. Table 10.4.3 below shows the unit costs that were assumed for fans on surface and underground, for the base-case, global and localised recirculation models. The electricity cost for fans was assumed at R1 120 per kW per annum.

Table 10.4.3
Unit costs for fans on surface and underground

Item description	**Maintenance cost (R/kW)**	**Capital cost (R/kW)**
Main fans on surface	320	3 500
Recirculation fans underground	380	3 200

A sensitivity analysis of the effect of a change in the capital cost for fans was done and it was found that in terms of the global figure, a change in the capital amount would not have a significant influence on the total cost. The reduction in total cost related to fans was associated more with the actual running cost. The reduction in fan power required would therefore have a major impact on the results for the running costs. A reduction in the capital outlay would therefore also be applicable due to the reduced total power input requirement for fans on surface and underground, as mentioned before.

10.5. PV costs of global re-circulation of air

The total PV cost for the air being recirculated globally is made up of the sum of the total PV costs for the fan requirements and the total PV costs for the cooling and pumping required. It was therefore necessary to evaluate these two aspects in detail in order to be able to compare the various total PV costs related to each recirculation model. These aspects will be dealt with in detail in the sub-sections that follow.

10.5.1. PV costs for cooling and pumping

From all the relevant physical input parameters specified, as well as the cooling that was required for all the levels, a costing model was drawn up for the base-case, as well as for all the relevant simulation models for the global recirculation of return air. Table 10.5.1 below summarises the PV costs related to the cooling and pumping needed for various percentages of air recirculated globally.

__Table 10.5.1__
Total PV costs of cooling and pumping for global recirculation of return air

Costs in (kR)	**Percentage of air recirculated**					
	0%	**20%**	**30%**	**40%**	**50%**	**60%**
Running costs:						
Surface	9 096	9 096	9 096	9 096	9 096	9 096
Underground	77 640	80 866	82 310	85 289	89 615	92 882
Maintenance costs:						
Surface	9 313	9 313	9 313	9 313	9 313	9 313
Underground	50 068	50 450	50 102	50 207	50 178	50 138
Capital costs:						
Surface	299 000	299 000	299 000	299 000	299 000	299 000
Underground	796 935	802 846	798 300	799 870	799 020	797 867
Total costs:						
Surface	317 409	317 409	317 409	317 409	317 409	317 409
Underground	924 643	934 162	930 712	935 366	938 813	940 887
Total cooling costs - Surface and underground:	1 242 052	1 251 571	1 248 121	1 252 775	1256 222	1 258 296
Total PV cooling costs:	1 829 260	1 853 279	1 854 233	1 871 281	1891 997	1 907 039

The plant capacity on surface was kept the same for all the simulation models and therefore the amount of water that was sent down the shaft was kept at a constant figure of 750 kg/s. This meant that the only cooling figure required for a plant that would change would be for the plant on the level 3 500 m underground. This aspect is clearly shown in the table above. The results show that there is an increase in the PV costs for cooling and pumping as the amount of air that is recirculated increases. This could be expected due to the increase in cooling requirements, as was indicated before. The costs related to surface cooling stayed the same because a decision was made that the surface cooling requirement would stay the same for all the simulation models. Therefore, only the underground cooling requirements increased.

The table above is a summary of all the costs relating to the base-case and global recirculation models (various percentages). The details are given in Annexure A.

10.5.2. Total PV costs of fans

Annexure B gives a complete breakdown of the running, maintenance and capital costs associated with fans on surface and underground. The unit cost for maintenance and capital was an estimated figure, as was mentioned before. These figures were repeated in all the simulation models and made it possible to undertake a PV cost comparison.

Table 10.5.2 below gives a summary of all the various costs. The purpose of the exercise was to obtain an indication of the total PV cost associated with the global recirculation of return air and, if possible, to detect any trends in terms of a reduction or increase in total PV costs when the amount of recirculated air was changed.

Table 10.5.2
Total PV of fan costs for global re-circulation of return air

Costs in (kR)	**Percentage of air recirculated**					
	0%	**20%**	**30%**	**40%**	**50%**	**60%**
Running costs:						
Surface	20 707	9 120	6 571	4 602	3 105	2 004
Underground	0	760	1 131	1 497	1 860	2 221
Maintenance costs:						
Surface	5 914	2 605	1 877	1 314	887	572
Underground	0	258	383	508	631	753
Capital costs:						
Surface	64 686	28 491	20 526	14 375	9 700	6 262
Underground	0	2 171	3 229	4 276	5 312	6 344
Total costs:						
Surface	91 308	40 216	28 974	20 290	13 692	8 839
Underground	0	3 190	4 744	6 281	7 803	9 318
Total fan costs - Surface and underground	91 308	43 405	33 717	26 572	21 495	18 157
Total PV costs - Fans surface and underground	198 292	94 617	73 750	58 404	47 549	40 466

From the results obtained it was obvious that there was a large decrease in the PV costs for the fans when compared with the base-case scenario. This was due to the large decrease in pressure drop and air volume flow when global recirculation of air took place. This led to an overall decrease in the running, maintenance and capital costs for all the various recirculation models as the percentage of recirculated air was decreased.

10.5.3. Total PV costs for cooling and fans

From the results obtained above, a summary was compiled of all the costs related to cooling, pumping and air-flow requirements. The costs were subdivided into running, maintenance and capital costs relating to cooling and fans for surface and underground. PV costs for the models were then also derived. Table 10.5.3 below gives a breakdown of the total PV costs for different percentages of global recirculation of air.

__Table 10.5.3__
Total PV costs for global recirculation of return air

Costs in (kR)	**Percentage of air recirculated**					
	0%	**20%**	**30%**	**40%**	**50%**	**60%**
Running costs:						
Surface	29 803	18 216	15 667	13 698	12 201	11 100
Underground	77 640	81 626	83 441	86 786	91 475	95 103
Maintenance costs:						
Surface	15 227	11 918	11 190	10 627	10 200	9 885
Underground	50 068	50 708	50 485	50 715	50 809	50 891
Capital costs:						
Surface	363 686	327 491	319 526	313 375	308 700	305 262
Underground	796 935	805 017	801 529	804 146	804 332	804 211
Total costs:						
Surface	408 717	357 625	346 383	337 699	331 101	326 248
Underground	924 643	937 352	935 456	941 647	946 616	950 205
Total fan and cooling costs - Surface and underground:	1333 360	1294 976	1 281 838	1 279 347	1 277 717	1 276 453
Total PV costs - Fans and cooling:	2027 553	1947 896	1 927 984	1 929 685	1 939 546	1 947 505

The comparative results shown in the table above indicated a very interesting trend with regard to the total PV cost. The total PV cost for the base case was an amount of R 2,03 billion, which decreased gradually with an increase in recirculation up to 30%, after which it increased again. This finding is very important as it indicates that the optimum amount of recirculation would be around 30% global recirculation of return air.

The results given above are shown more clearly in graphical form, specifically with regard to the trend in terms of the total PV cost. Figure 10.5.3 below is a graphical representation of the total PV cost versus the amounts of air recirculated globally. The amounts recirculated varied as indicated before, from 0% to 60%.

The graph also clearly shows the downward trend in the total PV cost for the recirculation fans, as well as the increase in the total PV cost for cooling for the various recirculation percentages.

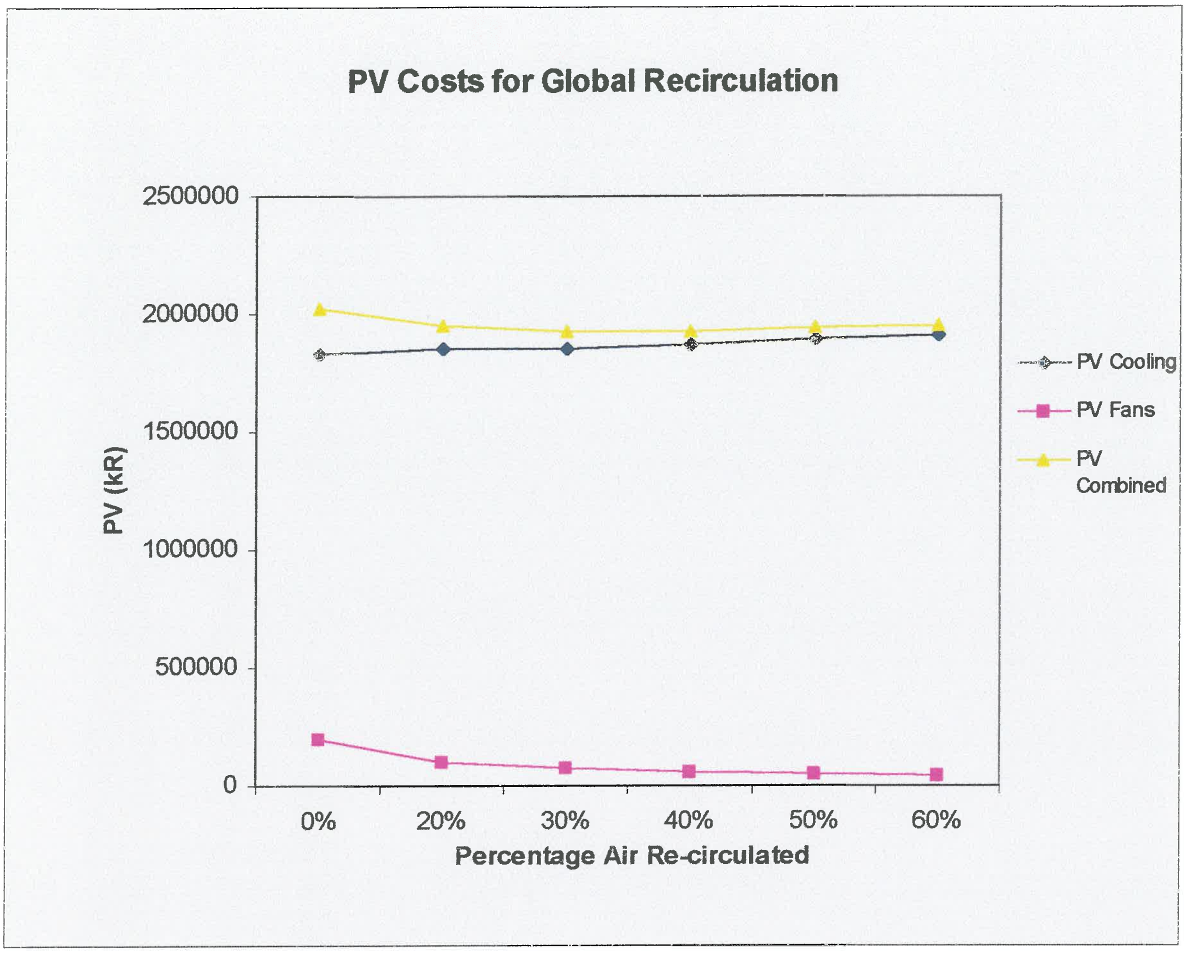


Figure 10.5.3 Total PV costs for the global recirculation of return air

10.5.4. Interpretation and evaluation of PV results for global recirculation

From the results obtained it is obvious that not many of the various parameters used in the base case changed in the global air recirculation simulation. This was to be expected as it was decided to keep the basic layout the same, but the factor expected to change would be the fan input power requirements on surface and underground. It was mentioned before that the cooling should stay the same because of the fact that the total amount of air down the sub-vertical shaft stayed the same as in the base case. The cooling required for each level was also expected not to change and this was confirmed by the results obtained. However, the results for the fan input power showed quite remarkable changes with regard to the power required for the base case compared with the combined power required for the global recirculation fans and the reduced input power required for the fans on surface. This was the result of a very large decrease in the pressure drop across the fans on surface when global recirculation was introduced. The total fan input power requirements for surface and underground were lower for all the recirculation percentages compared with the base case (almost 50 to 80% lower than the figure for the base case). From the graph (Figure 10.5.3) it is also obvious that the optimum percentage of air to be recirculated globally would be in the region of 30%. This is therefore an important aspect to keep in mind when the air and cooling requirements for an ultra-deep mine are being planned. From this result it is also obvious that recirculation of air is not only important but, in the context of ultra-deep mining planning, compulsory.

10.6. PV costs of localised recirculation of air

The total PV cost for the air being recirculated locally on each level is made up of the sum of the total PV costs for the fan requirements and the total PV costs for the cooling and pumping required. It was therefore necessary to evaluate these two aspects in detail to be able to compare the various total PV costs related to each recirculation model. These aspects will be dealt with in detail in the sub-sections that follow.

10.6.1. Total PV costs for cooling and pumping

From all the relevant physical input parameters specified, as well as the cooling that was required for all the levels, a costing model was drawn up for the base case and for all the relevant simulation models for the localised recirculation of return air. Table 10.6.1 below summarises the PV cost related to the cooling and pumping needed for various percentages of air re-circulated locally.

<u>Table 10.6.1</u>
Total PV costs of cooling and pumping for localised recirculation

Costs in (kR)	**Percentage of air recirculated**					
	0%	**20%**	**30%**	**40%**	**50%**	**60%**
Running costs:						
Surface	9 096	9 096	9 096	9 096	9 096	9 096
Underground	77 640	82 338	82 345	82 800	84 241	86 567
Maintenance costs:						
Surface	9 313	9 313	9 313	9 313	9 313	9 313
Underground	50 068	52 403	52 362	53 007	53 224	53 365
Capital costs:						
Surface	299 000	299 000	299 000	299 000	299 000	299 000
Underground	796 935	822 085	826 238	831 956	832 816	831 051
Total costs:						
Surface	317 409	317 409	317 409	317 409	317 409	317 409
Underground	924 643	956 826	960 945	967 763	970 281	970 983
Total cooling costs - Surface and underground	1 242 052	1 274 235	1 278 354	1 285 172	1 287 690	1 288 392
Total PV costs cooling	**1 829 260**	**1 889 707**	**1 893 689**	**1 904 928**	**1 914 109**	**1 924 725**

As mentioned before, the capacity of the plant on surface was kept the same for all the simulation models and therefore the amount of water that was sent down the shaft was kept at a constant figure of 750 kg/s. As in the case of global recirculation of air, this meant that the only required cooling figure for a plant that would change would be for the plant on level 3 500 m underground. The results obtained show that the PV costs for cooling and pumping increase as the amount of air that is recirculated increases. This was expected due to the increase in cooling requirements, as was indicated before. The costs related to surface cooling stayed the same because it was decided that the surface cooling requirement would stay the same for all the simulation models. The only increase in cooling requirements was therefore underground. The table above is a summary of all the costs relating to the base-case and localised recirculation models (various percentages) and the detailed analysis for the running, maintenance and capital costs for the cooling and pumping are shown in Annexure C. It therefore appears that the increased cooling required on the various levels had a negative impact on the total PV cost structure for increased air recirculation percentages. The decrease in the bulk air cooling required on level 3 500 m below surface therefore did not help in terms of the total cost-savings structure.

10.6.2. Total PV costs of fans

Annexure D gives a complete breakdown of the running, maintenance and capital costs associated with fans on surface and underground. The unit cost for maintenance and capital was an estimated figure, as was mentioned before. These figures were repeated in all the simulation models and made it possible to undertake a PV cost comparison. Table 10.6.2 below gives a summary of all the various costs. The purpose of the exercise was to obtain an indication of the total PV cost associated with localised recirculation of return air and, if possible, to detect any trends in terms of a reduction or increase in total PV costs for fans when the amount of recirculated air was changed.

Table 10.6.2.
Total PV costs of fans localised recirculation of return air

Costs in (kR)	**Percentage of air recirculated**					
	0%	**20%**	**30%**	**40%**	**50%**	**60%**
Running costs:						
Surface	20 707	11 697	8 474	5 966	4 031	2 520
Underground	0	36	53	70	86	102
Maintenance costs:						
Surface	5 914	3 341	2 420	1 704	1 151	720
Underground	0	12	18	24	29	35
Capital costs:						
Surface	64 686	36 540	26 471	18 638	12 591	7 873
Underground	0	104	153	200	247	292
Total costs:						
Surface	91 308	51 578	37 366	26 308	17 773	11 113
Underground	0	152	224	294	363	428
Total fan costs - Surface and underground	91 308	51 730	37 590	26 602	18 136	11 541
Total PV costs	198 292	112 359	81 658	57 804	39 426	25 111

From the results obtained it was obvious that there was a large decrease in the PV costs for the fans when compared with the base-case scenario. This was due to the large decrease in pressure drop and air volume flow when localised recirculation of air took place. This led to an overall decrease in the running, maintenance and capital costs for all the various recirculation models as the percentage of recirculated air was decreased.

10.6.3. Total PV costs for cooling and fans

From the results obtained above, a summary was compiled of all the costs related to cooling, pumping and air-flow requirements. The costs were subdivided into running, maintenance and capital costs relating to cooling and fans for surface and underground. PV costs for all the models were then also derived. Table 10.6.3 below gives a breakdown of the total PV costs for different percentages of localised recirculation of air.

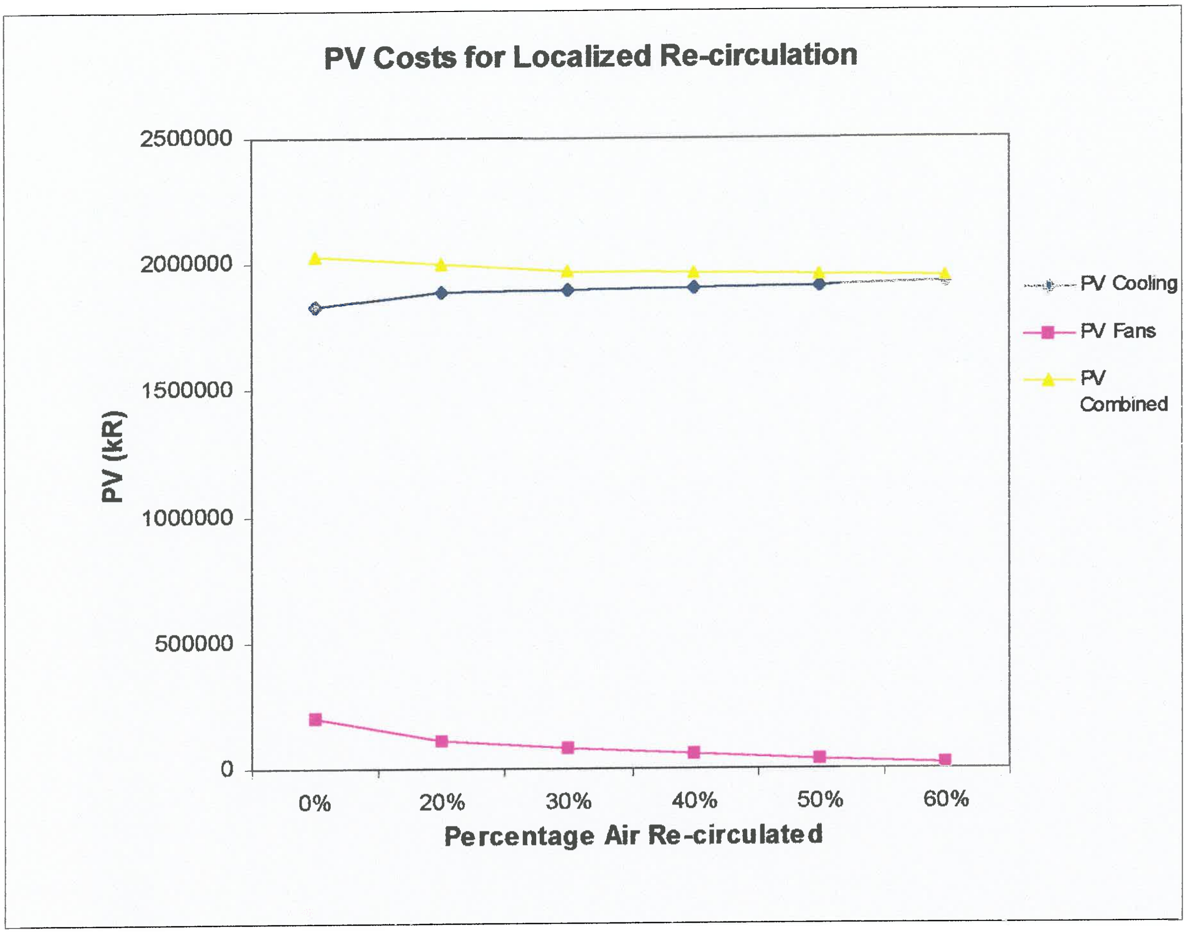
Table 10.6.3
Total PV costs for cooling and fans for localised re-circulation of return air

Costs in (kR)	**Percentage of air re-circulated**					
	0%	**20%**	**30%**	**40%**	**50%**	**60%**
Running costs:						
Surface	18 192	18 192	18 192	18 192	18 192	18 192
Underground	155 280	164 676	164 690	165 600	168 482	173 134
Maintenance costs:						
Surface	18 626	18 626	18 626	18 626	18 626	18 626
Underground	100 136	104 806	104 724	106 014	106 448	106 730
Capital costs:						
Surface	598 000	598 000	598 000	598 000	598 000	598 000
Underground	1 593 870	1 644 170	1 652 476	1 663 912	1 665 632	1662 102
Total costs:						
Surface	634 818	634 818	634 818	634 818	634 818	634 818
Underground	1 849 286	1 913 652	1 921 890	1 935 526	1 940 562	1941 966
Total fan and cooling costs - Surface and underground	1 333 360	1 325 965	1 315 944	1 311 774	1 305 826	1299 933
Total PV costs - fans and cooling	2 027 553	2 002 066	1 975 348	1 962 732	1 953 535	1949 837

The comparative results shown in the table above also indicated a very interesting trend with regard to the total PV cost. The total PV cost for the base case was a total amount of R2,03 billion, as mentioned before, the main difference being that the there was no 'turning point' in terms of the total PV cost profile. The graph continued a downward trend but did not show total PV cost figures lower than those achieved with the global recirculation model. This finding is also very important as it indicates that when recirculation is being considered in the preliminary design of air and cooling requirements for an ultra-deep mine, global recirculation would, in most cases, be the better option to consider.

The results given above are shown more clearly shown in graphical form, specifically with regard to the trend in terms of the total PV cost. Figure 10.6.3 below is a graphical representation of the total PV cost versus the amount of air recirculated locally. The amounts recirculated varied as indicated before, from 0% to 60%.

The graph also clearly shows the downward trend in the total PV cost for the recirculation fans, as well as the increase in the total PV cost for cooling for the various recirculation percentages.



<u>Figure 10.6.3</u> Total PV costs for the localised recirculation of return air

10.6.4. Interpretation and evaluation of results for localised re-circulation

From the graph it is obvious that the total PV cost shows a downward trend but, when compared with the results obtained for the global recirculation models, it also shows a higher PV cost for all the localised recirculation percentages considered. This aspect has to be kept in mind in planning the ventilation requirements for an ultra-deep mine when a longwall follow-behind mining layout is considered. It must also be noted that the saving in costs incurred with a lower bulk air requirement was cancelled out by the fact that there was a higher cooling requirement for all the localised recirculation levels.

10.7. Comparative PV costs of global and localised recirculation

The combined total PV costs for global and localised recirculation for various recirculation percentages is shown in Figure 10.7 below.

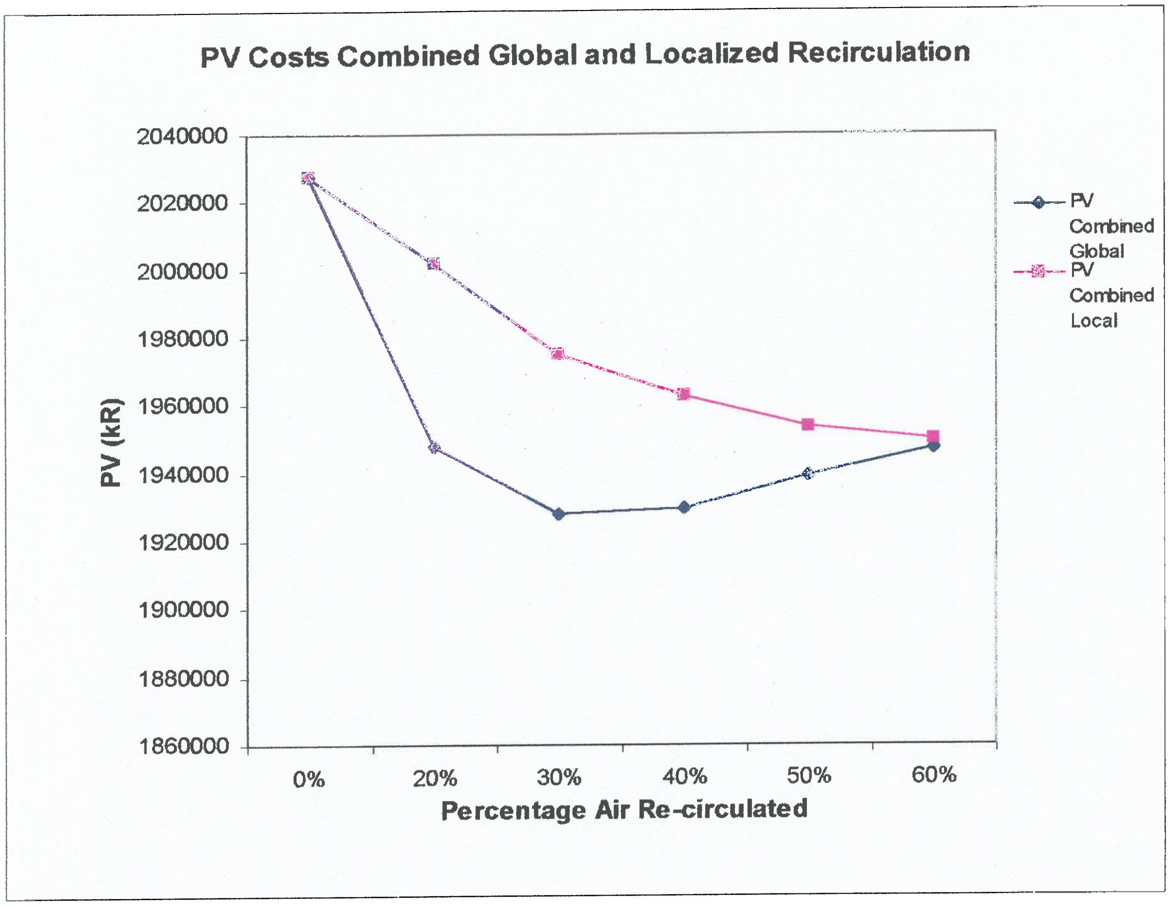


Figure 10.7 Combination of total PV costs for global and localised recirculation

This graph is a clear indication that for any percentage of air recirculated, global recirculation would be the best option to consider in planning the ventilation requirements for an ultra-deep mine when a longwall follow-behind mining layout is planned. The optimum percentage of air globally recirculated to use in such planning is indicated as between 30 and 40%. In order to quantify the total PV cost finding in terms of dollar/ounce produced, the following assumptions and calculations have to be made:

Tons mined from stope per month	192 954	(from base case)
Tons produced per annum (million)	2.32	
Average grade assumed (g/t)	10	
Gold produced (kg)	23 155	
Gold produced (ounces)	815 038	
Rand/dollar exchange rate	6.,1	

Table 10.7.1 shows a summary of the total cost in dollar/ounce produced. For the 30% global recirculation option, a figure of $38.9/ounce of gold produced is indicated.

Table 10.7.1
Summary of total costs in terms of dollar/ounce of gold produced

	Percentages of air recirculated					
	0%	**20%**	**30%**	**40%**	**50%**	**60%**
Total PV costs Global recirculation	2 027 553	1 947 896	1 927 984	1 929 685	1 939 546	1 947 505
Total PV costs Localised recirculation	2 027 553	2 002 066	1 975 348	1 962 732	1 953 535	1 949 837
Costs in dollar/ounce Global recirculation	40.9	39.3	38.9	39.0	39.2	39.3
Costs in dollar/ounce Localised recirculation	40.9	40.4	39.9	39.6	39.4	39.4

The results obtained in the table above can be represented in graphical format and are shown in Figure 10.7.1 below.

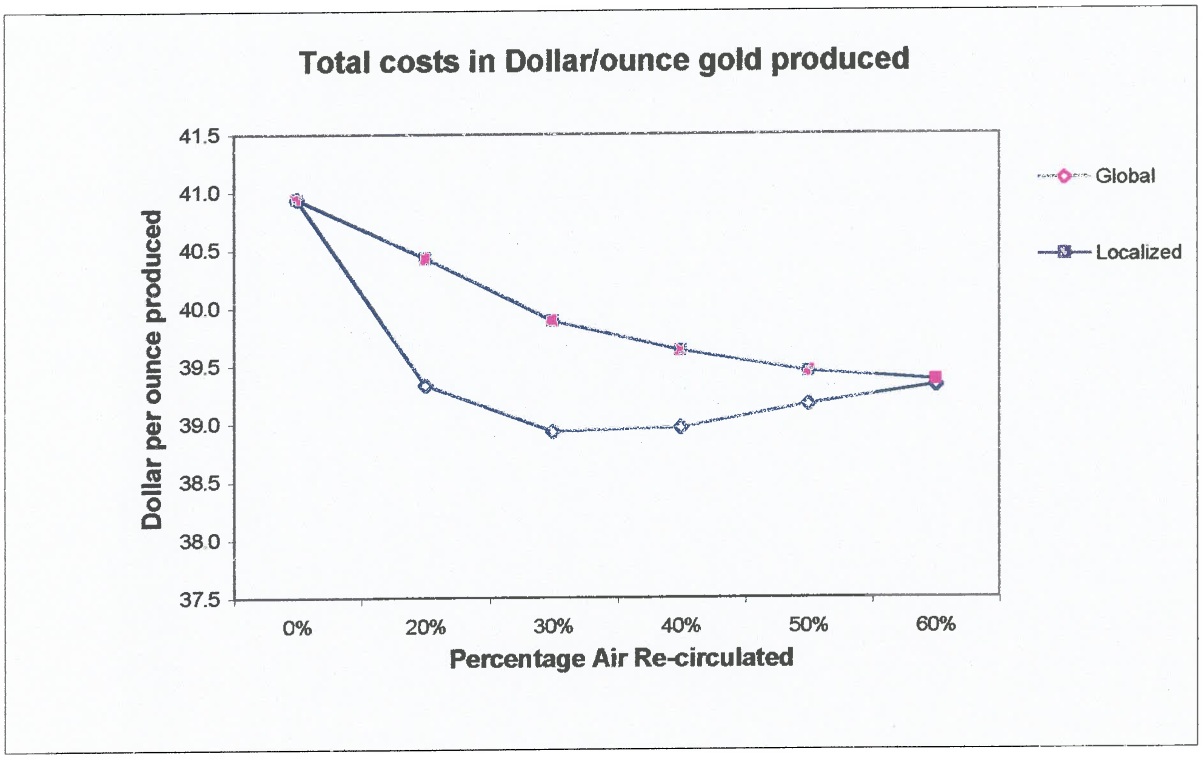


Figure 10.7.1 *Total costs in terms of dollar/ounce of gold produced*

10.8. Evaluation of results for recirculation of return air

It was shown in this study that the inclusion of controlled recirculation strategies in the planning of the ventilation requirements for an ultra-deep mine, when using a longwall follow-behind mining layout, would have beneficial economic effects. The proper application of recirculation strategies can result in significant reductions in the fan input power requirements. Recirculation greatly reduces the impact of auto-compression on total heat load. For the purposes of this study, the negative impact of 'too much' recirculated air was ignored as it was assumed that no matter what the recirculation percentage is, it would be viable in terms of ensuring a safe working environment.

Burton specified a minimum amount of 2,5 kg/s/kt of fresh intake air. In the worst-case scenario of 374 kg/s of air down the main vertical shaft, with 60% air being recirculated globally in this study, which is 216 kg/s/kt less than proposed by Burton, a possible problem becomes apparent. The total amount of air available for the dilution of gases and the minimum supply of fresh air in terms of underground mines need to be investigated.

In planning a recirculation system for an ultra-deep mine, it appears from this study that it would be best to adopt a global recirculation system when a longwall follow-behind mining layout is considered since a localised recirculation system will then be less cost-effective in terms of the total PV cost for cooling and fans. For the purpose of this exercise, a combination of local and global recirculation was not considered and this needs to be investigated further.

When a longwall follow-behind mining layout is used, the optimum percentage for global recirculation of air has been found to be approximately 30%, which means a possible saving of 5% in total PV costs. In the example used in this study, the total PV cost for the base case without any recirculation was R2.03 billion, which gives a total PV cost saving of R110 million if the life of the mine is taken at 10 years and an interest rate of 15% is used. It must be noted that in all the recirculation models used, the cooling requirements were not optimised because in almost all the stopes an ACP of more than the 300 W/m^2 that was proposed earlier was available. On the basis of the total PV cost for the proposed design, this could imply large savings in terms of cooling requirements. For the global recirculation of 30% used in this example, a ventilation cost of $38.9/ounce was indicated. It must be emphasised and kept in mind that a single method and layout were used and therefore this is a simplistic and conservative example of possible savings.

11. Conclusions and recommendations

The work in this document has been subdivided into various sub-sections and the conclusions will be dealt with according to the various objectives that were set.

11.1. Relevant environmental factors and dependence on depth

- The findings of the investigation indicated that the cost-effective provision of acceptable thermal conditions in the workplace will be the greatest environmental control challenge in ultra-deep mining, with the impact of most other environmental aspects not expected to differ materially from what prevails at current mining depths.

- The most notable exception, barometric pressure (and its potential to cause baro-trauma and increase the toxicity of airborne pollutants), is separate field of expertise and needs to be dealt with on its own in detail.

- Owing to their independence from depth, physical stresses such as noise, vibration, lighting/visibility, etc. are not expected to differ materially from what prevails at current depths and accordingly, present standards and exposure limits for their control can be regarded as sufficiently protective for workers in ultra-deep mining environments. In contrast, heat stress will tend to increase with depth.

11.2. Controlling the effects of heat stress on workers

- The findings on heat stress were based on 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 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 the combined best features of relevant heat stress indices and locally developed knowledge of human tolerance limits for safe and productive work.

- The ability of the environment to remove metabolic heat from workers' bodies, and thus, to limit the negative impact on their health, safety and productivity, depends primarily on wet-bulb temperature and air velocity, with wet-bulb temperature having been proved to be the most useful single-measurement indicator of environmental heat stress. Although 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. Possible exceptions involving high radiant temperature, as a result either of newly exposed rock or the use of diesel-powered equipment, would indicate the need to consider this parameter in assessing such situations, 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.

11.3. 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 for which it will be used
- 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 determining and enforcing regulatory standards and exposure limits.

11.4. Design and planning

❖ A number of heat stress indices meet the above requirements to varying extents, but only a few satisfactorily address criteria for underground applications. 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 determinants of environmental cooling capacity and relates directly to engineering design parameters. For planning purposes, an ACP level of 300 W/m^2 should be considered the minimum requirement.

11.4.1. 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, Wet-bulb Globe Temperature (WBGT) is the most widely used heat stress index, 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 practical as a means of routinely assessing environmental heat stress underground, mainly due to the number of parameters 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 because it considers the combined effects of convection, radiation and evaporation.

❖ 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. 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 (ACP), 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, with the upper limit for routine work set at 32,5°C. 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 take into account the impact of heat stress on workers' performance and cognitive ability.

11.5. Issues identified by industry practitioners

- 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. Examples of this are discussed in detail in this dissertation/report.

- This dissertation/report also incorporates the concerns and ideas of various practitioners in the industry and highlights various issues to consider in planning the environmental requirements for an ultra-deep mine.

11.6. Costing comparison for thermal standards and limits

- It has been the mining industry's experience thus far that small improvements in thermal conditions have been achieved through large increases in ventilation and, particularly, cooling costs.

- In contrast, the results of this study indicate that reducing the reject wet-bulb temperature would have less impact on the overall cost of ventilation and cooling than increasing the stope face air velocity. Over the range of reject wet-bulb temperatures considered (25 to 31°C), cooling and ventilation costs were shown to have a possible variation of up to 30% from the base case of 31°C.

- Reducing temperatures in ultra-deep mines would increase the absolute cost of environmental control, but the increase in relative or percentage terms would be less significant than for current mining depths. The work carried out in this study indicates that a given level of ACP in an ultra-deep mine can be achieved at far lower costs by reducing wet-bulb temperature than by increasing air velocity and air quantity. It then follows that, should health, safety and productivity-related requirements dictate a design reject wet-bulb temperature of, say, 25°C, it should be feasible (in terms of ventilation and cooling costs) to meet that criterion, provided a design temperature of 31°C was economically viable in the first place.

- Previous studies quantifying heat stress in terms of ACP have indicated that a level of 300 W/m^2 can be regarded as both safe and conducive to high productivity in nearly all instances.

- The significant cost increases associated with higher air velocities highlight the main conclusion of this analysis, namely that total air-flow quantity should be minimised and wet-bulb temperature reduced to achieve the required ACP in ultra-deep mines. Designing an environmental control system in accordance with these criteria would allow higher wet-bulb temperatures in areas that naturally have higher air velocities, e.g. intake airways, but the general approach indicated is to reduce wet-bulb temperature through cooling, and not to increase air velocity.

- The practicability of thermal design limits, including those for air velocity and wet-bulb temperature, and the physiologically/psychologically related requirements of the work force will be principal determinants of the design criteria ultimately adopted for ultra-deep mines. The investigation of worker-related factors should also receive attention.

- Cost simulations demonstrated the significant impact of higher stope face air velocities on both cooling and ventilation costs. The results therefore forms the basis for the recommendation that environmental control systems in ultra-deep mines should be designed to provide the required thermal environment (in accordance with the many and various criteria relevant to this critical decision) at a minimal total air mass flow rate. Considering the possible high cost variations, minimising the air mass flow rate should certainly be an integral part of an ultra-deep mine's ventilation strategy.

11.7. Recirculation of return air

- It was shown in this study that the inclusion of controlled recirculation strategies into the planning of the ventilation requirements for an ultra-deep mine would have beneficial costing effects.

- The proper application of recirculation strategies can result in significant reductions in the fan input power requirements.

- Recirculation greatly reduces the impact of auto-compression on total heat load. For the purposes of this study, the negative impact of 'too much' recirculated air was ignored as it was assumed that no matter what the recirculation percentage is, it would be viable in terms of ensuring a safe working environment.

- It appears from this study that in planning a recirculation system for an ultra-deep mine using a longwall follow-behind mining layout, a global recirculation system should be adopted.

- There is an indication that when a longwall follow-behind mining layout is used, the optimum recirculation percentage for global recirculation of air is approximately 30%.

- In all the recirculation models used, he cooling requirements were not optimised because in almost all the stopes an ACP of more than the 300W/m^2 that was proposed earlier was available.

- A possible saving of 5% in total PV costs can be achieved through the adoption of a 30% global recirculation system for a longwall follow-behind mining layout. In the example used in this study, the total PV cost for the base case without any recirculation was R2.03 billion, which gives a total PV cost saving of R110 million. Further savings are possible if the cooling requirements for specific mining areas are optimised and also if a combination of local and global recirculation can be used. This aspect needs further investigation.

- The total cost in terms of dollar/ounce of gold produced when a global recirculation system was used for a longwall follow-behind mining layout was $38.9/ounce.

- It must again be emphasised that the cost analysis conducted during the present investigation was of a comparative and relatively simplistic nature as a result of the need to use a single simulation model. Accordingly, these findings should be interpreted and applied with circumspection and, more importantly, validated for specific mine designs as they are developed.

- In a similar vein and to underscore previous comments, the heat stress limits ultimately adopted for ultra-deep mining should include criteria for work performance in order to ensure that productivity levels contribute to the profitability of such mining projects.

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Annexure A

Cooling Requirements and Costs for Gobal Recirculation of Air

	Running costs						Maintenance cost						Capital cost						Present value cost					
	0%	20%	30%	40%	50%	60%	0%	20%	30%	40%	50%	60%	0%	20%	30%	40%	50%	60%	0%	20%	30%	40%	50%	60%
SURFACE RESULTS																								
COSTS (kR)																								
Pre-cooling tower	240	240	240	240	240	240													1205	1205	1205	1205	1205	1205
Condenser cooling tower	645	645	645	645	645	645													3237	3237	3237	3237	3237	3237
Refrigeration plant	6527	6527	6527	6527	6527	6527	8833	8833	8833	8833	8833	8833	275000	275000	275000	275000	275000	275000	352088	352088	352088	352088	352088	352088
Ice plant																			0	0	0	0	0	0
Water treatment plant																			0	0	0	0	0	0
Chilled water dam							240	240	240	240	240	240	12000	12000	12000	12000	12000	12000	13205	13205	13205	13205	13205	13205
Clean return water dam							240	240	240	240	240	240	12000	12000	12000	12000	12000	12000	13205	13205	13205	13205	13205	13205
Dirty return water dam																			0	0	0	0	0	0
All surface pumps	1684	1684	1684	1684	1684	1684													8452	8452	8452	8452	8452	8452
Total Surface Cooling Costs	9096	9096	9096	9096	9096	9096	9313	9313	9313	9313	9313	9313	299000	299000	299000	299000	299000	299000	391390	391390	391390	391390	391390	391390
TOTAL LEVEL RESULTS																								
Refrigeration plant (RW)																			0	0	0	0	0	0
Refrigeration plant (CT)	23047	26245	28354	31646	36246	39804	9871	9946	9931	9954	9918	9870	261673	263672	263275	263885	262930	261651	426880	445306	455418	472665	494616	510953
Condenser cooling tower	1120	1084	1066	914	896	878													5621	5440	5350	4587	4497	4406
Pelton turbine	-11592	-11665	-11505	-11554	-11610	-11682	1790	1803	1777	1784	1793	1804	16114	16225	15992	16060	16138	16237	-33080	-33270	-32830	-32973	-33131	-33338
Hydrolift device																			0	0	0	0	0	0
Throttle valve (OC at Dam)															1				0	0	1	0	0	0
Throttle valve (CC)							892	899	894	897	898	899	4458	4497	4469	4486	4491	4497	8935	9009	8956	8988	8998	9009
Water treatment plants																			0	0	0	0	0	0
High pressure pumps	60649	61218	60645	60753	60775	60797	16245	16398	16244	16273	16279	16285	270753	273295	270736	271219	271316	271417	656665	662831	656623	657794	658031	658273
Low pressure pumps	4416	3984	3750	3530	3308	3085	315	285	268	252	236	220	2760	2490	2344	2206	2067	1928	26504	23915	22509	21187	19853	18515
Ice mixing dams																			0	0	0	0	0	0
Chilled water dams							3994	4023	3990	4003	4006	4009	36191	36454	36158	36277	36303	36334	56236	56644	56183	56367	56408	56454
Clean return water dams							15659	15794	15696	15742	15746	15749	141910	143137	142249	142661	142699	142727	220499	222403	221023	221666	221724	221767
Dirty return water dams																			0	0	0	0	0	0
Settling dams																			0	0	0	0	0	0
Pipes - down (ch. water)							501	501	501	501	501	501	33841	33841	33841	33841	33841	33841	36355	36355	36355	36355	36355	36355
Pipes - up (return water)							801	801	801	801	801	801	29235	29235	29235	29235	29235	29235	33255	33255	33255	33255	33255	33255
Pipes - Ice																			0	0	0	0	0	0
Total level Cooling Costs	77640	80866	82310	85289	89615	92882	50068	50450	50102	50207	50178	50138	796935	802846	798300	799870	799020	797867	1437870	1461889	1462843	1479891	1500607	1515649

SUMMARY OF COST RESULTS FOR COOLING AND PUMPING

Base Case versus Global Recirculation

		Percentage of air re-circulated					
		0%	20%	30%	40%	50%	60%
Running costs	Surface	9096	9096	9096	9096	9096	9096
	Underground	77640	80866	82310	85289	89615	92882
Maintenance costs	Surface	9313	9313	9313	9313	9313	9313
	Underground	50068	50450	50102	50207	50178	50138
Capital costs	Surface	299000	299000	299000	299000	299000	299000
	Underground	796935	802846	798300	799870	799020	797867
Total costs	Surface	317409	317409	317409	317409	317409	317409
	Underground	924643	934162	930712	935366	938813	940887
Total Cooling Cost: Surface and underground		1242052	1251571	1248121	1252775	1256222	1258296
Present Value (PV) Total Costs Cooling		1829260	1853279	1854233	1871281	1891997	1907039

Annexure B

	Underground	796935	822085	826238	831956	832816	831051
Total costs	Surface	317409	317409	317409	317409	317409	317409
	Underground	924643	956826	960945	967763	970281	970983
Total Cooling Cost: Surface and underground		1242052	1274235	1278354	1285172	1287690	1288392
Present Value (PV) Total Costs Cooling		1829260	1889707	1893689	1904928	1914109	1924725

Fan Requirements and Costs for Gobal Recirculation of Air

Costs (kR)	Running costs						Maintenance cost						Capital cost						Present value cost					
	0%	20%	30%	40%	50%	60%	0%	20%	30%	40%	50%	60%	0%	20%	30%	40%	50%	60%	0%	20%	30%	40%	50%	60%
Surface Fans	20707	9120	6571	4602	3105	2004	5914	2605	1877	1314	887	572	64686	28491	20526	14375	9700	6262	198292	87336	62922	44064	29735	19195
Underground Recirculation Fans	0	760	1131	1497	1860	2221	0	258	383	508	631	753	0	2171	3229	4276	5312	6344	0	7281	10829	14339	17814	21271

SUMMARY OF COST RESULTS FOR FANS: GLOBAL RE-CIRCULATION OF AIR

		Percentage of air re-circulated					
		0%	20%	30%	40%	50%	60%
Running costs	Surface	20707	9120	6571	4602	3105	2004
	Underground	0	760	1131	1497	1860	2221
Maintenance costs	Surface	5914	2605	1877	1314	887	572
	Underground	0	258	383	508	631	753
Capital costs	Surface	64686	28491	20526	14375	9700	6262
	Underground	0	2171	3229	4276	5312	6344
Total costs	Surface	91308	40216	28974	20290	13692	8839
	Underground	0	3190	4744	6281	7803	9318
Total Fan Costs: Surface and Underground		91308	43405	33717	26572	21495	18157
Present Value (PV) Total Fans Costs		198292	94617	73750	58404	47549	40466

Annexure C

Cooling Requirements and Costs for Localized Re-circulation of Air

	Running costs						Maintenance cost						Capital cost						Present value cost					
	0%	20%	30%	40%	50%	60%	0%	20%	30%	40%	50%	60%	0%	20%	30%	40%	50%	60%	0%	20%	30%	40%	50%	60%
SURFACE RESULTS																								
COSTS (kR)																								
Pre-cooling tower	240	240	240	240	240	240	0	0	0	0	0	0	0	0	0	0	0	0	1205	1205	1205	1205	1205	1205
Condenser cooling tower	645	645	645	645	645	645	0	0	0	0	0	0	0	0	0	0	0	0	3237	3237	3237	3237	3237	3237
Refrigeration plant	6527	6527	6527	6527	6527	6527	8833	8833	8833	8833	8833	8833	275000	275000	275000	275000	275000	275000	352088	352088	352088	352088	352088	352088
Ice plant	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water treatment plant	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chilled water dam	0	0	0	0	0	0	240	240	240	240	240	240	12000	12000	12000	12000	12000	12000	13205	13205	13205	13205	13205	13205
Clean return water dam	0	0	0	0	0	0	240	240	240	240	240	240	12000	12000	12000	12000	12000	12000	13205	13205	13205	13205	13205	13205
Dirty return water dam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
All surface pumps	1684	1684	1684	1684	1684	1684	0	0	0	0	0	0	0	0	0	0	0	0	8452	8452	8452	8452	8452	8452
Total Surface Cooling Costs	9096	9096	9096	9096	9096	9096	9313	9313	9313	9313	9313	9313	299000	299000	299000	299000	299000	299000	391390	391390	391390	391390	391390	391390
TOTAL LEVEL RESULTS																								
Refrigeration plant (RW)																			0	0	0	0	0	0
Refrigeration plant (CT)	23047	27204	27646	28088	29800	32441	9871	10393	10142	10128	9954	9736	261673	269227	268855	268483	263883	258095	426880	457917	458504	460280	463399	469771
Condenser cooling tower	1120	1094	1082	1069	1056	1043													5621	5491	5430	5365	5300	5235
Pelton turbine	-11592	-12578	-13097	-13627	-14162	-14715	1790	1943	2023	2105	2187	2273	16114	17465	18205	18941	19685	20454	-33080	-35909	-37373	-38885	-40415	-41989
Hydrolift device	0						0						0						0	0	0	0	0	0
Throttle valve (OC at Dam)	0						0						0						0	0	0	0	0	0
Throttle valve (CC)	0						892	958	964	989	1008	1017	4458	4789	4819	4946	5016	5083	8935	9597	9657	9910	10075	10187
Water treatment plants	0						0						0						0	0	0	0	0	0
High pressure pumps	60649	62403	62657	63334	63752	64148	16245	16715	16783	16964	17076	17183	270753	277849	279717	281585	284608	286376	656665	674923	678407	684581	690264	694556
Low pressure pumps	4416	4215	4057	3936	3795	3650	315	301	290	281	271	261	2760	2634	2536	2460	2372	2281	26504	25299	24353	23624	22778	21909
Ice mixing dams	0						0						0						0	0	0	0	0	0
Chilled water dams	0						3994	4271	4314	4406	4467	4523	36191	38269	39098	39927	40482	40987	56236	59704	60749	62040	62901	63687
Clean return water dams	0						15659	16520	16544	16832	16959	17070	141910	148776	149932	152538	153694	154699	220499	231686	232962	237014	238807	240369
Dirty return water dams	0						0						0						0	0	0	0	0	0
Settling dams	0						0						0						0	0	0	0	0	0
Pipes - down (ch. water)	0						501	501	501	501	501	501	33841	33841	33841	33841	33841	33841	36355	36355	36355	36355	36355	36355
Pipes - up (return water)	0						801	801	801	801	801	801	29235	29235	29235	29235	29235	29235	33255	33255	33255	33255	33255	33255
Pipes - Ice	0						0												0	0	0	0	0	0
Total level Cooling Costs	77640	82338	82345	82800	84241	86567	50068	52403	52362	53007	53224	53365	796935	822085	826238	831956	832816	831051	1437870	1498317	1502299	1513538	1522719	1533335

SUMMARY OF COST RESULTS FOR COOLING AND PUMPING

Base Case versus Localized Recirculation

		Percentage of air re-circulated					
		0%	20%	30%	40%	50%	60%
Running costs	Surface	9096	9096	9096	9096	9096	9096
	Underground	77640	82338	82345	82800	84241	86567
Maintenance costs	Surface	9313	9313	9313	9313	9313	9313
	Underground	50068	52403	52362	53007	53224	53365
Capital costs	Surface	299000	299000	299000	299000	299000	299000
	Underground	796935	822085	826238	831956	832816	831051
Total costs	Surface	317409	317409	317409	317409	317409	317409
	Underground	924643	956826	960945	967763	970281	970983
Total Cooling Cost: Surface and underground		1242052	1274235	1278354	1285172	1287690	1288392
Present Value (PV) Total Costs Cooling		1829260	1889707	1893689	1904928	1914109	1924725

Annexure D

Fan Requirements and Costs for Localized Recirculation of Air

Costs (kR)	Running costs						Maintenance cost						Capital cost						Present value cost					
	0%	20%	30%	40%	50%	60%	0%	20%	30%	40%	50%	60%	0%	20%	30%	40%	50%	60%	0%	20%	30%	40%	50%	60%
Surface Fans	20707	11697	8474	5966	4031	2520	5914	3341	2420	1704	1151	720	64686	36540	26471	18638	12591	7873	198292	112011	81146	57132	38598	24134
Underground Recirculation Fans	0	36	53	70	86	102	0	12	18	24	29	35	0	104	153	200	247	292	0	348	512	672	828	978

SUMMARY OF COST RESULTS FOR FANS: LOCALIZED RE-CIRCULATION OF AIR

		Percentage of air re-circulated					
		0%	20%	30%	40%	50%	60%
Running costs	Surface	20707	11697	8474	5966	4031	2520
	Underground	0	36	53	70	86	102
Maintenance costs	Surface	5914	3341	2420	1704	1151	720
	Underground	0	12	18	24	29	35
Capital costs	Surface	64686	36540	26471	18638	12591	7873
	Underground	0	104	153	200	247	292
Total costs	Surface	91308	51578	37366	26308	17773	11113
	Underground	0	152	224	294	363	428
Total Fan Costs: Surface and Underground		91308	51730	37590	26602	18136	11541
Present Value (PV) Total Fans Costs		198292	112359	81658	57804	39426	25111