

IMPORTANT BASICS OF MINE VENTILATION AND COOLING PLANNING

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1. INTRODUCTION

The objective of this paper is to review the important basics of planning mine ventilation and cooling systems. As such it is as much concerned with the planning process and methodology as it is with some of the basic technical aspects.

Vent/cooling planning includes many related sciences such as: noise, illumination, fires, explosions, escape strategies, instrumentation, water quality, etc. All of these related topics cannot be addressed in a single paper and, to provide correct emphasis, only the broader issues are considered. The paper relates to the long-term general planning of ventilation and cooling system for hot-rock mines.

In mine planning it is important to recognise that:

- During the life-of-mine the demands on the vent/cooling systems vary and generally grow with age. The detailed requirements are not always evident in the early stages, yet the primary infrastructure must be established at the start and cannot be modified later.
- Although mine plans continually evolve, it is important for far-sighted decision making to identify overall design constraints and critical design scenarios for the longer term.
- Effective planning involves all disciplines and singularly the most important in hot-rock mines is that of vent/cooling.

It is essential to know the long-term needs in designing for the short-term [and vice-versa]. In addition, the capital costs of vent/cooling equipment can be so high that an optimised phase-in strategy can be almost as important as correct equipment sizing.

The vent/cooling requirements must be taken into account in the early planning stages to ensure that adequate facilities are provided over the life-of-mine. This does not imply a commitment to capital equipment prematurely, but rather that expenditure is made in the knowledge of a structured understanding of the long-term needs. The objective is to make far-sighted decisions on the present and future requirements on air flow rates, cooling capacities, shaft sizes, intake and return airway carrying capacities, etc.

2. SYSTEMATIC APPROACH

For effective mine planning it is important to create and adhere to a systematic approach. This is often difficult for many reasons, for example, as planning evolves new information becomes available and new ideas emerge. However, adherence to a

systematic approach can be assisted by clearly appreciating the following [and recognising where one is in the process]:

- role of the vent/cooling specialist within multidisciplinary team
- steps in specialist vent/cooling system design
- phases in overall mine project planning
- stages in life-of-mine

Each of these issues is discussed below.

2.1 Multidisciplinary nature

Effective mine planning requires collaboration, communication and the full team-involvement of specialists from the disciplines of geology, mining engineering, rock engineering, metallurgy, occupational hygiene/safety, mech/elec engineering, industrial engineering, scheduling and financial analysts. However, rock handling and men/material criteria often dominate mine layout designs with little consideration taken of the primary ventilation requirements [in initial planning]. This results in sub-optimum vent/cooling designs and often production limitations related to ventilation constraints at later parts of the life-of-mine. For effective and successful overall hot-rock mine planning the vent/cooling designs must command a high priority in a structured, systematic and multi-disciplinary forum. Future underground mining, particularly in RSA gold and platinum mining, will inevitably progress deeper and will have extremely high vent/cooling costs. The potential extent of these costs in relation to the other aspects must be clearly understood by all team members. For example, there are projects in which the vent/cooling related capex can exceed 25% of total project capex and vent/cooling power utilisation exceeds 50% of life-of-mine power costs.

Clearly, effective planning requires that vent/cooling issues play a dominant role in early planning. Vent/cooling aspects impact seriously on project feasibility decisions and this must be genuinely appreciated by the full team.

The vent/cooling optimisation process is highly iterative both within itself [see later] and within the overall planning process [between disciplines]. For example, consider the effect of stope layout and methodology on heat load and vice-versa. There are numerous cases in which attention to heat criteria has improved stoping designs to the significant benefit of the project.

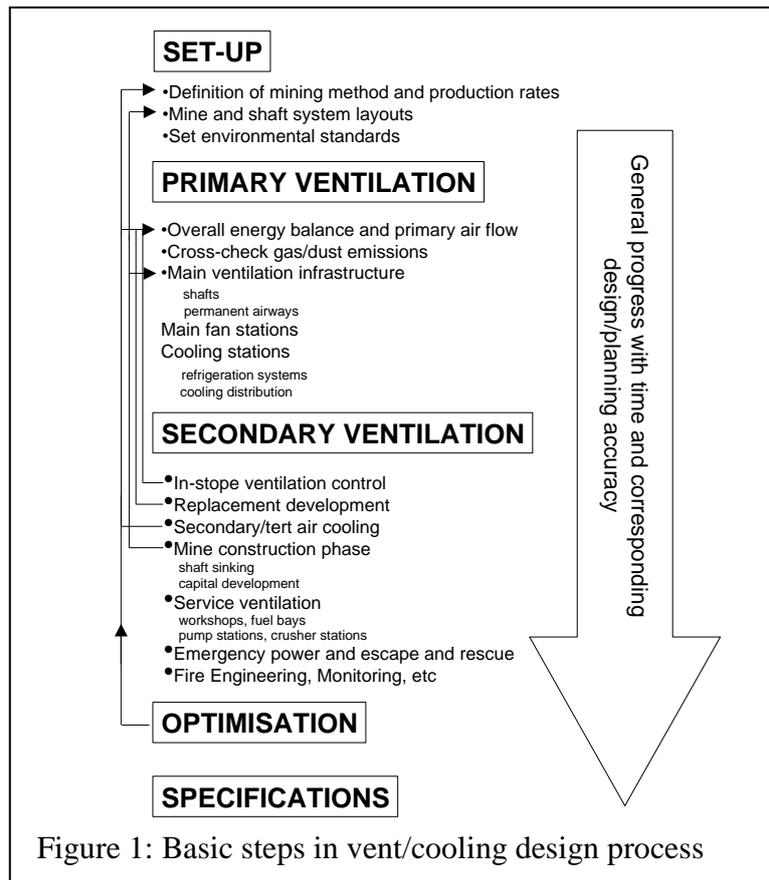
The point to note is that close collaboration of all the discipline specialists is an essential ingredient of effective mine planning. Indeed, creating a suitable 'atmosphere' to achieve this interaction should be a critical aim of project management.

2.2 Steps within the vent/cooling planning process

It is useful to differentiate between primary and secondary ventilation systems. Primary ventilation relates to the main ventilation and cooling infrastructure. It includes the main surface fans, main booster fans, upcast and downcast shafts, vent raises, main airways, bulk air coolers, central refrigeration systems, etc. The objective of the primary system is to provide air flow to the sections and service zones in sufficient quantity and at appropriate temperatures and quality. Obviously without this provision, the secondary systems will never be able to create acceptable conditions in the workings. Secondary ventilation relates to the control of ventilation in the actual sections and service zones.

It includes all in-stope and development auxiliary fans, ducting systems, secondary air cooling, etc, as well as requirements for service ventilation of pump stations, tips, workshops, hoist chambers, crusher stations, etc. Long-term planning of vent/cooling systems often focuses on the primary requirements because this defines large single capex items but the secondary systems, with the multiplicity of auxiliary fans, ducts, etc, can also require surprisingly high costs and power inputs.

Figure 1 shows some of the basic steps in the vent/cooling design process. The essential starting point is the basic/initial definition [normally by others] of the stoping method, general layouts and expected production rates.



It is important to first estimate the primary ventilation and refrigeration needs. These estimates should be made at an early stage as many of the other factors follow-on. For hot-rock mining, heat energy balances generally dictate the primary requirements rather than gas/dust control criteria or face velocity/flow criteria, which would however, dominate considerations in shallow underground mines. However, having initially estimated the primary needs by energy balance all these other criteria must be cross-checked.

Careful design of the secondary systems is critical for achieving acceptable conditions but also it is critical because it affects the heat loads and hence in-turn the primary requirements. Notwithstanding the possible preoccupation with the primary needs, secondary ventilation planning must be comprehensively addressed at the correct time within the process. Vent/cooling system design is a complex process with many interacting features. Within a mine network, the air flow, heat flow and contaminant flows must be simultaneously analysed for each component [airway, stope, development, etc]. Heat flow affects air temperature and hence density which in turn

affects pressure and flow quantity which in turn affects temperature changes, etc. Sophisticated computer programs are available for the purpose of this type of analysis, but these must only be applied at the correct time in the systematic process and then only at the correct level-of-detail [see later].

The basic iterative process as well as the iterations between specialist disciplines is important to understand in adhering to a systematic approach [and recognising where one is in the process].

2.3 Phases in overall mine project planning

Mine planning and design, like most other industrial system designs, will generally evolve through a number of phases from pre-concept level to full implementation. In the interests of adopting a systematic approach to the planning it is important to recognise these phases. In typical applications, these planning phases may include:

Concept phase [prefeasibility] characterised by the following [amongst other issues]:

- preliminary geological definition and evaluation of: ore-body, production rates, candidate mining methods, candidate mine/shaft system layouts, etc
- preliminary definition of alternatives and general vent/cooling tactics
- preliminary assessment of primary ventilation quantities and heat loads [shaft sizes based on rule-of-thumb design approaches]
- preliminary sizing of main components and concept designs
- generation of initial programme schedules
- initial design work, sketches, layouts, flow diagrams, etc
- order-of-magnitude capex Estimate
- documents for executive decision on progressing to next level of planning detail

Optimisation phase characterised by the following [amongst other issues]:

- optimisation analyses of all the sub-systems
- refinement of initial programme schedules
- comparison of alternatives for different sub-systems [refrigeration machines, main fan configurations, etc]
- design freeze on all concepts [preliminary specifications]
- refinement of Estimate and planning documentation

Formal feasibility phase characterised by the following [amongst other issues]:

- high-level geological definition, definitive statement on production rates, mining methods, mine and shaft system layouts, etc
- definitive statement on vent/cooling tactics, primary vent flows, heat loads, refrigeration capacity, shaft sizes, secondary vent control, equipment lists/schedules
- definition of life-of-mine phase-in profiles of vent/cooling requirements
- definition of full project schedules for all disciplines
- engineering design work, drawings, process flow diagrams, equipment and system specifications, etc
- definition of control budget Estimate [CBE], life-of-mine opex costs and full life-cycle financial evaluations, etc
- comprehensive documentation for purpose of both
 - executive decision on project implementation
 - specifications, guidance, rules and controls for project execution

Although, in practice, these individual phases are not always clearly distinct, it is extremely important to recognise these phases and to concentrate on the correct phase at the appropriate level-of-detail at the right stage of the process. For example, carrying out detailed ventilation network computer simulations [or CFD work] at an early stage of planning is inappropriate - however sometimes professional enthusiasm can lead to doing the right things at the wrong time.

2.4 Stages in life-of-mine

Typically a mine or mine section undergoes a number of stages in its life and again it is important to recognise these stages in the interests of adopting a systematic approach to the planning. Most importantly the following two stages must be distinguished:

Mine-construction stage which is characterised by shaft [or decline/incline] sinking, capital development, opening initial stope lines and generally establishing of the operation up to the stage when production is achieved. This stage has the major capex allocation and has a cut-off definition for tax and managerial control. This stage is generally characterised by the use of temporary ventilation systems. While most mine infrastructure is established in mine-construction phase, often the main vent/cooling equipment will be brought into service later during production build-up.

Build-up and full production stage which is characterised by main vent/cooling equipment coming onto load and the full establishment of the primary ventilation networks and secondary ventilation systems for follow-on development. During the full production regime, mining will generally move out on strike and get deeper and, in particular, the cooling systems will then be phased-in to their final capacity. This stage is then followed by production depletion, which is not really relevant in early planning, although consideration may be given to where the main equipment may be moved to other centres.

3. SETTING STANDARDS, CRITERIA AND CRITICAL DESIGN SCENARIOS

Systematic planning takes into account all known factors which may impinge on the underground environment, it then specifies any constraints and the standards which are to be applied [temperatures, gas and dust levels, velocities, etc.]. Only then should the development of an optimum ventilation network system commence. The design constraints constitute a checklist to ensure that all users of ventilation air or producers of heat are accounted for in the planning process. The design constraints also define the basis for heat and pollutant limits and acceptance criteria. It is recommended that a formal documented list is prepared early in the design process. The following includes some of the typical design criteria/aspects [amongst others].

- Existing mine characteristics and constraints [for brown-fields projects].
- Development and project schedule.
- Mining method statement and production programme [including clear statement on stoping methods, powering systems, support systems, 'life-of-mine' profiles, etc].
- Service ventilation requirements [including clear statement on workshops, pump stations, crusher stations, conveyors, sub-stations, etc].
- Main and secondary shaft requirements and infrastructure.*
- Inventory of all underground equipment and machinery and work cycles [electrical, diesel and other].

- Geothermal data [virgin rock temperatures, rock thermal properties].
- Ore body and surrounding rock mineralogy [as relates to dust make-up].
- Fissure water expectation and strata gas emission expectation.
- Underground thermal environmental criteria [temperature, cooling power] and airborne contaminant design criteria [dust, gases, diesel emissions, radiation].
- Service water usage.
- Power cost data and expected project rate-of-return.
- Surface weather data.

* It is important to clearly understand what is required for non-ventilation purposes and would in-any-event be needed, for example: shaft sizing for hoisting that is not subject to ventilation related optimisation.

3.1 Focus on critical design scenarios

The setting of design constraints is obviously fundamental. But equally important, and part of a similar thought process, is the identification of the critical design years for detailed analysis. Clear unambiguous descriptions at each of these points-in-time need to be stated. For these critical scenarios, detailed heat loads and vent/cooling capacities should be predicted [by network simulation if necessary]. Extrapolation between these periods will then allow a full life-of-mine profile to be built. The most important scenario is the ultimate, near the end of the full production life, for which the final ventilation and cooling capacities must be sized. In general, the operation will then be at its deepest and furthest out on strike. The most important vent/cooling scenario is late in the life-of-mine, but provision must be made for this right from the start [for example: vent shaft sizes]. In the interests of adhering to a systematic approach there are often great benefits in planning 'backwards' from the requirements for the ultimate position.

The selection of the interim critical dates or scenarios can generally be achieved simply from consideration of the overall production programme, depth of mining, intake and return distances, introduction of new levels, establishment of sub-shafts, change in number of stoping zones, change in the mining method, degree of scatter, etc. Detailed evaluation of only a few interim scenarios and the interpolation between can be very powerful in building up an understanding of the life-of-mine needs and of great assistance in overall optimisation. This process also helps build-up the phase-in picture [see later].

Identification of interim critical scenarios can also be very helpful for other purposes. For example, a fairly common application relates to diesel mechanised mining operations that get progressively deeper with time. In the initial periods, the primary ventilation needs are dictated by the diesel emissions alone. With the same production rate and diesel fleet, the ventilation flow requirements will remain constant as depth increases until, at a critical depth, heat becomes the dominant criterion. In long-term planning, it is very useful to identify when this change-over occurs. This scenario can then be studied in more detail and all the relevant parameters understood at a higher level of accuracy during that period.

For the mine construction phase, it is also useful to select a few scenarios and carryout relatively detailed design for each [and interpolate between]. This often helps define the phase-in of ducting requirements and the cross-checking of adequate space for ducts in excavation sections at critical times. It also assists with scheduling and preparation of procurement lists.

3.2 Some typical criteria and standards

The major pollutants are heat, dust, radiation, diesel fumes and toxic and explosive gases. The ventilation air distributes cooling and dilutes these pollutants to acceptable levels and removes them from the underground mine environment.

There are many different design standards which vary from country to country [in terms of legislation] and for different mining companies [in terms of corporate codes/standards]. It is not the aim of this paper, nor is it practical, to provide a complete list and planners should make use of the many standard reference texts and handbooks^[1,2].

Heat criteria

The physiological response of men working in hot humid conditions has been very carefully studied^[1] in RSA and the Heat Stress Management Programme^[3] has been developed. In this programme, workers are screened for heat intolerance and are then allowed to naturally acclimatise over working shifts during which special precautions are taken with environment, work-rate and medical response. The adoption of this programme is generally considered to be a fundamental design constraint.

The ability of a person to work efficiently depends upon the nature of work and the thermal environment. Figure 2 shows the relationship between wet-bulb temperature, accident rate and productivity^[4]. As the wet-bulb increases from 25°C to over 32°C, there is a significant increase in accident rate and a reduction in productivity [25°C maybe regarded as 'heaven' and 32°C as 'hell']. Indeed in RSA mines, the regulation temperature limit for normal work is 32.5°C wet-bulb.

The worker-cooling-capability of the air is measured by air cooling power and depends mainly on the wet-bulb temperature but also on the air speed. The air cooling power target for planning depends on specific situations but in general this will be between 250 W/m² and 290 W/m². For example, cooling power 290 W/m² corresponds to the following environmental conditions: 27.5°C with an air speed of 0.5 m/s, or 28.5°C and 0.75 m/s or 29°C and 1 m/s.

In long-term planning, it is not always realistic to predict air speeds at [say] stope reject locations and in practice a design wet-bulb temperature [average reject] is adopted as the basis for heat/energy balances. Again this best design value will depend on specific circumstances [such as corporate policy] but in general this will be between 27.5°Cwb and 29.5°Cwb. The costs of vent/cooling differ significantly with this design temperature and cost considerations obviously also play a role in determining optima.

Several other mining countries use the 'effective temperature' for setting limiting temperature conditions for underground and industrial workers. Although this approach does not have the same scientific basis as the air cooling power concept in the mining context, it is widely accepted internationally in statute and labour agreements.

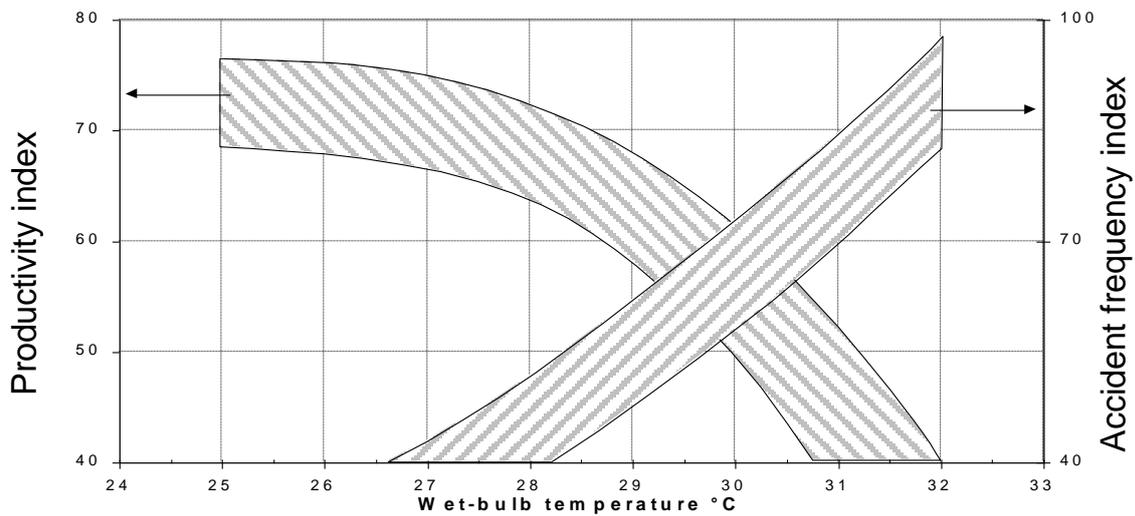


Figure 2: Effect of temperature on productivity and accident rate

Gases and dust criteria

Maximum standards for common individual gases and dust in RSA are as follows in terms of Occupational Exposure Limits [OEL]:

- | | | |
|-------------------------------|-----------------------------|-----------------------|
| • Carbon monoxide | CO | 50 ppm |
| • Carbon dioxide | CO ₂ | 5 000 ppm |
| • Nitrous oxide | NO | 25 ppm |
| • Nitrogen dioxide | NO ₂ | 3 ppm |
| • Sulphur dioxide | SO ₂ | 2 ppm |
| • Methane | CH ₄ | 1.4 % vol [ceiling] |
| • Hydrogen sulphide | H ₂ S | 10 ppm |
| • Respirable combustible dust | RCP | 2 mg/m ³ |
| • Mineral dust | < 5% quartz platinum mines | 3 mg/m ³ |
| | < 5% quartz gold/coal mines | 2 mg/m ³ |
| | 10% quartz | 1 mg/m ³ |
| | 20% quartz | 0.5 mg/m ³ |
| | 100% quartz | 0.1 mg/m ³ |

Diesel fumes and AQI

Diesel machinery provides high levels of equipment mobility and productivity, but it also produces high heat loads and potentially harmful gas and particulate emissions. The critical diesel emissions are diesel particulate matter [respirable carbon particles, RCP] as well as NO_x and CO. Diesel engines produce emissions over a wide range of concentrations depending on: engine type, work cycle, fuel type, operator habits, maintenance level, exhaust treatment system. NIOSH have adopted the following air quality index [AQI] to account for the combined effect of these emissions:

$$AQI = CO/50 + NO/25 + NO_2/2.5 + SO_2/2 + RCP/0.54$$

Gas concentrations in ppm and RCP in mg/m³

AQI values of < 3 are acceptable while situations with values > 4 require correction.

Typically RCP may contribute 80% of the AQI, while NO_x may contribute about 15% and the remaining gases the rest. In general, RCP is the dominating component and control of RCP [and NO_x] is the essence of the diesel emission problem.

Furthermore, most RCP material is less than 1 µm with typical mean particle size of 0.2 µm. This means most of this inhaled matter will deposit in the lungs and carcinogenic risk of RCP is considered high. MSHA recently lowered the RCP exposure limit from 2.0 to 0.4 mg/m³ with the stated intention of lowering further to 0.16 mg/m³ in year 2006. ACGIH recommend a limit of 0.05 mg/m³ [measured as total carbon] and are considering changing this recommendation to 0.02 mg/m³ [measured as elemental carbon].

On an order-of-magnitude basis, diesel engines produce about 0.2 g of RCP, 0.007 m³ of NO_x and 0.004 m³ of CO per kWh. These factors, applied to diesel fleet and work rate data, allow approximate estimation of these gases for different scenarios.

4. ROUGH PLANNING AND RULES-OF-THUMB

There are a number of design rules-of-thumb that can be useful in the initial stages of planning as a starting-point when details of the actual mining layout are not available. But it must be stressed that the use of these rules-of-thumb cannot be relied-on for detailed planning. Each mine presents its own unique characteristics and the general extrapolation of practices from one mine to another is often inappropriate and can lead to very serious planning and design mistakes. Thus while some general and useful rules-of-thumb are noted here, these should only be used as general global guide-lines in the early stages and even then with a great deal of caution.

4.1 Primary air quantities

The obvious approach for preliminary selection of primary ventilation quantities is based on the statistics of the ventilation-to-production ratio from past projects and existing mines. For example, for the larger RSA gold mines, the statistics indicate primary vent ratios ranging from low values of 3 kg/s per kt/m to high values of 8 kg/s per kt/m, while for the larger RSA platinum mines this ratio ranges from low values of 2 kg/s per kt/m to high values of 5 kg/s per kt/m.

The overall ventilation quantity requirements are generally dictated by the need to remove heat [carry cooling] and blasting fumes [during re-entry period] or for the dilution of diesel emissions. It is interesting to note that even in relatively low virgin rock temperature operations, heat from diesel engines can be the critical issue determining overall ventilation quantities.

For diesel mechanised operations, another global approach considers diesel emission dilution criteria only. The rule-of-thumb for estimating overall primary ventilation requirements for the dilution of diesel fumes is taken as 0.10 kg/s to 0.15 kg/s per kW [diesel rated] on a mine-wide basis. This factor includes service ventilation requirements and allowance for ventilation leakage [at final point-of-use specific dilution needs will be lower (typically 0.06 kg/s per kW) depending on engine specifics and state of maintenance].

Levels-of-mechanisation can be summarised statistically as ranging from low values of 10 kW [rated diesel] per kt/m to high values of 50 kW [rated diesel] per kt/m. But obviously this will depend on site-specific details. For example, using a dilution value of 0.12 kg/s per kW and a level-of-mechanisation of 25 kW per kt/m, relates to an overall ventilation specification of 3 kg/s per kt/m [which is often a reasonable starting point].

Minimum ventilation quantities can also be determined by reference to the relevant regulations which state required face velocities and quantities based on face areas. For example: RSA regulations for metal mines refer to the following minimum criteria [amongst others]: 0.25 m/s average air velocity along stope faces, 0.15 m³/s per m² development face area [timed-blast], 0.50 m³/s per m² development face area [multi-blast exhaust]. The planner can apply these factors, carryout an overall audit and hence evaluate the primary [and secondary] flow requirements. However, planners must be aware that these are minimum values only and planning on this minimum basis for hot-rock mines will often lead to serious shortfalls. In hot-rock mines heat dilution will generally require quantities in excess of these amounts.

In addition the primary ventilation must provide air for service ventilation [crushers, tips, workshops, pump stations, etc] and provision for leakage throughout the mine must also be made. Air leakage depends on mine layouts but typically provision is made for losses of primary downcast ventilation in the shaft system and in the intake airways of about 15% to 30%. The losses in the stoping horizon depend on ventilation controls and typically losses may vary between 25% to 75% of air reporting to a stoping connection. For example, typical overall ventilation audits may indicate primary ventilation breakdown as: 15% service ventilation, 20% uncontrolled leakage, 50% stoping and follow-on development, 15% multiblast development.

4.2 Air speeds and nominal carrying capacities

Excessive air speeds in airways will cause dust entrainment, general discomfort and high ventilation operating costs. However, intake airways normally represent a substantial investment and the potential ventilation carrying capacities of these excavations must be well used.

The greater the cross-section, the higher the excavation cost but the lower the velocity for the same airflow. Fan power costs vary with the velocity cubed and thus, for shafts [and airways] that are dedicated to ventilation use, economic optimum velocities can be determined. This is an important issue in containing overall investment and running costs. The economic optimum speeds depend on power costs, excavation costs and other factors and can change significantly from project to project [and country to country]. Typical optimum air speeds in dedicated ventilation shafts may vary from 16 m/s to 22 m/s.

There are many non-ventilation-dedicated excavations in which the velocity is constrained by other issues such as access for men, conveyance stability, dust entrainment, etc. In general recommended design air speeds are:

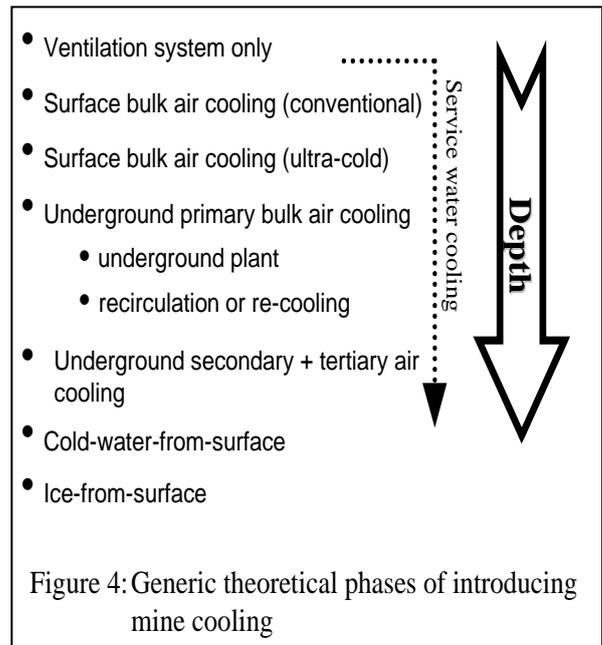
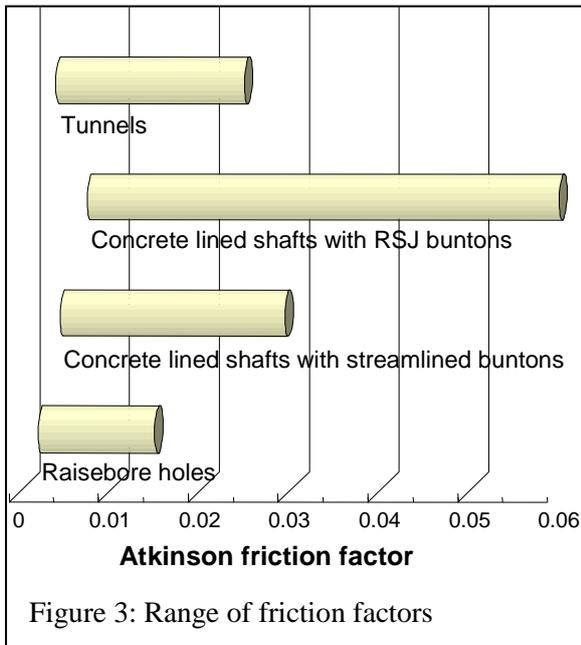
- Intake airways 5 m/s to 7 m/s
- Return airways 6 m/s to 9 m/s
- Vertical unequipped upcast shafts 16 m/s to 22 m/s
- Vertical equipped shafts 10 m/s to 12 m/s

In upcast shafts in which significant condensation occurs, air speed should not be in the range 7 m/s to 12 m/s to avoid the suspension of water droplets and the resulting oscillating load on main fans [and cascades of water].

4.3 Airflow resistance

Frictional pressure drop in a length of airway is proportional to the friction factor and the square of the air velocity [well known standard equations are applied]. Friction factors can vary by an order-of-magnitude, for example, from smooth unequipped shafts [K=0,004] to heavily timbered shafts [K=0,08]. It is important that planners give this aspect a reasonably high priority and carefully selected values should be selected through reference to the standard texts^[1,2] (aerodynamic and friction issues are important in containing costs). However, Figure 3 presents some basic data for general global purposes.

The combined effect of the excavations, regulators, leakage, etc. creates an overall pressure-drop and flow relationship or system resistance. For rough indication of system resistance, a single-critical-line can be selected through the network from inlet to return. Great care must be taken with the air flow distribution assumptions. This approach can be dangerous and should only be used in rough early planning. User friendly software products are available for this function and that is clearly the preferred approach.



4.4 Heat loads and refrigeration requirements

Refrigeration requirements are determined from the following overall heat balance equations.

$$\text{Air cooling duty}^a + \text{residual/natural air cooling capacity} = \text{Heat load} + \text{autocompression}$$

$$\text{Refrigeration system duty}^b = \text{Air cooling duty}^a + \text{losses}^c$$

- a. Air cooling duty includes effect of service water on atmosphere.
 b. System duty includes effects of pre-cooling tower if present.
 c. Losses include effects of thermal losses and of air leakage.

The ability of air to provide a natural cooling effect is severely limited by autocompression. Below depths of about 2 000 m un-cooled air acts as a heat load rather than a heat sink. Below this approximate horizon, all heat generated must be

removed by refrigeration and the provision of more and more un-cooled air from surface is not directly effective in cooling the mine. Under these conditions the ventilation must be considered as providing a vehicle for distributing refrigeration. Above this approximate horizon, depending on the actual heat loads in the mine, refrigeration may be required to remove some of the heat load while the natural cooling effect of the air will remove the balance.

The temperature of the air leaving surface is the significant factor in determining the cooling capacity of the air and bulk air cooling on surface is often the fundamental step in introducing cooling. The lower the temperatures to which air is cooled on surface the greater the depth to which cooling can be affected in this manner. However, for comfort in man-conveying shafts the temperature should not be less than about 10°C but in dedicated downcast shafts there is justification to cool the air to as low as 2°C and possibly less in future.^[5]

Note an additional advantage of surface cooling is that a constant cold downcast temperature ensures a constant and significant natural vent pressure [NVP] effect.

In ultra-deep mines, with secondary and tertiary vertical shafts the same logic may be applied by the creation of an artificial intermediate 'surface' horizon^[6] on the main transfer levels between the shafts.

Examination of existing mine cooling systems shows a great diversity of designs, mainly because of the great variety of mining operations and the unique features of each mine^[7]. No doubt individual mines will continue to be unique and each will be driven by specific circumstances. Mine cooling is, and will be in the future, generated by both surface and underground refrigeration plants as well as a diversity of air coolers and uses of chilled water. But for global planning purposes, and as a basis for initial considerations, a general 'hierarchy-with-depth' for introducing cooling may be considered. This is shown graphically in Figure 4 starting with ventilation only, cooled service water and surface bulk air cooling down to ice-from-surface systems for the ultra-deep mines.

The question of sizing underground refrigeration plant will often play a role in strategic planning and a useful rule-of-thumb in this regard is that about 100 kg/s of reject ventilation air will allow heat rejection from 6 MW capacity cooling plant.

For effective planning it should be noted that, while the ventilation system is the fundamental medium for controlling the environment, there is a complex interaction with the refrigeration and cold water systems. For detailed planning at the correct level of accuracy, there is a need for a balance-sheet, audit-type approach for evaluation of different scenarios on a systematic and consistent basis. The thermodynamic and flow calculations must be solved progressively, interactively throughout any particular mine network. Many variables are involved and again the best way to plan this systematically is through the use of specific software tools.

Mine heat loads are made up of many components the major ones of which include: surrounding rock, broken rock, machinery, fissure water. Again this is very wide subject and not a particular focus here, however some interesting points are highlighted below.

The most severe heat source is generally related to geothermal or rock heat flow. The temperature of virgin rock increases with depth below surface with the rate of increase

depending mainly on the thermal conductivity of the rock. The following data for the main RSA gold and platinum mining areas are useful for basic planning:

	Gold [Witwatersrand]	Platinum [Bushveld complex]
Geothermal gradient	1°C per 100 m	2°C per 100 m
Conductivity	6 W/m°C [quartzite]	3 W/m°C [norite]

Note the significant differences in these rock properties. There are also considerable sub-regional variations that occur and relevant measured data should be used whenever possible.

Although rock heat in the intake systems is important, perhaps of more interest during strategic planning are the stope heat loads and the effects of stope face advance and face utilisation. Important parameters in determining stope heat loads are: rock production, virgin rock temperature, air temperature, wetness, face advance, stoping width and distance between face and dip gully which defines the extent of the ventilated worked-out-area. Face utilisation defines, amongst other issues, the level of production per unit backlength. The better the face utilisation the higher the overall rate of face advance and the lower the heat load for the same tonnage. For example, increasing average face advance by 50% can reduce the stope rock heat load by more than 15% for the same tonnage. This is important to appreciate in strategic planning as good face and level utilisation must always be maximised [for minimising heat per ton and many other reasons].

Sophisticated computer methods have also been developed to calculate heat loads in the various areas of a mine. However, there are a number of approximate methods which can be used to estimate the heat loads and hence the refrigeration requirements. Many of these are presented graphically and can be found in the main standard texts^[1,2].

Important machinery categories to be accounted for in vent/cooling planning include: hoists, pumps, diesel vehicles, fans, lights, locomotives, winches, belts. Planners must be aware that each machine will have load cycles and heat factors depending on the specific application. Consider one selected example of diesel engines: at full load heat production is about 3 kW heat per rated kW and on average about 1.5 kW per rated kW. As noted, levels-of-mechanisation may range up to 50 kW [rated diesel] per kt/m and the associated heat load would be about 75 kW per kt/m. Hence diesel related heat loads can be very significant. In this regard, planners must be aware of the advantages of using electric machinery.

Fissure water can play an important role. Fissure water will enter mine workings at local virgin rock temperatures [and higher in some cases] and leave at close to the wet-bulb temperature. Fissure water heat loads can be significant, for example, for fissure water flows of 2 ton/ton and virgin rock temperatures of 55°C, the associated heat load will be about 85 kW per kt/m.

5. COMPUTER TOOLS

5.1 Network simulation and VUMA software

Detailed vent/cooling planning in the modern context must include the effective use of software tools such as ventilation network analysers and heat load calculators.

But as noted, planners must be wary of carrying-out these detailed studies too soon in the planning design process.

There are a number of generic programs available, but for hot-rock mines the VUMA-network^[8] simulation program is the most relevant. VUMA-network has been specifically developed to plan and design mine vent/cooling systems. VUMA-network is an interactive 'Windows' program that allows for the simulation of air flow, air thermodynamic behaviour, wide density variations and gas and dust emissions in an underground mine. For example, the program allows the calculation of all the heat loads and temperatures [pressures] throughout the mine for different cooling strategies and determines refrigeration requirements. What-if studies can be rapidly performed to determine optimal designs and system requirements. The planning is done by creating a simulated mine layout with a network of building-blocks or branches representing shafts, stations, tunnels, production zones, development headings, fans, control elements [coolers, filters, regulators]. Some of the principles of operation are:

- Input data for branches is used to calculate air pressure drop and air thermodynamic and contaminant level changes in a specific component of a network.
- Input data for nodes consists of the co-ordinates and virgin rock temperature and air temperatures [and pressure].
- Simulation networks are constructed in a two-dimensional graphical editor on level-by-level basis, the levels are then interconnected, typically by shafts or declines.
- If only an airflow solution is required, only information relating to the geometry and air resistance characteristics of the branches need be entered.
- Three-dimensional graphical viewer is used to view the network and output data.
- VUMA-network is compatible with other mine planning software such as Mine 2-4D.

VUMA-network uses algorithms based theoretical and empirical models that have been developed and verified by engineers and scientists at BBE, CSIR Miningtek and other RSA specialists over more than two decades.

5.2 Computational fluid dynamics [CFD]

Within the mine ventilation circuit, the consideration of specific aerodynamic and friction issues can be important in containing costs. Poorly designed bends, junctions and other high velocity zones can incur severe and unnecessary cost penalties. Detailed design evaluations using computation fluid dynamics [CFD] is often justified in critical areas such as: bends/drifts to main fan stations, bulk air cooler feeder bends/drifts to shafts, vent raise intersections and many others.

But again planners must be wary of carrying-out these detailed studies too soon in the planning design process.

The results of CFD analyses include the definition of stream lines, air pressure losses, air pressure contours, and velocity profiles throughout the geometry. CFD techniques represent an extremely powerful aerodynamic design tool to optimise configurations and

what-if analyses can be carried out before construction. Some typical examples are shown in Figure 5.

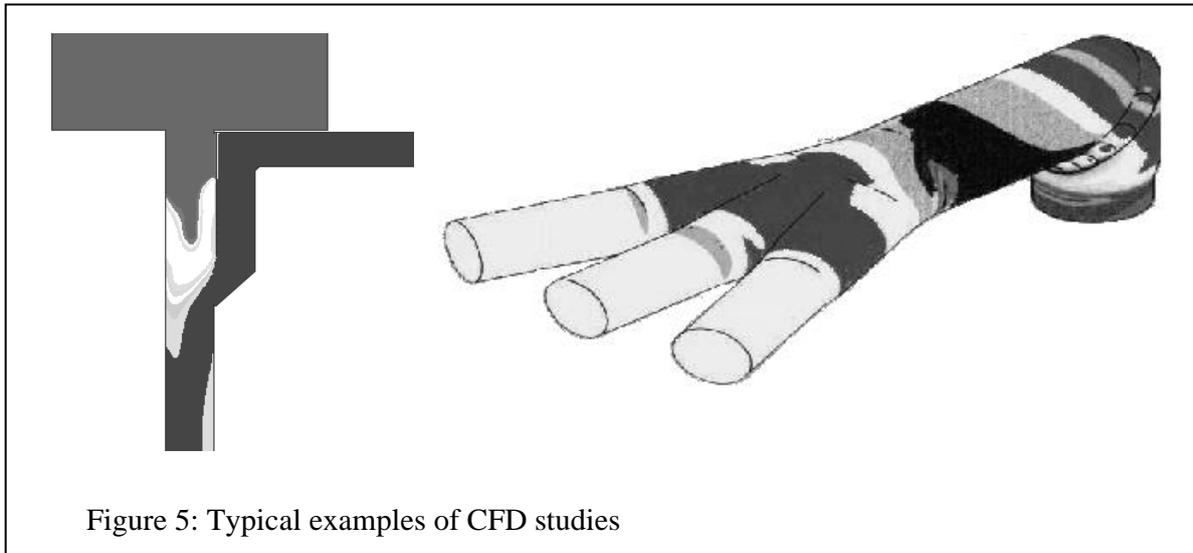


Figure 5: Typical examples of CFD studies

6. CAPEX VS OPEX TYPE CONSIDERATIONS

6.1 Life-of-mine and life-cycle costs

Effective planning and the selection of optimum system designs require the evaluation of full life-cycle costs including both capex and opex aspects. However, in mine planning there is often a pre-occupation with the former [for obvious reasons] and a neglect for the latter. The operation of vent/cooling equipment is highly power-intensive and evaluation of these costs is very important in the overall assessment.

For example, the present value of the power required to run a typical main surface fan station will normally be far in excess of its original capital cost. For this component it is obviously prudent to spend more capital on an efficient fan than purchase a cheaper less efficient fan [and then pay a higher power cost].

Electrical power costs are typically made up of components such as: basic rental charge for facility, consumption cost per kWhr and peak power demand charge per kW. In practice, for this application, these components are combined into an approximate total cost. The representative cost in RSA at present [Feb 2003] is about R 0.14 per kWhr [although this can vary between mining companies depending on specific negotiations], and the cost of a continuous kW of power will be R 1 230 per annum. The mining company will pay this equivalent value for each year of the project.

In order to assess projects on the basis of both capital and running costs, the present value concept can be used. Essentially, all running costs are adjusted to account for life-cycle [years] and net interest on investment. Net interest is related to the expected rate-of-return [basic difference between profit and inflation/escalation rate]. So-called 'PV-factors' based on the duration of project and net interest rate can be looked-up and the present per-annum running cost is multiplied by the PV-factor to give the life-cycle power cost.

For example: consider a fan station absorbing 10 MW power and running for 20 years in a scenario with an effective net rate-of-return of 8%. Present per-annum running cost will be R 12.3 m [10000x1230], the PV-factor is looked-up as 9.8 [20 years, 8%], thus this present value running cost for the life-cycle will be R 121 m [9.8x12.3].

Apart from the procedure, the magnitude of this value should also be noted.

Numerous good examples of using life-cycle costs to optimise planning have been published. The example highlighted here^[9], determined the most economical split between ventilation and refrigeration inputs as well as the correct split between surface bulk air cooling and underground air cooling [with recirculation] and main fan sizing. Life-cycle analyses included capital and running costs of: shafts, excavations, refrigeration plant, main and recirculation fans, pumps, turbines, pipes, etc. The results were plotted as a function of main downcast flow rate and are re-created in Figure 6. It is interesting to note that the power-perspective optimum is lower [and more pronounced] than the capital-perspective optimum. The selected optimum was obviously somewhere in-between.

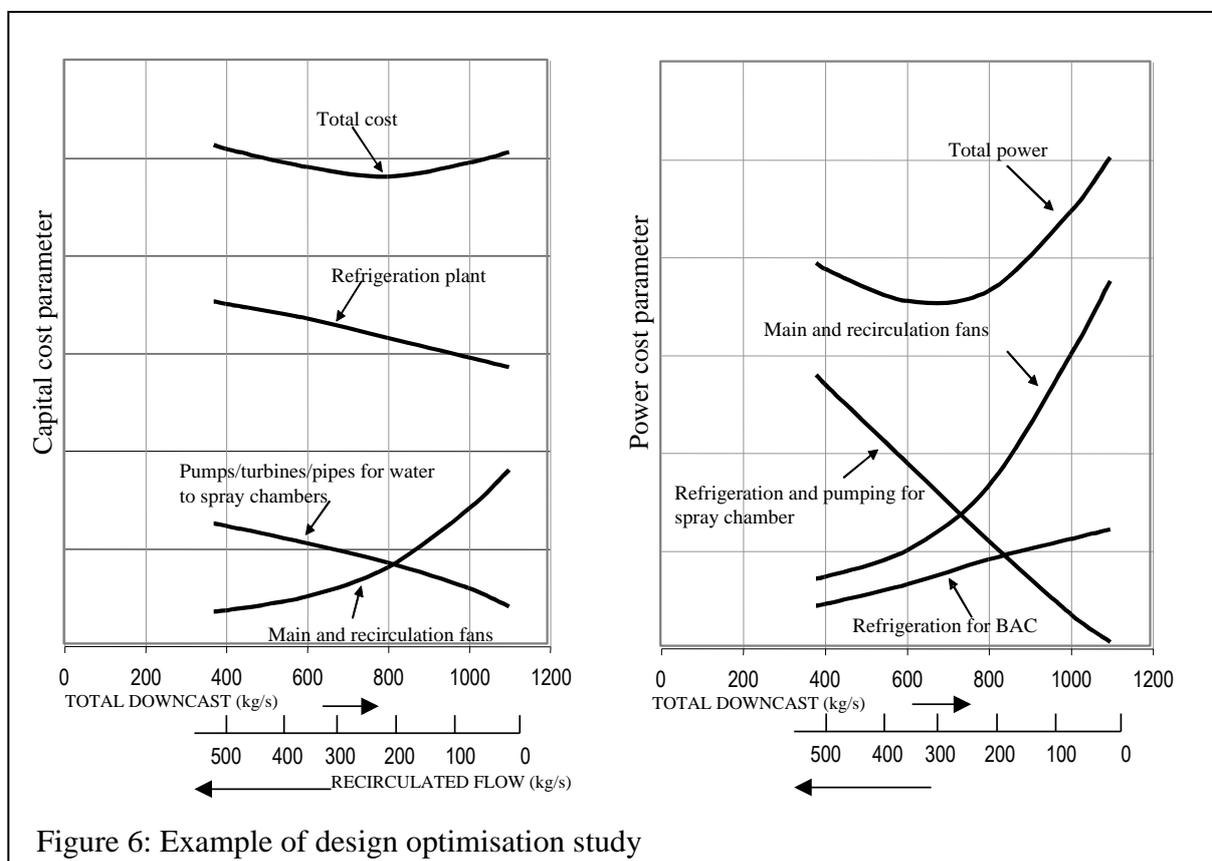


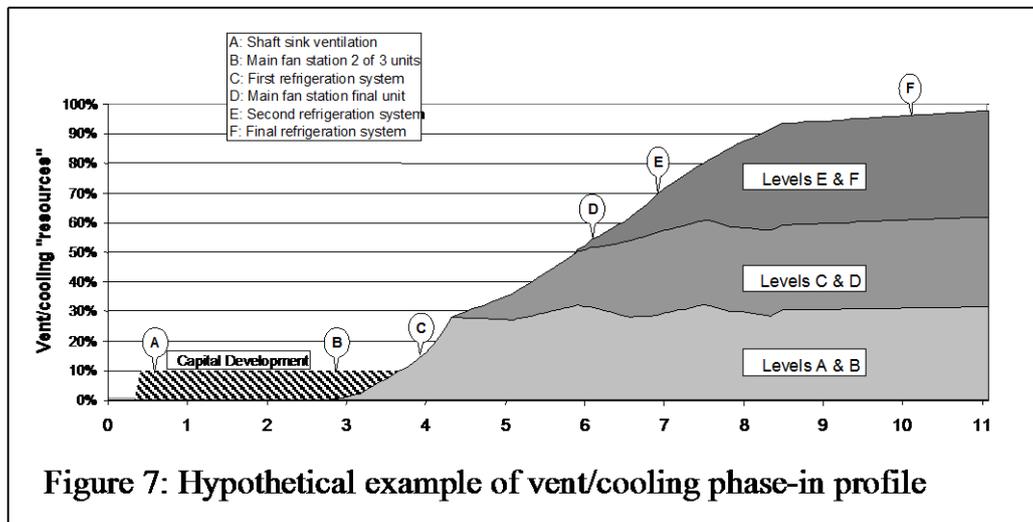
Figure 6: Example of design optimisation study

6.2 Phase-in of capital

While most project capex is utilised in the mine-construction stage often the main vent/cooling equipment is implemented later and, as noted earlier, the capital costs of the vent/cooling equipment can be so high that an optimised phase-in strategy is a very important consideration.

Detailed evaluation of critical scenarios and the interpolation between these allows an understanding of the life-of-mine needs and helps build-up the phase-in picture. Figure 7 presents a hypothetical but typical phase-in profile of vent/cooling resources for

a green-fields project. It should be noted that the investment in the vent/cooling equipment is well spread over the life-of-mine. Indeed final main fan modules can be delayed to year 6 and final refrigeration systems delayed to year 10. The understanding and prediction of the vent/cooling capex delay is important in planning. Effective planning deserves the effort required to produce this type of profile for both capex and opex requirements.



7. PLANNING FOR THE DYNAMIC NATURE OF MINING OPERATIONS

The single most fundamental issue that must be fully appreciated in mine planning is that mining is a continuously evolving, dynamic and flexible process. Invariably, the mining operations that produce the highest long-term profit are those that have mining, engineering and vent/cooling systems that are adaptable to change. Indeed some mining analysts are making use of 'flexibility indices' as well as the traditional IRR and NPV indices to assist in decision making and project assessment. While issues such as the refrigeration system design COP and main fan station design efficiency may be important initial considerations, in practice the best vent/cooling system in an overall sense will be that which is the most adaptable system over the life-of-mine.

It is critical that vent/cooling designs and planning incorporate a high degree of flexibility. Modular cooling and main fan systems must be applied which can be gradually phased-in, added-to or removed and the possibility of increasing vent/cooling resources must have a high priority throughout the planning process. Some of the design flexibility can be incorporated when drawing-up the engineering hardware specifications and indeed this versatility must be a pre-occupation of these specifications. However a powerful approach during the strategic planning is to carry out what-if sensitivity studies. These analyses can be very effectively carried out using the computer simulation tools by simply varying part of the network evaluation.

For example, the effect of using a sub-incline instead of a sub-vertical shaft system to access certain lowest levels can be assessed by determining the heat loads in the different excavations without having to recalculate the head profile for the complete mine. Similarly what-if questions of the following nature can be answered.

- what-if strike distances are increased by x%
- what-if improvements in stoping methods allow x% increase in face advance

- what-if a particular zone is found to have improved grades that must be exploited
- what-if rock thermal properties differ from expected
- what-if significant fissure water is encountered
- what-if back fill is introduced below a certain depth

Many possible future variations can be examined by keeping most of the parameters constant and only varying those aspects that require examination. However in carrying out sensitivity studies, only the effects of one type of variation should be examined at a time in order to gain a clear understanding of the trends. With the application of this approach the most flexible and versatile vent/cooling system can be designed for most future possibilities, combinations and permutations.

8. CONCLUDING COMMENT

This paper has reviewed the important basics of planning vent/cooling systems and has been concerned with the planning process as much as the technical details. The paper has stressed the need for a systematic approach, the multi-disciplinary nature, the setting-up of standards, use of modern software, life-cycle costing and the importance of flexibility and adaptability of designs.

References

1. Environmental Engineering in South African Mines. The Mine Ventilation Society of South Africa, Johannesburg, 1989
2. The mine ventilation practitioner's Data Book. The Mine Ventilation Society of South Africa, Johannesburg, 1999
3. Kielblock AJ and Schutte PC. Heat stress Management, A comprehensive guideline. Chamber of Mines of South Africa Research Organization, Johannesburg, 1991.
4. Smith O. Effects of a cooler underground environment on safety, labour and labour productivity, Proceedings: Third International Mine Ventilation Congress, Harrogate, England, June 1982.
5. Wilson RW, Bluhm SJ and Smit HJ. Surface bulk air cooler concepts, producing cold air and utilising ice thermal storage. Proceedings: Managing The Basics, CSIR Conference Centre, The Mine Ventilation Society of South Africa, Johannesburg, 2003
6. Bluhm SJ, Wilson RB and Biffi M. Optimised cooling system for mining at extreme depth, Proceedings: CIM/CMMI/MIGA Montreal '98, Canadian Institute of Mining, Metallurgy and Petroleum, Montreal, 1998.
7. Bluhm SJ, et al. Generation and distribution of refrigeration for ultra-deep mining: new challenges and insights. Proceedings: Frigair 2000, Gallagher Estate, South African Institute of Refrigeration and Airconditioning, Johannesburg, 2000
8. Bluhm SJ, von Glehn FH, Marx WM and Biffi M. Journal of the Mine Ventilation Society, vol 54, No 3, July 2001.
9. Rose HJM and Bluhm SJ. Ventilation and refrigeration design for a new shaft system at Impala Platinum Limited. Proceedings: Fifth International Mine Ventilation Congress, Mine Ventilation Society of South Africa, Johannesburg, 1992.