

Ventilation requirements of cave mines

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Abstract

Cave mining methods have been used at more than 30 operations globally. Projects are currently underway to plan block cave, panel cave, and sublevel cave operations. Cave mining methods are typically considered at near-vertical orebodies where precious and base metals will be produced. These mining methods are viable options as they offer high production rates and relatively low operating costs. Production footprints are generally concentrated with supporting services like material handling systems, workshops and other services close to the production footprint. These mines start with high upfront costs to access the production footprint before generating revenue at relatively lower operating costs.

Block cave and panel cave mines are established under the controlled collapse of the rock mass under the force of gravity from the bottom up. The block or panel is de-stressed at the apex and undercut levels. The orebody is allowed to cave on the extraction level, and rock is drawn from drawbells as the rock is broken up as it descends as part of the production process. A sublevel cave mine involves drilling and blasting between mining levels and uses a top-down approach to extract the orebody. Sublevel cave mines can start to generate revenue earlier at lower upfront costs. However, production rates achieved in sublevel caving operations are typically lower than for block cave mines.

One of the engineering disciplines requiring a unique approach for block and sublevel cave mining is ventilation. Ventilation designs must ensure production ramp-up is met during the construction phase and that steady-state operations can achieve unconstrained production. Ventilation benchmarking has been developed from the existing mines and provides confidence during the study phase. Benchmarks typically cater for steady-state operations, but the ventilation pinch-point of these cave mines is during the construction phase. Ventilation needs are significantly more during the construction phase than during steady-state operations. The construction phase includes development at the undercut, production, ventilation and ore transport levels and other fixed services that need to be ventilated simultaneously while production is started. Ventilation planning needs to include the construction and steady-state phases considering the mine design criteria to arrive at the required ventilation, potential mechanical refrigeration, and dust management strategies to support employees' safe and healthy underground conditions. As a result of concentrated mining, ventilation-on-demand and controlled partial recirculation of ventilation districts can be considered. During the construction phase, temporary versus permanent refrigeration can be carefully designed to provide production flexibility while keeping capital expenditure to a minimum. Trucking loops, strategic positioning of air coolers, dedicated return airways and airways eliminating worker exposure to dust loading and diesel heat need to be optimally designed. This paper provides design guidelines to arrive at ventilation requirements over life-of-mine to support unconstrained production and the health and safety of workers underground.

Keywords: *ventilation, block cave, sublevel cave, design, requirements*

1 Introduction

Cave mining methods have been used globally at more than 30 operations. Ventilation requirements are often overlooked and need to consider mining design criteria, ore handling systems, water management systems, and the health and safety of workers underground. Cave mining was introduced in the 1870s when the first South African mine was successfully converted to a block cave underground operation (Bartlett, 2010). This approach has become more popular and is typically considered at near-vertical orebodies where diamonds, precious and base metals will be produced. These mining methods are viable options, offering high production rates and relatively low operating costs (Calizaya and Mutama, 2004). Further, block cave, panel cave, and sublevel cave operations are currently in the project planning phase and are applied at porphyry copper, copper-gold, iron, molybdenum ores, and diamond-bearing kimberlite and lamprolite deposits.

Production footprints are generally concentrated with supporting services like material handling systems, workshops, and other services close to the production level. These mines start with high upfront costs to access the production footprint before generating revenue. Block cave and panel cave mines are established under the controlled collapse of the rock mass under the force of gravity from the bottom up. Block cave and panel cave mines are established under the controlled collapse of the rock mass under the force of gravity from the bottom up. The block or panel is de-stressed at the apex and undercut levels. The orebody is allowed to cave on the extraction level, and rock is drawn from drawbells as the rock is broken up as it descends as part of the production process as indicated in Figure 1.

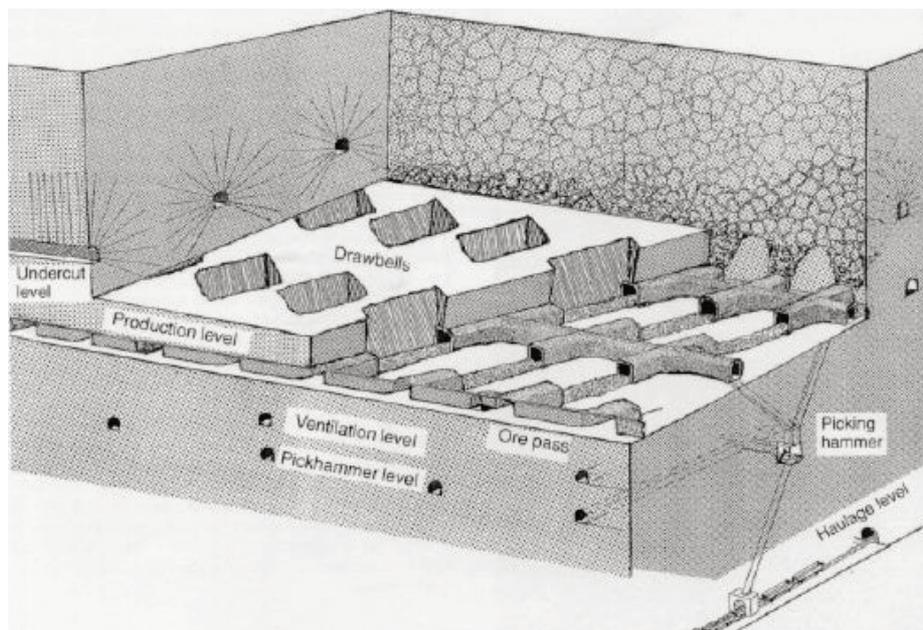


Figure 1 Simplified schematic of block, panel, and incline caving methods (Anon 2011)

A sublevel cave mine involves drilling and blasting between mining levels and uses a top-down approach to extract the orebody shown in Figure 2. Sublevel cave mines can start to generate revenue earlier at lower upfront costs. However, production rates achieved in sublevel caving operations are typically lower than for block cave mines.

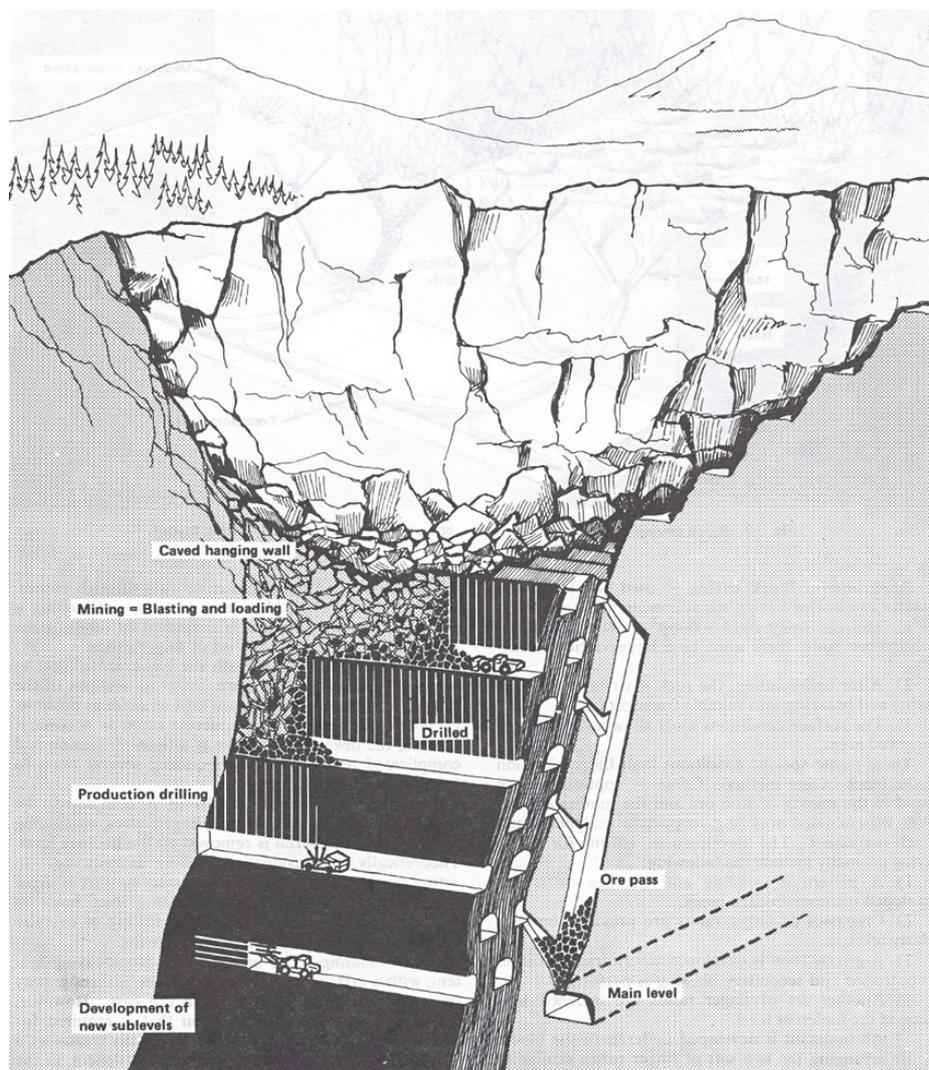


Figure 2 Simplified schematic of sublevel caving methods (Harraz 2015)

2 Ventilation design criteria

Mine ventilation ensures working places and travel ways in an underground mine are adequately ventilated to dilute contaminants and heat to acceptable levels (Howes 2011). Gasses and dust are contaminants that are generally ventilated as applicable. The quantity of air required at a workplace and travel way depends on the source and concentration of the contaminants. Depending on the regulations of a specific country and state, the occupational exposure levels will vary for different contaminants, and therefore contaminant dilution needs to be fit for purpose. In some cases, ventilation can effectively ventilate these areas, while others may need to be supplemented with other controls such as water, surfactants, foams, etc.

Heat dilution in an underground mine is a complicated science that must be carefully considered. Maximum workplace and travel way wet-bulb and dry-bulb temperatures need to be selected at the project's onset and the start of a mine. Cave mines operate at a certain depth (typically deeper than 1,000 m below surface) resulting in high geothermal rock temperatures, use mechanised mobile equipment, and aim at a high production rate to sustain feasible operations. These heat load parameters result in increased air temperatures, which frequently necessitate mechanical refrigeration systems to supplement the beneficial effects of ventilation.

In mechanised mines, using diesel-powered mobile equipment, exhaust gas dilution is typically based on 0.03 to 0.06 m³/s per kW of rated power (at the point of use). The engine type, fuel consumption, and whether any exhaust gas conditioning is used confirm the ventilation needs. Diesel engines are about one-third

efficient at converting the energy available in the fuel to usable power, and most of this is then used to overcome friction.

Ventilation design velocities influence capital (airway size) and operating cost (primary fan pressure). These costs are compared over the mine life to arrive at an economic velocity applicable to an operation. Ventilation design velocities are typically (Calizaya et al. 2005):

- Minimum velocity at 0.5 m/s.
- Conveyor belt relative velocity between 5 and 6 m/s.
- Primary intake airways where personnel travel range between 6 and 8 m/s.
- Primary return airways where personnel travel range between 7 and 10 m/s.
- Dedicated intake airways and shafts range between 12 and 14 m/s.
- Dedicated return airways and shafts range between 18 and 30 m/s.

It is essential that economic velocities are determined and applied to a specific mine site, geographical area and geotechnical constraints. Infrastructure such as conveyor belts, workshops, crushers, and ore transfer points need to be ventilated with fresh air that exhausts directly into return airways without being used in series for other areas.

3 Ventilation benchmarking and modelling

Ventilation quantities need to be carefully calculated considering ventilation design criteria. Ventilation quantities for peak production can be determined using an equation from Howes (2011):

$$\text{Air quantity} = \alpha t + \beta \quad (1)$$

where:

- α = 50 m³/s per Mt/a for block caves and 120 m³/s per Mt/a for sublevel caves.
- β = 50 to 100 m³/s depending on underground services.

Primary ventilation quantities based on Equation 1 need to be adjusted when more than one panel and orebody are produced simultaneously; due to the influence of additional ventilation services. The primary ventilation quantity can also be verified using benchmarking data based on current mining operations (derived from the BBE database), as shown in Figure 3 for block/panel/incline cave mines. Figure 4 shows the ventilation factors used for small, medium and large sublevel cave mines.

Primary Ventilation Benchmarking (Cave Mines)

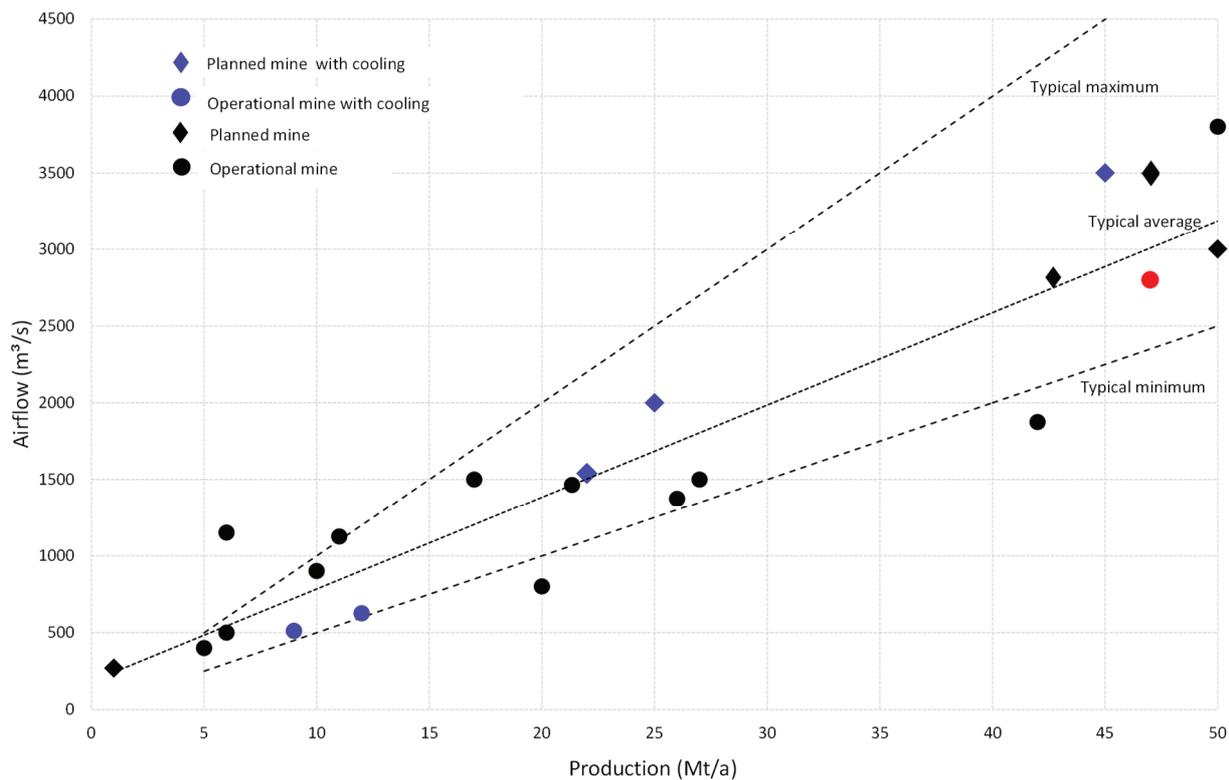


Figure 3 Block/panel/incline cave mines ventilation benchmarks

Primary Ventilation Benchmarking (SLC mines)

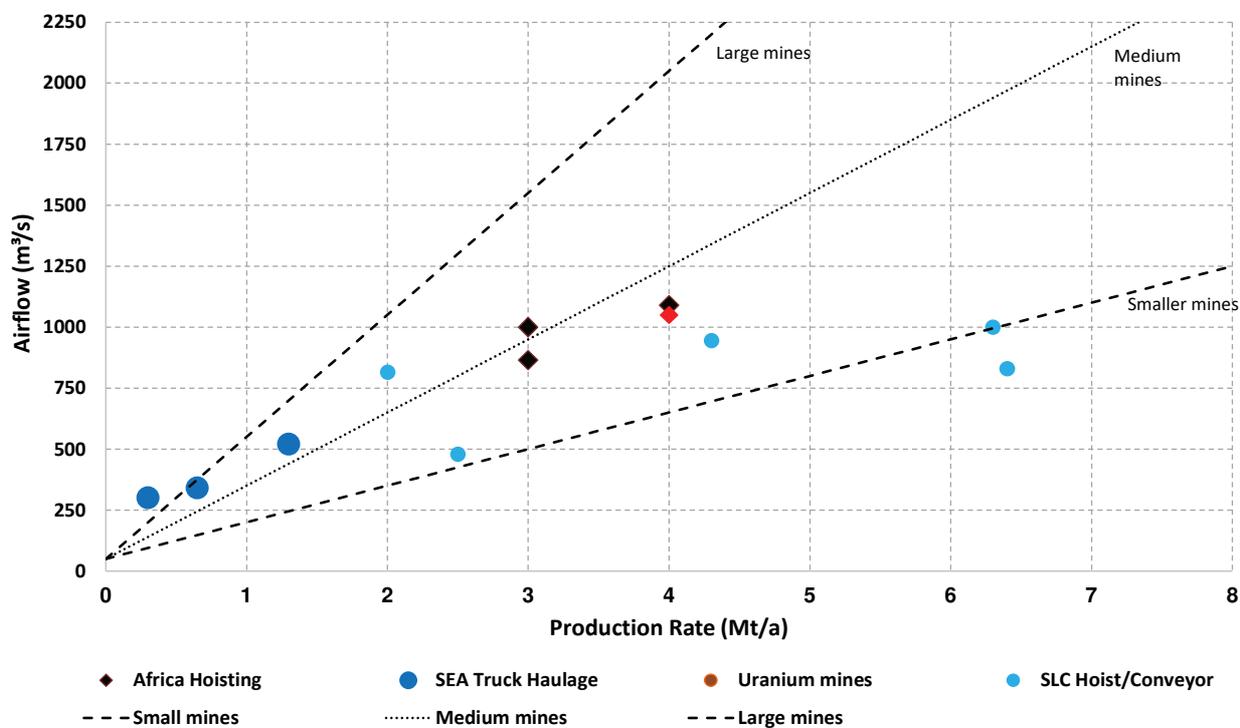


Figure 4 Sublevel cave mines ventilation benchmarks

The calculated primary ventilation quantities need to be modelled using ventilation software to verify that ventilation quantities are sufficient and extend to all workplaces and travel ways. Figure 5 shows a ventilation network for a panel cave and Figure 6 for a sublevel cave mine.

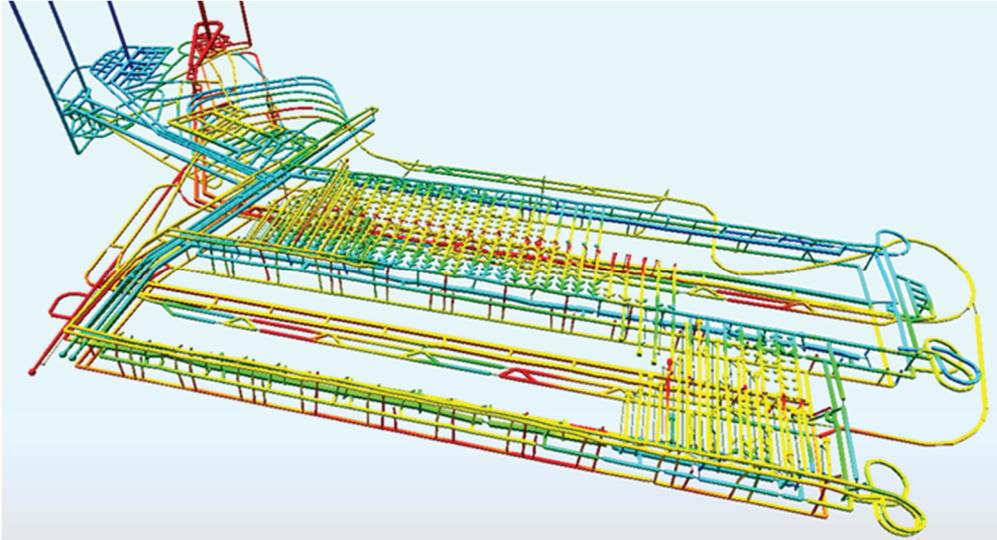


Figure 5 Panel cave mine network model

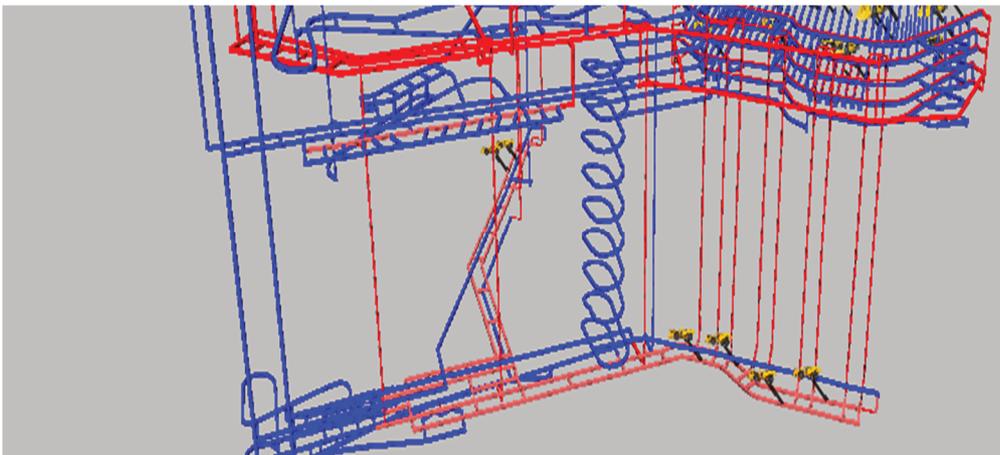


Figure 6 Sublevel cave mine network model

4 Ventilation considerations

4.1 Construction mining phase

The ventilation pinch-point of cave mines is during the construction phase. Ventilation needs are significantly more during the construction phase than during steady-state operations. The construction phase of block/panel/incline caves includes development at the undercut, production, ventilation and ore transport levels, and other fixed services, which all need to be ventilated simultaneously while production is started. Likewise, infrastructure development, production level development, and production ramp-up overlap for sublevel cave mines.

It is typical to have single twin development headings as the only access during this phase. One drive is used for fresh intake air and the other for exhaust return air. Typically, rock transport is by truck whilst crusher, and conveyor belt systems are being installed. Trucks must travel in the return air drift, and the ventilation design must provide adequate airflow velocity (relative to trucking speed). Good ventilation ensures trucks are not overheating or driving in dust clouds and that heat and exhaust gasses are sufficiently diluted. Airflow

velocity must be kept to the design criteria in the intake drive to ensure safe conditions. The intake barrel is used for the workforce to access underground to construct conveyors, electrical equipment bays, refuge chambers, cooling installations, storerooms, and workshops.

Figure 7 shows twin haulages require connecting crosscuts at regular intervals to allow through-ventilation during development, refuge locations, re-mucking, storage, etc. These inevitably become leakage paths due to the air pressure difference between intake and return (Calizaya et al. 2005). Connecting crosscuts have to be sealed appropriately to minimise primary air leakage. The primary airflow quantity will be governed by velocities and will subsequently determine the allowable rate of development once levels are opened up.

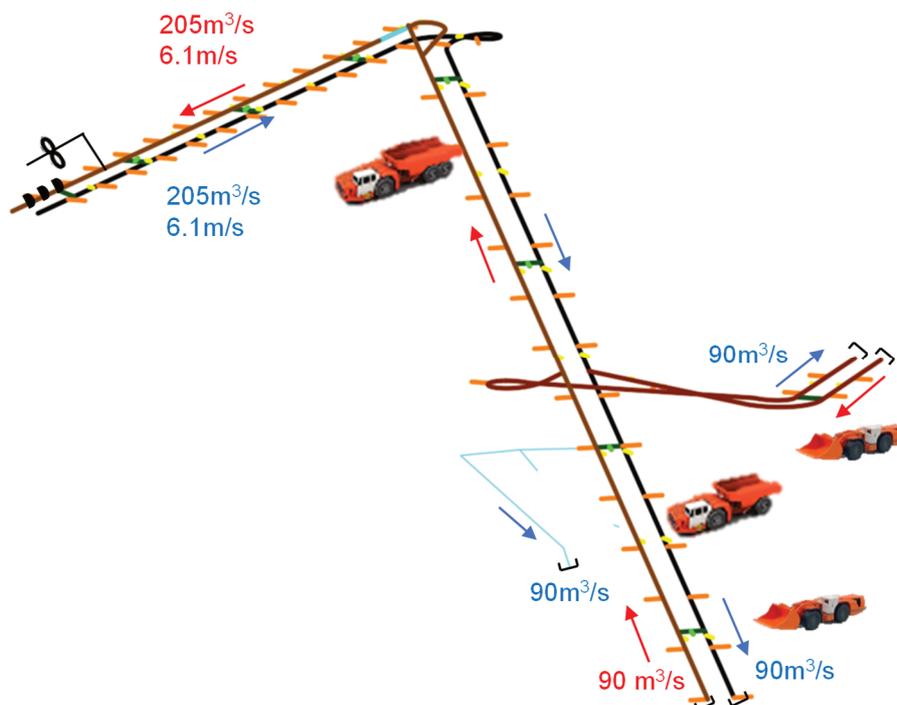


Figure 7 Typical twin decline development ventilation layout

Fixed-time multi-blast firing is generally applied at cave mines. In some cases, when development and/or production rates need to be increased, multi-blast conditions may be required. Multi-blast ends require additional ventilation and forced-exhaust overlap secondary ventilation systems to cater for the overlap ventilation quantity. Under these mining conditions re-entry periods need to be minimised, and the ventilation design needs to fully consider the dynamics of blast fume throw-back and clearing mechanisms.

Secondary ventilation systems are challenging to design and operate during the capital development phase. During development, auxiliary fans and ducting have to be moved forward continuously. Once the levels are opened up, many ends have to be ventilated simultaneously. It is sometimes inevitable to ventilate ends in series, and heat and diesel exhaust gas build-up must be controlled carefully. Figure 8 shows a typical capital development layout where a decline and production level are developed.

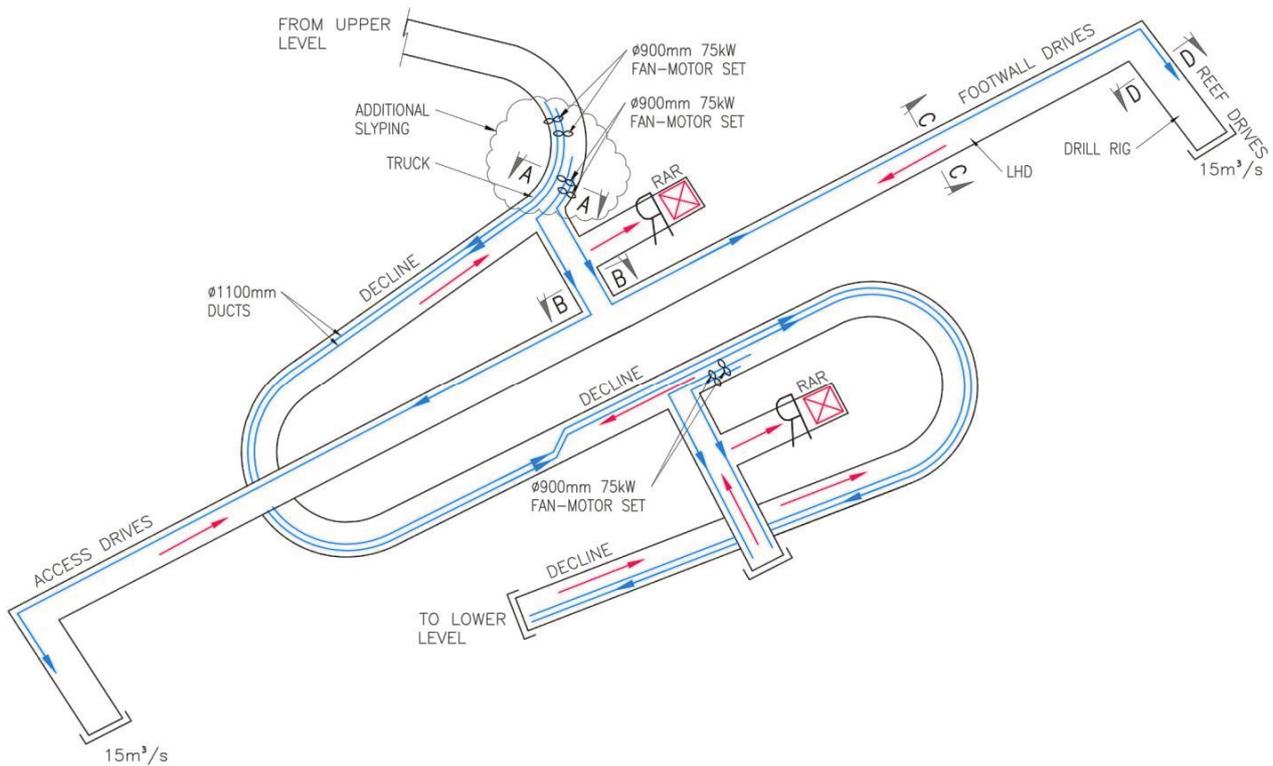


Figure 8 Typical capital development ventilation layout

Selection of secondary fans and ducting is essential as it needs to serve short development ends (below 50 m), medium development ends (200 m to 400 m), and long development ends (above 600 m) before through ventilation between intake and return systems are established. Long development ends will require a loader and a truck with two twin fans and ducts to adequately ventilate contaminants and heat. Short and medium development ends can be adequately ventilated with a single fan and duct.

Mechanised equipment is mainly used in cave mines and will frequently introduce a heat load near or above the thermal design criteria. Therefore, a heat stress management programme must be developed that includes heat tolerance screening, work-rest cycles, and nutrition and hydration regimes, allowing thermal design conditions to be adjusted upwards. As part of this programme, shift cycles should also be assessed to ensure safe and healthy practices are employed. Functional work assessment could be implemented in addition to the above to provide overall physical work fitness (Hofmann & Kielblock, 2007).

The opportunity exists to change thermal design criteria temporarily by having interim design criteria approved by regulators. However, this is a risky practice and requires extensive risk assessments and control to protect the mine owner and workers in case of heat stress incidents.

Spacing of refuge chambers is critical to ensure accessibility during an emergency from all working areas. Travelling time to refuge chambers should fall within the duration of self-contained self-rescuers capacity and depends on whether the escape route is up or down a decline.

4.2 Permanent mining phase

Block-cave operations require continuous production to ensure the caving process are not stop unnecessarily. For sublevel cave mines, production starts when the production drive development is complete. Sublevel caves are generally started 40 m to 60 m below the bottom of the pit and in other instances a few hundred metres below surface. Some top levels risk holing into the pit sidewall and increasing loader driver hanging wall/back failure risk. Subsequently, ventilation will short circuit through those levels, and controls will be crucial during these events.

Cave mines have a very concentrated nature of mining, meaning that large amounts of pollutants are generated in a relatively small area (Calizaya et al. 2004). Diesel exhaust gas is caused by a large fleet of loaders concentrated in the production level footprint. Adequate air quantities to dilute exhaust gas must be supplied to every loading crosscut due to the frequent loading required from all drawpoints to ensure continuous and controlled caving of the orebody.

Substantial quantities of dust are generated during loading, transport, and tipping operations (Calizaya et al. 2004). Adequate air velocities and quantities are essential to ensure acceptable dilution and relative vehicle speeds to avoid overheating and driving in dust clouds. Carefully designed spray systems must be used at loading and tipping points to control dust to satisfactory levels. Another consideration is the necessary airflow velocities for the proper scouring of drawpoints to remove heat, dust and gases.

Cave mining layouts, in general, require a simple intake and return infrastructure network due to the concentrated nature of the extraction area, however, the production footprint consists of many loading levels and crosscuts in parallel resulting in a low-pressure mining zone. The challenge is balancing airflow between levels and crosscuts to ensure equal flow (Duckworth et al. 2004).

One of the biggest challenges of cave mining is the cooling system. These mines are generally deep, but conventional cooling systems used in hard rock mining do not always apply. It would naturally be assumed that surface bulk air cooling would be the best option for the depth; however, the positional efficiency of these systems is not always suitable for the concentrated type of mining. Surface bulk air cooling results in intake systems being over cooled while the production footprint's extremities exceed thermal reject temperatures. Cooling of cave mines should ideally be positioned near the production footprint since the majority of heat is concentrated here, as shown in Figure 9 (Marx et al. 2010; Bluhm et al. 2014).

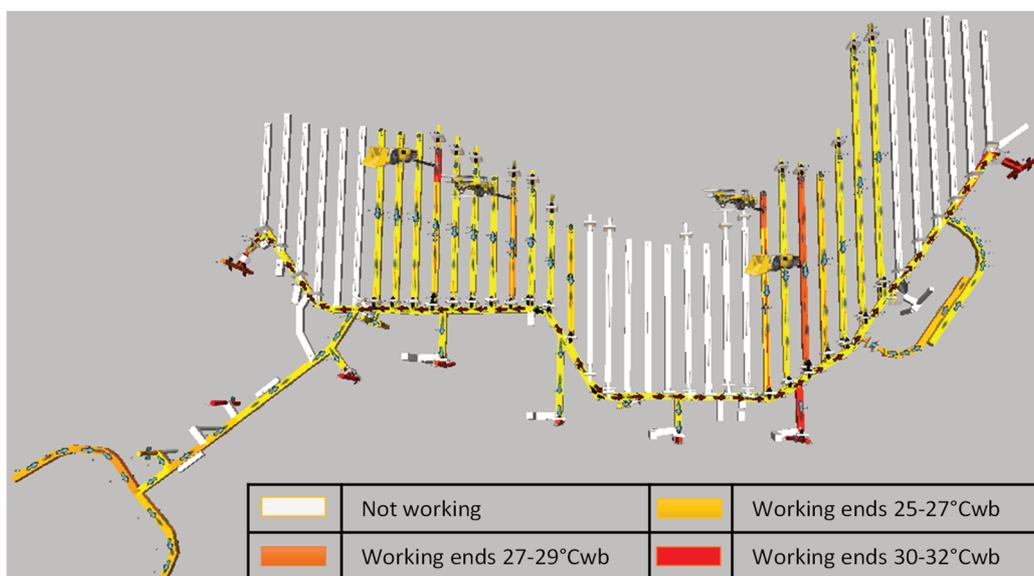


Figure 9 Schematic of temperature profile across a production footprint

Energy balance calculations of the production level should include the significant heat from broken rock being transported along loading crosscuts from drawpoints. The next heat source to consider is that of the crushers. The heat from the conveyor system is complex and includes heat from the conveyor motor drives and broken rock as it travels along the conveyor drive.

Loaders tip ore into crusher feeding bins parallel with the main intake drives. Airflow naturally wants to equalise in parallel airways, resulting in excessive velocities in the tipping area. Dust from tipping is therefore not contained to the tip but conveyed to the intakes of downstream loading crosscuts. Well-engineered airflow control designs are required at the tipping points to resolve potential complications (Wallace et al. 2014).

Cave mines generally make use of conveyor belt transport systems to handle the high production rate. In addition, these belts are operated at reasonably high speeds; hence the counter-flow air velocity over the belts has to be kept low, which is challenging to regulate and control (Duckworth et al. 2004).

4.3 Services

Crusher ventilation systems can be controlled using ventilation and dust suppression systems (Wallace et al. 2014). Control systems typically include bratticing, air curtains, auxiliary fans and ducts, water sprays, etc. An adequately designed crusher ventilation system effectively captures dust generated by tipping and crushing operations and directly removes pollutants, including heat, to a return airway. Figure 10 shows a design for a four-access crusher tip.

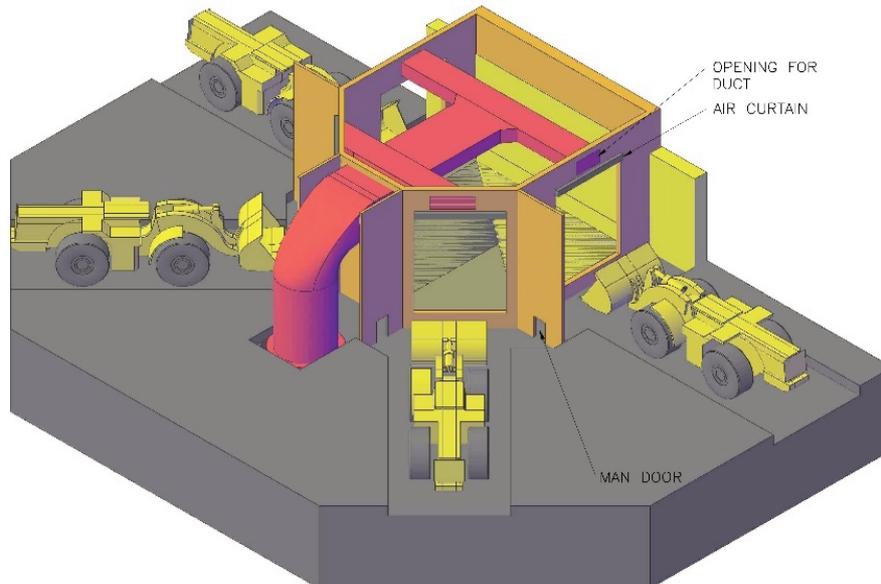


Figure 10 Four-access crusher tip ventilation design

4.4 Ventilation-on-demand

Due to the nature of cave mining, concentrated mining and high production rates, many production drives need to be ventilated to support the mining cycle. To effectively distribute the available ventilation, ventilation-on-demand techniques should be considered. Ventilation-on-demand systems can be established using series or parallel installed secondary ventilation systems. These systems usually consist of secondary ventilation fans or duct control devices that control the amount of air supplied to a specific production drive and production area to effectively ventilate a mining activity (loader, drill rig, others) (Figure 11).

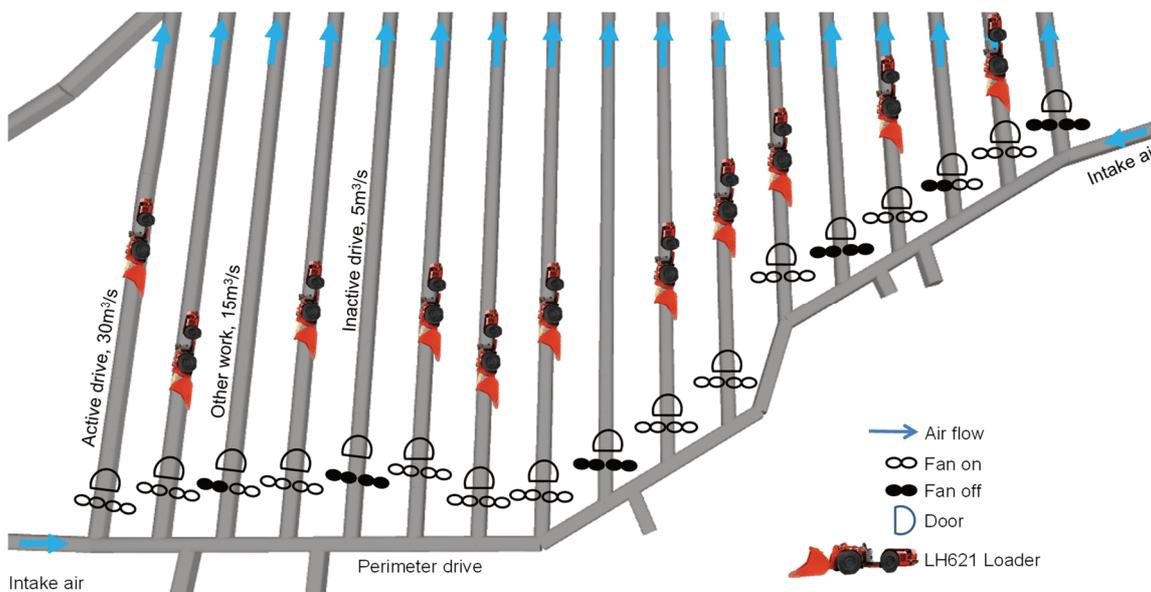


Figure 11 Typical ventilation-on-demand ventilation layout

These systems must consist of monitoring and control equipment to increase/decrease ventilation air when required. When vehicles enter an area, airflow can be increased to ensure adequate dilution. Design and maintenance of control systems can be challenging but will provide huge capital and operating cost savings if maintained and monitored correctly.

4.5 Controlled partial recirculation of specific ventilation districts

Mass caving mines provide an opportunity to recirculate reconditioned air due to their concentrated mining as is done at Palabora Mining Company (Marx et al. 2010). This is due to the proximity of primary intake and return airways, typically on one side of the production footprint. This process is commonly known as controlled partial recirculation, see Figure 12.

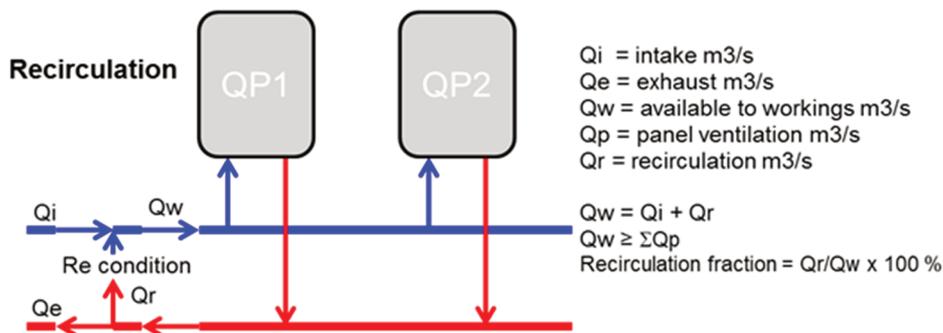


Figure 12 Typical controlled partial recirculation ventilation layout (Hooman et al. 2015)

Controlled partial recirculation reduces the overall air requirement to be down-casted from surface with some savings in infrastructure, main fan power and heat from auto-compression. Typically, a recirculation fraction of no more than 30% should be used (Hooman et al. 2015). The recirculation fraction is defined as the ratio of recirculating air to total ventilation reaching working places $Q_r/Q_w \times 100\%$, e.g. 350 kg/s (Q_i) from the intake shaft(s) with 150 kg/s (Q_r) recirculating provides 500 kg/s total with a recirculation fraction of $Q_r/Q_w = 150/500 = 30\%$.

In controlled partial recirculation systems, the air must be reconditioned by cooling and scrubbing contaminants. An open spray chamber is an ideal system to provide both; however, additional controls such as atomising sprays will be required to capture the finer dust particles. The water quality must be carefully

monitored to keep mud loads within acceptable limits by removing contaminated water by blow-down or removal of mud via settlers.

Some contaminants are significantly more complex to manage, such as radon, flammable gas, diesel particulate matter, and carbon monoxide. Controlled partial recirculation is not recommended for mines with high concentrations of these contaminants. In addition, controlled partial recirculation should typically be turned off during a blast to ensure blasting fumes are not circulated back into the footprint.

Highly specified and well-maintained safety systems will be required to monitor the levels of contaminants in the recirculated air and stop recirculation (by turning off fans) when pre-selected alarm levels are exceeded. These systems will also be essential to mitigate the risk of recirculating smoke in the event of a fire.

5 Conclusion

Cave mining methods are implemented across the globe and provide attractive business cases for mines. These mines typically have steeply dipping orebodies that can be extracted via block/panel/incline cave, sublevel cave, etc., mining methods. Some important ventilation design considerations were discussed in the paper and can be applied to all these cave mining operations during the planning and steady-state optimisation phases.

Ventilation design criteria form the basis of the design and need to be available as planning starts. The primary and secondary ventilation designs can then be commenced once the mine design is complete. Some unique opportunities for these mines are ventilation on demand and controlled partial recirculation of specific ventilation districts. These opportunities frequently exist due to the nature of concentrated mining over a low number of production levels and/or drives, and are continually considered to optimise ventilation requirements provided it can be implemented safely.

Considering all design aspects listed above will allow the mine to accurately determine an optimal ventilation design that is fit-for-purpose, safe for personnel, and will provide huge economic advantages to the mining company.

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