Variations in ultra-deep, narrow reef stoping configurations and the effects on cooling and ventilation

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Introduction

In exploiting the ultra-deep, narrow reef ore bodies of the Witwatersrand, the ventilation and cooling systems within the stopes play a critical role because of high concentrations of active workers. This paper examines the heat, ventilation and cooling effects of a number of different stoping layouts for narrow reef mining in ultra-deep operations in very hot rock.

The stope ventilation and cooling needs are driven primarily by the difference between the air temperature and that of the rock front being excavated. These needs depend on the face utilization, geometry, face advance (rate and direction), layout, backfill, use of water and machinery[1,2,3].

Detailed studies of different stoping configurations have been undertaken for mining operations extending to depths of 5 000 m below surface, where virgin rock temperatures approach 70°C. Extensive work has been completed with regard to evaluating ventilation and cooling requirements to maintain air reject temperatures of 28°C wet-bulb and better. This knowledge is being used to determine overall cooling requirements, reduce operational costs and maximize the efficiency of cooling systems. These issues are important when considering both the local and regional air conditioning systems and the most effective application of in-stope chilled water.

This paper includes aspects from the DEEPMINE Research Programme. Some of the original analysis was part of an overall feasibility study of extending an existing mine from 3 500 m to 5 000 m below surface. In the original work the ventilation and cooling aspects were examined for different stoping layouts on a **macro-level** (mine-wide) and **micro-level** (in-stope). The different stoping layouts considered had a broad division between those using strike pillars and those using dip pillars as follows:

- Strike pillars — breast mining
- Dip pillars — down-dip mining; breast mining (overhand or underhand)

Up-dip configurations were excluded from this particular study because of the high risk related to rock support. However, up-dip layouts have merits for many other mining districts and in particular have advantages regarding ventilation control.

The macro-analysis had to account for the scheduling of the ventilation requirements in relation to other infrastructure needs. Significant factors included the build-up of production and the related capital and running costs of the ventilation and cooling systems. Other considerations that affected the macro-analysis related to the large-scale ventilation tactics including re-circulation and the use of primary and secondary bulk air coolers as well as in-stope coolers.

However, this paper is mainly concerned with the micro-layout aspects of this work and the effect that the different stoping methodologies would have on ventilation and cooling requirements. This was used to verify the information obtained in the macro simulations and to identify possible problem areas in the design of stoping methods and possible ways of improving the performance of the ventilation systems.

Apart from the DEEPMINE study, this paper also includes aspects from many other studies that have been undertaken separately (by BBE and Miningtek), and in particular, some parts of the new VUMA software for simulating underground ventilation conditions are utilized.

The paper first discusses the approach used for predicting cooling needs in these kinds of stopes. The specific different stoping layouts are then described and compared from a ventilation and cooling perspective. General notes on the effects of backfill as well as the use of chilled water and the cyclical effects of the mining operation are also included.

Method of heat, cooling and ventilation analysis

The stope heat load analyses[2,4,5] for this work have been done on an overall cyclical averaged basis. The averaging philosophy greatly simplifies the explanations and can be usefully applied in this type of study. The validity of averaging the heat load over the mining cycle has been the subject of a number of thorough studies in the past[6,7] and the clear conclusion is that it is acceptably accurate for these purposes. This is largely because of the effective heat transfer mechanisms and thermal storage effects which tend to damp out the cyclical variations. Notwithstanding, there is much interest in the cyclical changes with respect to optimizing opportunities in applying cooling and ventilating stopes and this is discussed, as a separate topic below.

The thermal effects are evaluated by auditing all the different heat, cooling and flow components. These include (but are not necessarily limited to):

Q1 heat from rock surrounding dip gullies
Q2 heat from rock surrounding strike gullies

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- Q3 heat from rock surrounding worked-out areas (footwall and hangingwall)
- Q4 heat from rock surrounding face zone (footwall and hangingwall and face)
- Q5 heat from broken rock (and its 'flow')
- Q6 heat from backfill drainage
- Q7 heat from fissure water
- Q8 heat from equipment such as winches, power packs
- Q9 heat from men and many other secondary sources
- Q10 cooling effect of ventilation air
- Q11 cooling effect of compressed air
- Q12 cooling effect of cold service water (be it conventional or hydropower)
- Q13 cooling effect of in-stope air coolers.

Analysis requires simultaneous and interactive evaluation of all these effects. Some effects are temperature dependent, some are flow dependent, some are production rate dependent and others depend on a combination of all these issues. The calculation procedures also account for different air speeds and different wetness in different zones and are based on well established and published algorithms[1–5] originally derived from finite difference/element numerical methods.

Numerous field trials have been carried out in which all the heat/cool components were monitored over extended periods of time and these results have reflected very positively on the above approach and these, with much other historical data, have validated this general approach.[8,9]

With regard to cooling and ventilation, and for all-else-equal in terms of production, face advance and utilization, the different stope layouts/methods differ in the following main aspects (see Figures 1a and 1b):

- ➤ number and size of the building blocks Q1 to Q4 differ to a greater or lesser extent
- ➤ flow configurations, in relation to each other, of the rock movement, the ventilation and all the various water components
- ➤ leakage paths for ventilation
- ➤ position of critical design locations (see intermediate observation points in Figure 1).

As an example, the breakdown of the heat flow components and the cooling components for a typical dip-pillar underhand breast layout, is shown in Figure 2.

There are a number of different combinations and permutations of inputs regarding the way in which the in-stope cooling can be achieved. For example, this may involve a greater or lesser use of the following:

- ➤ more ventilation at stope inlet
- ➤ colder ventilation at stope inlet
- ➤ cold mining water and free discharge over rock surfaces
- ➤ in-stope air coolers.

Ever since the introduction of chilled service water in the late 1970s as a means of assisting in cooling distribution, there has been much debate as to the optimum combination of these components. The debate continues but the DEEPMINE research programme is systematically showing that the optimum for ultra-deep mining in very hot rock will involve the introduction of relatively cold ventilation (with coolers at stope entrance) and the use of high efficiency in-stope air coolers.

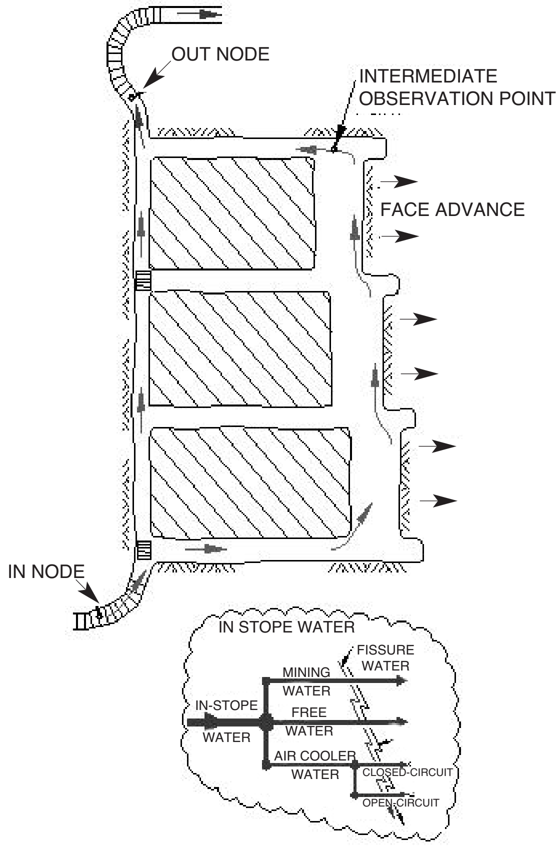

Figure 1a—Blast layout

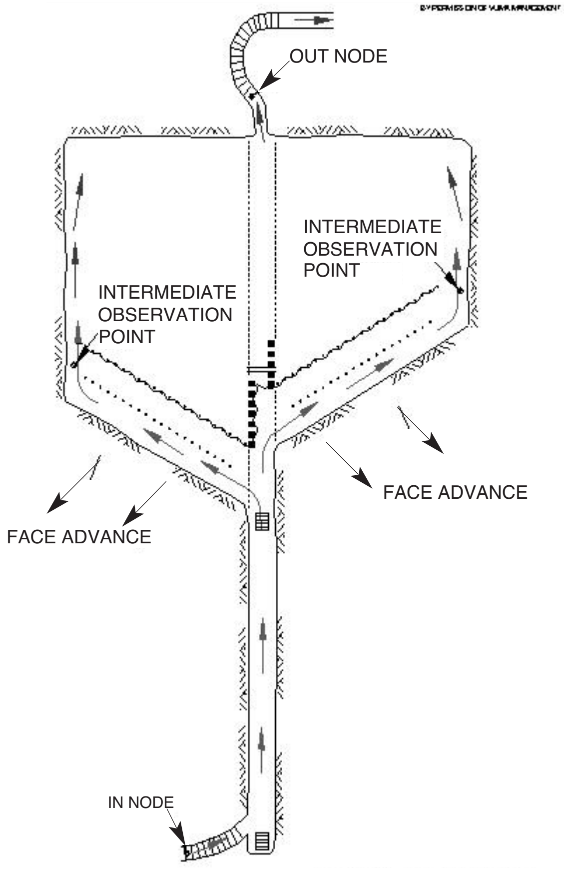

Figure 1b–Down-dip layout

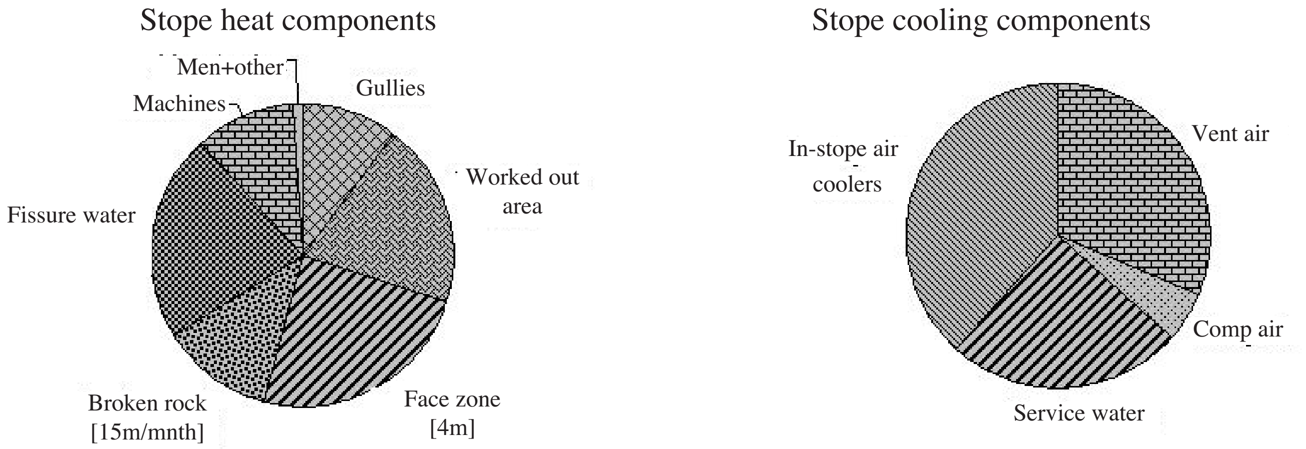

Figure 2—General breakdown of stope heat and cooling components

Discussion of different stoping scenarios

As noted above, the different stoping layouts considered had a broad division between those using strike pillars and those using dip pillars. Examples of each are discussed, in turn, below.

Strike pillars and breast layout

This is the 'traditional long-wall' layout adopted originally for deep mining operations, see typical layout in Figure 3. In this method over-hand breast mining of panels takes place in an area established between a main level and a point extending above an inter-level. Crosscuts are developed from the footwall drives in both the main and inter-level at approximately 60 m intervals. Typically ventilation on the main level might be drawn through an air cooler and conveyed to development ends prior to entering the reef horizon. Spot cooling of the air would be provided for each development end. The air moves up through the panels with some allowance being made to ventilate the dip gully and any vamping or recovery operations in the worked-out section. Centre gully brattices and backfill are used to maximize the airflow on the panels, faces. In order to maintain acceptable reject temperatures, in-stope cooling is provided. The air leaves the reef horizon through a strike gully developed next to the upper strike pillar and a connection down to the inter-level. The ventilation might then be used for development on the inter-level and coolers would be provided to reduce the temperature to acceptable levels in the development ends as well as along the inter-level. Careful attention must be given to airflow at the top of the longwall to ensure no methane accumulates[11].

Depending on the depth, the strike pillar width would be about 45 m wide and rock engineering constraints preclude the development of airways through the strike pillar to allow the passage of air from one stoping block to the next further up-dip. The back lengths would be about 240 m and six panels would be established in each 'longwall'. The strike distance from the crosscut intersection to the face will be less than 100 m. Dip walls would be installed to prevent the leakage of air from the face area deep into the worked-out sections. It is noted that careful planning will be required to co-ordinate the timing between the holing of crosscuts from the main and inter-level into the reef horizon to minimize the strike distance through which the air has to travel to reach the face. This layout defines a 'closed' air pathway with the main level serving as intake airway and the inter-level as return. The strike distances over which this system extends will be long with numerous crosscuts and hence large potential for leakage. On a macro scale, this arrangement places obstacles on strike in the way of the flow of the air which is generally travelling on dip. This can add to the complexity of the infrastructure required to convey air into and out of the reef horizon. Generally this stoping approach has a moderate ventilation need per ton and a moderate in-stope heat load per ton.

Dip pillar and underhand breast layout

This method has recently been implemented successfully in the mining of narrow reefs at depth. Dip pillars are left behind in the reef horizon defining spans between which stoping takes place under-hand in a carefully sequenced manner. This method is shown in Figure 4. The pillars are about 35 m wide, the crosscuts are developed at 200 m intervals resulting in spans of about 165 m depending on the mining depth. Since dip gullies are developed over the centrally located crosscut, the strike distance through which the air travels will not exceed 85 m. Stoping takes place on breast with faces generally moving in one direction and then in the opposite direction once the pillar position is reached. This implies that at times, airflow would be required on both sides of the raise. Mining takes place only between two main levels. The back length is 240 m and up to seven panels may be mined between consecutive levels.

Ventilation enters the reef horizon through the crosscut. Coolers may be provided near the stope entrance to reduce the air temperature to acceptable levels. The use of backfill and brattices direct the air onto the faces on either side of the centre raise. Some air is leaked through the centre raise to ventilate winches and travelling ways. The stope heat may be partially countered by introducing in-stope coolers at a frequency as high as every second panel depending on specific circumstances and tactics. At the top of each stope, a connection is provided to the return airway located in parallel

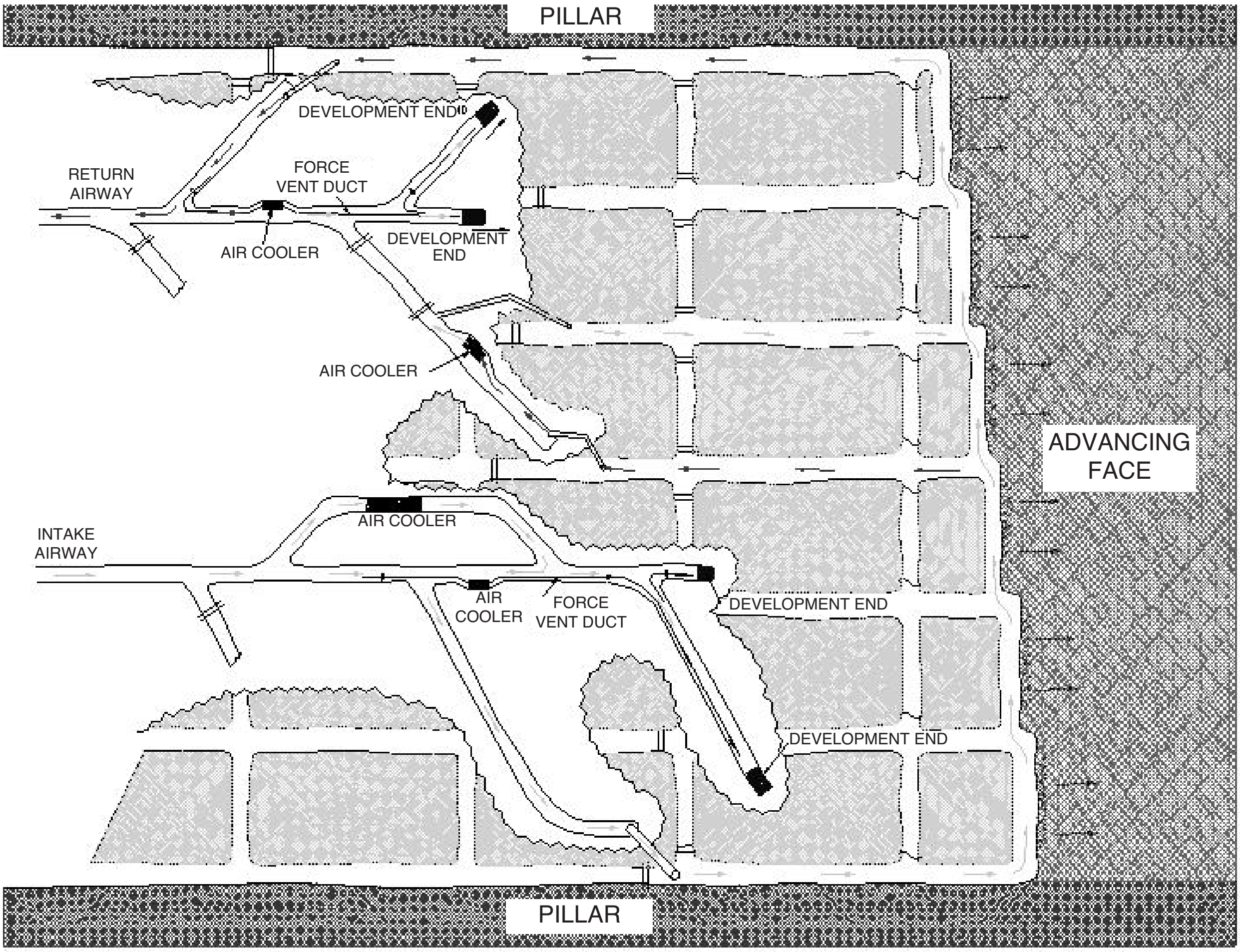

Figure 3—Strike pillar breast mining

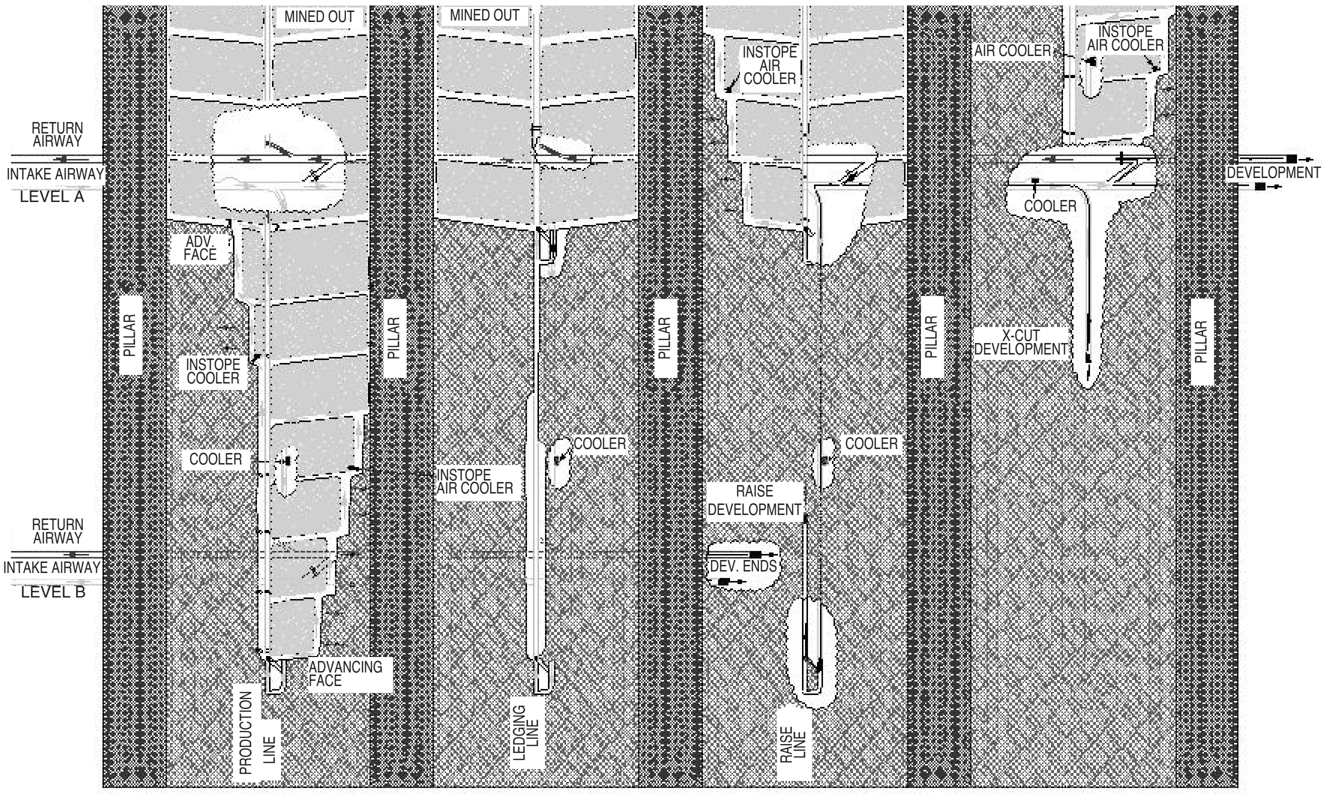

Figure 4—Dip pillar underhand breast mining

with the main level below. The sequencing of stoping operations will be such that stoping will not take place above a block being stoped. The area above any stoping block would be abandoned or, in the limit, it would be vamped while the area below is stoped. The worked-out stope can be sealed-off on strike and all the air in the reef horizon may be coursed to the return airway or to the level above for possible re-use (this sequential use of the air is not used widely at present but it has potential for cost reductions if used as part of a planned sequence). The layout reduces the propensity for air to leak on strike and is generally well suited to control ventilation between levels. Also, the relatively short strike distance through which the air travels reduces the heat absorbed. Generally this stoping approach has relatively low ventilation needs per ton and the in-stope heat loads per ton are also relatively low.

Dip pillar and overhand breast layout

This method is geometrically similar to the sequential method discussed above, in that the pillars are established in a dip structure giving narrower spans of about 140 m. The widths of the pillars remain unchanged at about 45 m and the back length between levels are about 175 m. Figure 5 shows details of this layout. The most significant feature of this layout is the fact that the stope is mined overhand and mining is concentrated in 24 panels on either side of the centre raise, effectively creating an up-dip shape as shown. This implies that stoping extends over four levels with vamping operations taking place down-dip and ledging and equipping up-dip of the stoping.

The general ventilation tactic is to supply air at the bottom and reject it at the top where twin return airways are provided. The ventilation is conveyed into each stoping line via the bottom intake level reef crosscut. Air coolers may be provided at each crosscut and backfill and air brattices would be used to direct the air onto the faces. Leakage is allowed along the centre gully to ventilate winches and travelling ways. Since the air would flow in the reef horizon for distances in excess of 300 m, in-stope cooling is essential with coolers installed at a frequency as high as every second panel depending on specific circumstances and tactics. Sequencing of mining operations can be utilized to move intakes upwards to keep them as close as possible to the lowest panels. However, this has the drawback that if vamping falls behind, there is a risk of supplying cold air for vamping operations and having to maintain in-stope coolers along the dip pillars to serve the stoping panels. The concentration of mining in this fashion is good with respect to fire risk since the timber density is low. The short strike distance of about 70 m reduces the heat absorbed but control of airflow on dip can be difficult as the result of the extensive dip length served. Generally this stoping approach has relatively low ventilation needs per ton and the in-stope heat loads per ton are also relatively low.

Dip pillar and down-dip layout

This method is also based on the mining of the area bounded by two dip pillars. However, unlike all others, this option does not utilize backfill. The method consists of mining two faces approximately 45 m long between reef intersections

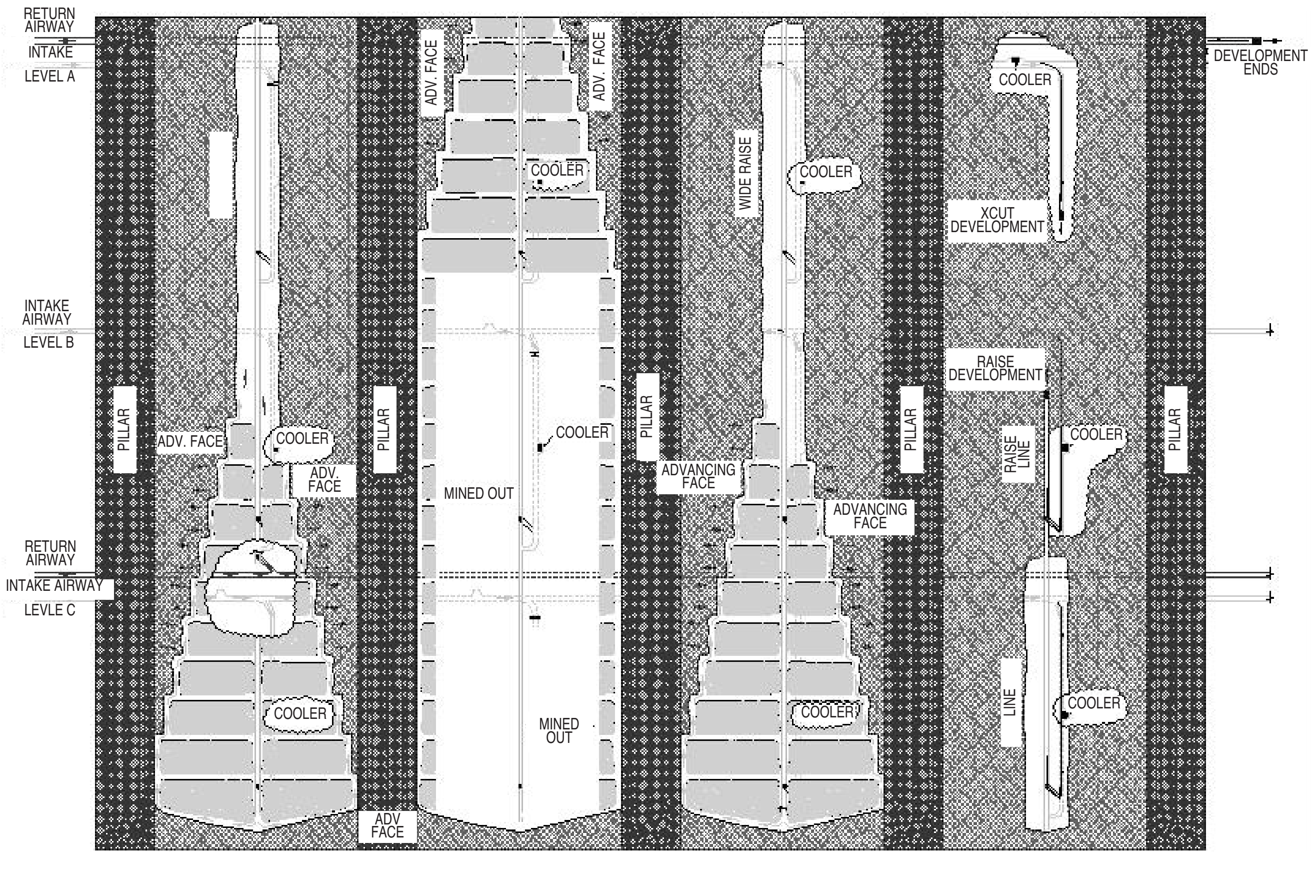

Figure 5—Dip pillar overhand breast mining

established between main levels about 80 m apart. The layout of this method is shown in Figure 6. Raises are developed from reef crosscuts located about 100 m apart. The pillars are about 25 m wide and the faces are inclined to the dip with the span between pillars limited to about 75 m. This arrangement is ventilated by allowing air to up-cast from the bottom level to the upper level. Brattices are provided to direct the air from the centre raise onto the face once it reaches the panel divergence point.

The significant aspect of this layout is the absence of backfill. In addition, the up-cast ventilation travels against the flow of rock and spent service water as it travels upwards from the inlet towards the face. This contact may be extensive and may be of the order of 200 m for newly established stopes. The velocity however is high, reducing the effect of temperature and humidity change but possibly increasing the dust levels in the air. Ventilation control is somewhat difficult as faces are underhand and there is no backfill making it difficult to channel air flow close to the face[11]. Once the air reaches the stoping panels, it absorbs contaminants very quickly and is released to the upper levels where only limited travelling takes place. If the air is to be re-used it would need to be removed from the reef horizon as close to the panels as possible (next level) and re-conditioned before being used in another production block.

Generally this stoping approach has relatively high ventilation needs per ton and the in-stope heat loads per ton can be relatively high particularly if the (unfilled) worked area is considered to be within the air-conditioned zone.

General comparative notes

In order to compare the layouts qualitatively, the following list of criteria were devised and assessed for each layout.

- Planning and general layout criteria such as: degree of concentration of ventilation areas and potential for: creating ventilation districts, controlled re-use and recirculation of air, minimizing secondary ventilation leakage, multi-shift blasting, reducing re-entry periods, vamping and closure.
- In-stope vent control criteria such as: potential for in-stope ventilation control, minimizing in-stope vent

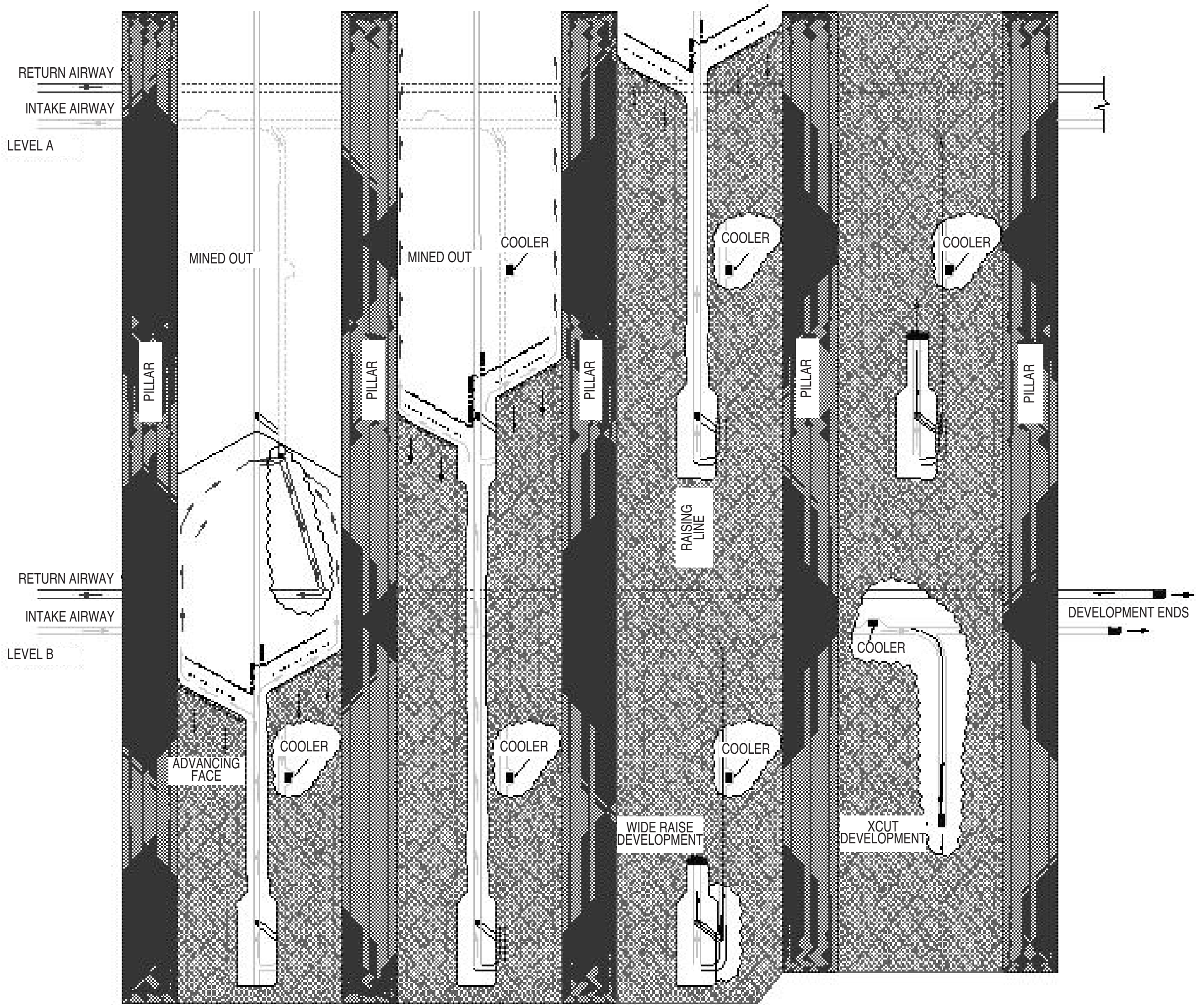

Figure 6—Dip pillar down dip mining

leakage, reducing uncontrolled recirculation and avoiding short-circuiting.
- Cooling arrangement criteria such as: potential for using in-stope air coolers and for water handling/management (in-stope and crosscuts).
- Development requirements criteria such as: potential for minimizing need for multi-blasting.
- Contaminants criteria such as: potential for minimizing build-up in air contaminants.
- Escape and rescue criteria such as: ease of escape and evacuation, ease of fire fighting within layout, potential for minimizing fire risk and its impact on safety and production.

Weighting factors were set to each of these criteria and these issues were assessed through discussions and workshops with many deep mine ventilation specialists and practitioners.

Overall the dip-pillar down-dip mining layout fared better than the others. This layout seemed to be better in terms of planning and layout requirements, in-stope ventilation control requirements and potential exposure to contaminants. The dip-pillar underhand breast fared best in terms of escape and rescue considerations, offering the best opportunity for locating, fighting and sealing-off underground fires. The strike-pillar layout offered the best advantages in terms of development requirements and demand for multi-blasting in each layout.

Notwithstanding the above comments, the four layouts were grouped fairly closely together with 18 percentage-points separating the best from the worst. It should be noted that, qualitatively, the down-dip layout was deemed to be the best despite the fact that in the quantitative analysis it seemed to be the least suited in terms of heat, overall cooling and power requirements.

Note on effects of backfill

Backfill has important spin-offs in ventilation condition control beyond the obvious rock support and regional stability roles, these include:

- reducing the heat from surrounding rock released into the air stream
- assisting in the control of airflow in the stope
- reducing the use of timber thus minimizing the associated fire risk.

The effect of backfill was examined for each of the layouts (except the down-dip configuration). The modelling analysis showed that the stope heat load per kt/month increases by up to 30 per cent if backfill is not used and that this relative effect is the same irrespective of the particular layout examined. Despite these advantages, the use of backfill does not obviate the need for in-stope cooling.

However, through drainage, the use of backfill has the potential to create an in-stope heat load if the slurry is allowed to arrive at a temperature greater than the desired stope climatic condition. This is indeed a possibility, particularly when backfill preparation plants are situated on surface and the flow suffers the full conversion of potential energy into heat within the slurry. But, this effect can be relatively simply reversed by cooling the backfill (in pipe-in-pipe heat exchangers) prior to it being placed.

Note on cyclical effects of mining operation

Recent work has indicated that, where possible, the optimum approach to temperature control in stopes is to cool the ventilation in coolers at stope entrance. But even with this approach, the air temperature gradient will be such that a significant amount of in-stope cooling is required. This is clearly evident from the wet-bulb temperature increases obtained from the modelling and shown in Figure 7 for all four of the stoping methods. Research into the best way in which to apply the in-stope cooling is nearing completion and indicating that this is best applied in high efficiency air cooler devices rather than simply to spray the water freely onto rock surfaces (irrespective of stope water pressure).

This new work has included the transient study of the cyclical mining processes with drilling, blasting and cleaning activities taking place as the excavation advances further into the rock mass at each blast. As noted, the cyclical averaging philosophy to analyse heat flow can be usefully applied in the type of study described above. However, the cyclical changes are important in optimizing methods of applying cooling and using thermal storage to advantage. The heat transfer mechanisms are complex since there is thermal interaction between water, rock mass and ventilation air taking place simultaneously. New finite-difference simulation models have been developed[10] for predicting the transient cooling effect of chilled service water usage in stopes. The models calculate the heat gain to the various components of in-stope water over a mining cycle (see insert in Figure 1 for different water components). The new models consider diffusion heat transfer and thermal storage effects in the rock, sensible and latent heat transfer between ventilation air and stope water and radiation heat transfer. The models have been verified against data from recent field trials[10]. Some typical results are shown in Figure 8.

Through systematic study, the use of these models is now leading to significant observations. For example, there are obviously different combinations of cold supply ventilation, cold water in free discharge and use of in-stope air coolers that can achieve adequate stope cooling. But some of these combinations will be significantly more expensive than others. Current research (within the DEEPMINE programme) is systematically showing that the optimum for ultra-deep mining in very hot rock will involve:

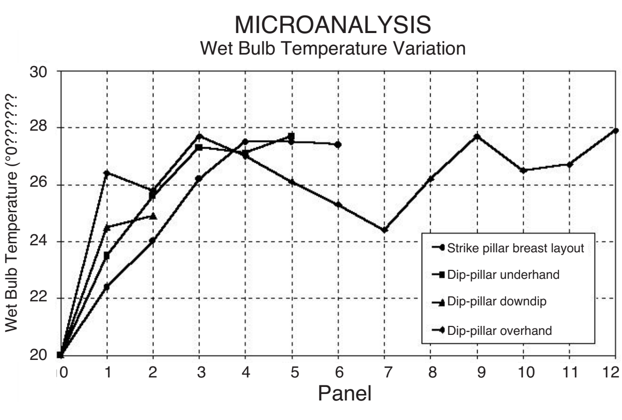

Figure 7—In-stope wet-bulb temperatures variations

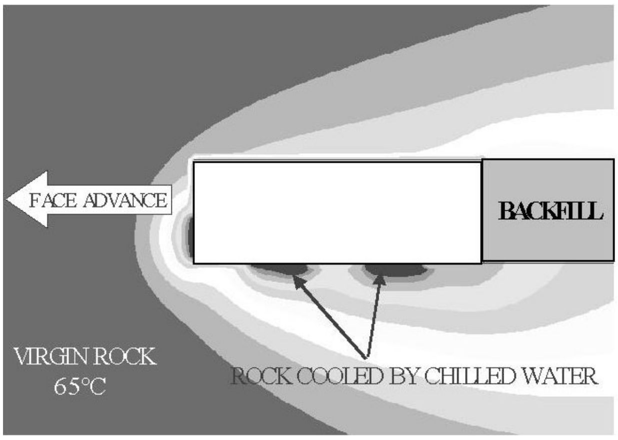

Figure 8—Isotherms in rock

- ➤ supplying relatively cold ventilation (with coolers at stope entrance)
- ➤ use of cold water as mine service water (irrespective of water pressure)
- ➤ use of high efficiency in-stope air coolers (irrespective of water pressure)
- ➤ modest quantities of free water introduced a half-hour[3] before re-entry after blast.

Discussion and conclusions

This paper examines the heat, ventilation and cooling effects of a number of different stoping layouts for narrow reef mining in ultra-deep operations in very hot rock. The different stoping layouts compared were: strike-pillars with breast layouts, dip-pillars with down-dip and breast layouts (both overhand and underhand). It was observed that the in-**stope** heat load generated per ton mined varied for the different layouts. The dip pillar underhand and overhand scenarios were relatively low while the down-dip scenario was higher. However, these differences can be explained in terms of face length (plus gully length) utilization and the effect of backfill. Detailed lists of criteria were used to judge the merits of the different layouts qualitatively. Each criterion and each layout was scored through consensus with many deep mine ventilation specialists and practitioners. Qualitatively, the dip-pillar down-dip mining layout fared better than the others. The dip-pillar breast layouts fared best in terms of escape and rescue considerations, while the strike-pillar layout offered the best advantages in terms of development and multi-blasts needs. However, the four layouts were grouped fairly closely. The work has identified strengths and weaknesses in each of the mining methods[11].

Sensitivity studies on the effect of backfill showed that the stope heat load per kt/month increased by 30% without backfill (and that this is the same irrespective of the layout examined). However, through drainage, backfill has the potential to create a heat load if the slurry is allowed to arrive hotter than the desired stope temperature. But this effect can be relatively simply reversed by cooling the backfill prior to placing it.

New finite-difference models[10] for predicting the transient cooling effects of cold water in stopes are now systematically leading to important observations. One of these is that the cooling optimum approach for stopes in very hot rock will require the supply of relatively cold ventilation (with coolers at stope entrance), the use of high efficiency in-stope air coolers, the use of cold service water and modest quantities of free water (about a half-hour before re-entry)].[3]

Although this paper is mainly concerned with the micro-level (in-stope), there are two important observations to note on the macro-level. First, the contribution of in-stope heat to the total mine heat load is less than that of the intake tunnelling (for all 4 layouts). This means that, for these ultra-deep mines, the air conditioning energy balances of the stopes are less than that of the intake system. Second, the total mine-wide costs of owning and operating the ventilation and cooling systems vary by about 20% for the different layouts, with the strike-pillar breast mining the highest and dip-pillar overhand breast mining the lowest.

Acknowledgements

The paper has included results from the DEEPMINE collaborative research programme, this is clearly acknowledged and DEEPMINE management thanked for this permission. The paper however also includes observations from many other independent studies and expresses the authors' opinion and not necessarily that of DEEPMINE management.

The paper has also included aspects of the new VUMA software for simulating underground ventilation conditions, this is clearly acknowledged and VUMA management thanked for this permission.

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