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

Mr RCW Webber

Presented in partial fulfilment of the requirements for the degree

M.ENG. (MINING ENGINEERING)

IN THE FACULTY OF ENGINEERING

DEPARTMENT OF MINING

UNIVERSITY OF PRETORIA

NOVEMBER 2000
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.
# CONTENTS

**ACKNOWLEDGEMENTS** 11  
**NOMENCLATURE** 12  
**LIST OF FIGURES** 14  
**LIST OF TABLES** 15  
**LIST OF ANNEXURES** 18  

1. **INTRODUCTION** 19  
1.1. Background 19  
1.2. Problem statement 20  
1.3. Objectives 20  

2. **METHODOLOGY** 21  

3. **LITERATURE SEARCH** 23  
3.1. Identification of factors influencing environmental conditions 23  
3.2. Heat stress indices - an international comparison 23  
3.3. Recirculation of mine air 23  

4. **FACTORS INFLUENCING ENVIRONMENTAL CONDITIONS** 24  
4.1. Literature review and evaluation of previous research 24  
4.2. Environmental factors - assessment of their depth-dependence 24  
4.3. Practitioners’ input 27  
4.4. Dependence of environmental factors on depth 29  
4.5. Environmental effects on workers 30  

5. **HEAT STRESS INDICES** 31  
5.1. Literature search 31  
5.2. Background 32  
5.2.1. Aim of heat stress indices 33  
5.2.2. Classification of heat stress indices 35
5.3. Comparison of relevant heat stress indices 51
5.3.1. Empirical heat stress indices 52
5.3.2. Rational heat stress indices 53
5.4. Design of workplace air temperatures 55
5.5. Heat stress limits for work in mines 56

6. INTERNATIONAL STANDARDS 57
6.1. Background 57
6.2. International Labour Organisation 57
6.3. World Health Organization 58
6.4. NIOSH and ACGIH standards 58
6.5. OHSA standards 58
6.6. Assessment of hot environment using ISO standards 59
6.7. Regulatory requirements 60
6.7.1. Introduction 60
6.7.2. Search for a standard index 66

7. RESULTS AND DISCUSSION 68
7.1. Relevant environmental factors and dependence on depth 68
7.2. Controlling the effects of heat stress on workers 68
7.3. Heat stress indices and limits 69
7.4. Design and planning 69
7.4.1. Workplace monitoring 69
7.5. Issues identified by industry practitioners 70

8. SIMULATIONS - COST IMPLICATIONS OF IDENTIFIED PARAMETERS 71
8.1. Introduction 71
8.2. Design criteria identified and range of values assessed 71
8.2.1. Representative mine layout for simulation 72
8.3. Costs: Results and discussion 74
8.3.1. Cost implications of thermal standards and limits 74
8.3.2. Conclusion on costing for thermal standards and limits 78

9. RECIRCULATION OF MINE AIR 80
9.1. Introduction 80
9.2. The role of controlled recirculation
9.2.1. Background
9.3. The use of controlled recirculation
9.4. Effects of controlled recirculation on the environment
9.4.1. Background
9.4.2. Recirculation model for gaseous contaminants
9.4.3. Recirculation model for blasting fumes
9.4.4. Recirculation model for dust
9.4.5. Recirculation model for air cooling
9.5. Summary of simulation models
9.6. Factors affecting the introduction of controlled recirculation
9.6.1. Background
9.6.2. Reasons for using controlled recirculation
9.6.3. Potential hazards of controlled recirculation
9.6.4. Prohibition of recirculation
9.7. Design of a controlled recirculation system
9.7.1. Introduction
9.7.2. Determination of air quantities
9.7.3. Ventilation arrangements
9.7.4. Cooling arrangements
9.7.5. Safety arrangements
9.8. Operation of controlled recirculation systems
9.9. Aspects relevant to controlled recirculation
9.10. Simulation models and ENVIRON modelling parameters
9.10.1. Introduction
9.10.2. Other ENVIRON modelling parameters

10. COMPARISON OF SIMULATION MODEL RESULTS
10.1. Introduction
10.2. Base-case simulation and global recirculation results
10.2.1. Cooling and pumping requirements
10.2.2. Requirements for fans on surface and underground
10.3. Base-case simulation and localised recirculation results
10.3.1. Cooling and pumping requirements
10.3.2. Requirements for fans on surface and underground
10.4. Costing for base-case simulation model
10.4.1. Physical cooling and pumping parameters
10.4.2. Unit costs for pumping and cooling requirements
10.4.3. Unit costs for fan requirements
10.5. PV costs of global recirculation of air
10.5.1. PV costs for cooling and pumping
10.5.2. Total PV costs of fans
10.5.3. Total PV costs for cooling and fans
10.5.4. Interpretation and evaluation of PV results for global recirculation
10.6. PV costs of localised recirculation of air
10.6.1. Total PV costs for cooling and pumping
10.6.2. Total PV costs of fans
10.6.3. Total PV costs for cooling and fans
10.6.4. Interpretation and evaluation of results for localised recirculation
10.7. Comparative PV costs of global and localised recirculation
10.8. Evaluation of results for recirculation of return air

11. CONCLUSIONS AND RECOMMENDATIONS
11.1. Relevant environmental factors and dependence on depth
11.2. Controlling the effects of heat stress on workers
11.3. Heat stress indices and limits
11.4. Design and planning
11.4.1. Workplace monitoring
11.5. Issues identified by industry practitioners
11.6. Costing comparison for thermal standards and limits
11.7. Recirculation of return air

REFERENCES
Acknowledgements

The author gratefully acknowledges the assistance provided by the following organisations and people:

❖ The South African Labour Organisation (Mrs Charlene Stepischneck)
❖ The World Health Organization - South African Branch (Dr W. Shasha)
❖ The International Labour Organisation
❖ The Australian Industrial Relations Department
❖ The German Embassy to South Africa (Pretoria)
❖ The United States of America Information Services (USAIS)
❖ The following staff members of the CSIR Division of Mining Technology (Miningtek): Mr Wynand Marx, Mr Mike Franz, Mr Mark Butterworth, Mr Russell Hattingh, Mr Jason Matesa and Mrs Martie van Deventer
❖ Mr Dirk van Greunen, Chief Environmental Officer on Oryx Mine
❖ Mr Ken Gudmanz, Department of Minerals and Energy
❖ Professor André Fourie, University of Pretoria
❖ The Deepmine Project Team - Co-operative Research Programme
❖ Bluhtm Burton Engineering (Pty) Ltd.
❖ Diane Nortje (née Webber) for her typing parts of this document
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
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW&lt;sub&gt;req&lt;/sub&gt;</td>
<td>Required Sweat Rate index</td>
</tr>
<tr>
<td>T&lt;sub&gt;db&lt;/sub&gt;</td>
<td>Dry-bulb temperature</td>
</tr>
<tr>
<td>T&lt;sub&gt;g&lt;/sub&gt; or T&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Globe temperature/radiant temperature</td>
</tr>
<tr>
<td>T&lt;sub&gt;mr&lt;/sub&gt; or MRT</td>
<td>Mean radiant temperature</td>
</tr>
<tr>
<td>T&lt;sub&gt;nwb&lt;/sub&gt; or T&lt;sub&gt;w&lt;/sub&gt;</td>
<td>Natural or unventilated wet-bulb temperature</td>
</tr>
<tr>
<td>T&lt;sub&gt;wb&lt;/sub&gt;</td>
<td>Psychrometric or ventilated wet-bulb temperature</td>
</tr>
<tr>
<td>TLV</td>
<td>Threshold limit value</td>
</tr>
<tr>
<td>UDM</td>
<td>Ultra-deep mining</td>
</tr>
<tr>
<td>U/G</td>
<td>Underground</td>
</tr>
<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>V or u</td>
<td>Air velocity</td>
</tr>
<tr>
<td>VRT</td>
<td>Virgin rock temperature</td>
</tr>
<tr>
<td>W</td>
<td>Watt</td>
</tr>
<tr>
<td>WB</td>
<td>Wet-bulb</td>
</tr>
<tr>
<td>WBGT</td>
<td>Wet-bulb globe temperature</td>
</tr>
<tr>
<td>WGT</td>
<td>Wet globe temperature</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
</tr>
</tbody>
</table>
List of Figures

Figure 5.2.2.2.1 Permissible exposure periods for acclimatised workers with respect to WBGT and metabolic work rate .................................................. 40

Figure 5.2.2.3.3 Environmental design parameters in relation to Air Cooling Power (ACP) ................................................................. 47

Figure 5.3.2.1 Air Cooling Power (M scale) or ACPM ........................................... 54

Figure 5.3.2.2 SCP values for various air velocities ........................................ 55

Figure 6.7.1.4a US heat stress criteria in relation to Basic Effective temperature (BET) and work rate .............................................. 65

Figure 6.7.1.4b NIOSH and ISO heat stress limits for acclimatised mineworkers in terms of WBGT and metabolic heat load .................. 66

Figure 8.3.2 Annual costs for various combinations of wet-bulb temperature and air velocity that provide 300 W/m² of Air Cooling Power .......... 78

Figure 9.3 Simplified section of a controlled recirculation system .................. 81

Figure 9.4.2 Relationship between carbon dioxide concentration and recirculated fraction ................................................................. 84

Figure 9.4.3 Relationship between the exponential time constant and the intake air quantity ................................................................. 85

Figure 9.4.4 Effects of recirculated dust filtration on the mixed intake and return air dust concentrations ..................................................... 86

Figure 9.7.3 Simplified drawing of a layout for the recirculation of air ............ 90

Figure 9.10.1a Simplified drawing of a global recirculation layout .................. 94

Figure 9.10.1b Simplified drawing of a localised recirculation layout ............ 95

Figure 9.10.2.2 Simplified numbering of sections and average depth ............ 98

Figure 10.5.3 Total PV costs for global recirculation of return air .................. 123

Figure 10.6.3 Total PV costs for localised recirculation of return air ............. 127

Figure 10.7 Combination of total PV costs for global and localised recirculation... 128

Figure 10.7.1 Total costs in terms of dollar/ounce of gold produced ............... 129
List of Tables

Table 2  Methodology for achieving objectives .................................................22
Table 4.2  Relevance of operational constraints and contributors to environmental factors at increased depth .........................................................26
Table 4.3  Practitioners’ comments regarding planning for environmental control in ultra-deep mines .................................................................27
Table 5.2.2.1.4  Metabolic rates and associated limits for wet-bulb temperature .................................................................37
Table 5.2.2.2.4  Relative effect of various levels of environmental cooling power .................................................................43
Table 5.2.2.3.4  Recommended combinations of wet-bulb temperature and air velocity .................................................................48
Table 5.3  Underground thermal conditions for comparison of heat stress indices .................................................................52
Table 5.3.1a  Assessment of given conditions by single measurement and empirical heat stress indices .................................................................52
Table 5.3.1b  Characterisation of given thermal environment based on results from four empirical heat stress indices .................................................................53
Table 5.3.2.1  Air Cooling Power for a given thermal environment in relation to clothing .................................................................53
Table 6.4  ACGIH wet-bulb globe temperature (WBGT) TLVs for various workloads in hot environments .................................................................58
Table 6.5  OSHA-recommended WBGT TLVs for various workloads .................................................................59
Table 6.7.1.2  Australian prescribed actions for various levels of ACP .................................................................63
Table 6.7.1.4  Comparison of heat stress criteria used in various countries .................................................................64
Table 8.2.1  Inputs to simulation model for estimated annual capital and operating costs of ventilation and cooling systems .................................................................73
Table 8.3.1.1  Impact of reject wet-bulb temperature on annual costs for two different stope face-air velocities .................................................................74
Table 8.3.1.2  Impact of stope air velocities on annual costs for two different reject temperatures .................................................................76
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.3.1.4</td>
<td>Impact of reject wet-bulb temperature on annual costs for various cooling strategies</td>
<td>77</td>
</tr>
<tr>
<td>9.10.2.3</td>
<td>Basic features of simulation model</td>
<td>99</td>
</tr>
<tr>
<td>10.2</td>
<td>Summary of physical parameters for base-case and global recirculation models</td>
<td>100</td>
</tr>
<tr>
<td>10.2.1a</td>
<td>Summary of cooling requirements for the base-case model and the models with various percentages of global recirculation</td>
<td>102</td>
</tr>
<tr>
<td>10.2.1b</td>
<td>Summary of total cooling requirements for global recirculation</td>
<td>103</td>
</tr>
<tr>
<td>10.2.2</td>
<td>Summary of total air-flow and fan requirements for global recirculation</td>
<td>105</td>
</tr>
<tr>
<td>10.3</td>
<td>Summary of physical parameters for the base-case and localised recirculation models</td>
<td>106</td>
</tr>
<tr>
<td>10.3.1a</td>
<td>Summary of cooling requirements and heat loads for the base-case model and the models with various percentages of localised recirculation of return air</td>
<td>108</td>
</tr>
<tr>
<td>10.3.1b</td>
<td>Summary of total cooling requirements and heat loads for localised recirculation</td>
<td>109</td>
</tr>
<tr>
<td>10.3.2</td>
<td>Summary of total air-flow and fan requirements for localised recirculation of air</td>
<td>111</td>
</tr>
<tr>
<td>10.4.1c</td>
<td>Physical parameters for cooling and pumping</td>
<td>112</td>
</tr>
<tr>
<td>10.4.1d</td>
<td>Additional input figures for turbines on level 1 750 m underground</td>
<td>114</td>
</tr>
<tr>
<td>10.4.1e</td>
<td>Additional input figures for turbine on level 3 500 m underground</td>
<td>115</td>
</tr>
<tr>
<td>10.4.1f</td>
<td>Input for pumping and cooling parameters for all levels</td>
<td>116</td>
</tr>
<tr>
<td>10.4.1g</td>
<td>Changing cooling loads and water flow rates for each level</td>
<td>116</td>
</tr>
<tr>
<td>10.4.1h</td>
<td>Constant input parameter figures for dams, pumps and pipes for all levels</td>
<td>117</td>
</tr>
<tr>
<td>10.4.2</td>
<td>Unit cost figures as used in Deepmine 6.4.1 cooling cost model</td>
<td>118</td>
</tr>
<tr>
<td>10.4.3</td>
<td>Unit costs for fans on surface and underground</td>
<td>119</td>
</tr>
<tr>
<td>10.5.1</td>
<td>Total PV costs of cooling and pumping for global recirculation</td>
<td>120</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>---------------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>10.5.2</td>
<td>Total PV of fan costs for global recirculation of return air</td>
<td>122</td>
</tr>
<tr>
<td>10.5.3</td>
<td>Total PV costs for global recirculation of return air</td>
<td>123</td>
</tr>
<tr>
<td>10.6.1</td>
<td>Total PV cost of cooling and pumping for localised recirculation of return air</td>
<td>125</td>
</tr>
<tr>
<td>10.6.2</td>
<td>Total PV of fan costs for localised recirculation of return air</td>
<td>126</td>
</tr>
<tr>
<td>10.6.3</td>
<td>Total PV costs for cooling and fans for localised recirculation of return air</td>
<td>127</td>
</tr>
<tr>
<td>10.7.1</td>
<td>Summary of total cost in terms of dollar/ounce of gold produced</td>
<td>130</td>
</tr>
</tbody>
</table>
List of Annexures

Annexure A  Cooling requirements and costs for global recirculation of air........... 141
Annexure B  Fan requirements and costs for global recirculation of air ................ 142
Annexure C  Cooling requirements and costs for local recirculation of air .......... 143
Annexure D  Fan requirements and costs for global recirculation of air ............. 144