MANDELA MINING PRECINCT
MINDS FOR MINES

TECHNICAL SERVICES OPTIMISATION

Work Package 4.3.2: Ventilation Design Optimisation

Draft Final Report

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LIST OF ABBREVIATIONS

ANFO	:	Ammonium Nitrate and Fuel Oil
ASD	:	Advance Strike Drive
ASG	:	Advanced Strike Gully
Ag	:	Silver
Au	:	Gold
BC	:	Bushveld Complex
BEV	:	Battery Electric Vehicle
BIC	:	Bushveld Igneous Complex
BIF	:	Banded Iron Formation
CAPEX	:	Capital Expenditure
CG	:	Centre Gully
cm	:	Centimetre(s)
CLR	:	Carbon Leader Reef
COP	:	Code of Practice
CSDP	:	Closely Spaced Dip Pillars
°	:	Degree(s)
DTH	:	Down-the-Hole
DEE	:	Diesel Exhaust Emissions
DSS	:	Development Service Strategy
ERR	:	Energy Release Rate
FCEV	:	Fuel Cell Electric Vehicles
Fe	:	Iron
FOG	:	Fall of Ground
HLGE	:	Haulage
HPE	:	Hydro Power Equipment
hrs	:	Hour(s)
i.e.	:	Id Est (in other words)
JV	:	Joint Venture
km	:	Kilometre(s)
kN/m2	:	Kilo-newton(s) per square-metre
ktpm	:	Kilotons per month

Kt	:	Kilotons
LTIFR	:	Lost Time Injury Frequency Rate
mm	:	Millimeter(s)
m	:	Meter(s)
m^2	:	Square-meter(s)
min	:	Minute(s)
MJ/m^2	:	Mega-joule(s) per square-metre
MPa	:	Mega-Pascal
MRM	:	Mineral Resource Management
MSB	:	Massive Sulphide Body
OPEX	:	Operational cost
RDO	:	Rock Drill Operator
ROI	:	Return on Investment
RMR	:	Rock Mass Rating
RSE	:	Raise or Raise-line
VOD	:	Ventilation on Demand
VRT	:	Virgin Rock Temperature
WRR	:	Wide Raise Rig
X-cut	:	Crosscut
XLP	:	Extra Low Profile

1 INTRODUCTION

1.1 Executive Summary

Underground narrow reef hard rock mines are experiencing lower profit margins or running at a loss due to production process inefficiency. Conventional mining methods are labour intensive and face time is getting ever shorter due to workplace distance from the shaft stations. This results in poor quality work that results in inefficient blasting, less than expected face advance, and spiralling production costs. A novel mining method is required to address these challenges. This report covers work package 4.1 of the MDB programme, which entails the following:

- A review of existing narrow reef hard rock mining equipment technology in drilling, charging, blasting, temporary support, cleaning, tramming, engineering services, and any existing concept designs.
- The review of the existing support from the services will support the novel mining method in terms of the new technology related to drilling, charging, and blasting; and new engineering equipment will ensure a fully mechanized drill and blast operation.

One of the most important aspects of underground hard rock mining is ventilation. Ventilation is the primary method of clearing hazardous gases and/or dust which are created from drilling and blasting activity (e.g., silica dust, NOx), diesel equipment (e.g., diesel particulate, carbon monoxide), or to protect against gases that are naturally emanating from the rock (e.g., radon gas). Ventilation is also used to manage underground temperatures for the workers. In deep, hot mines ventilation is used to cool the workplace; however, in very cold locations the air is heated to just above freezing before it enters the mine. Ventilation raises/holes are typically used to transfer ventilation from the surface to the workplaces and can be modified for use as emergency escape routes. The primary sources of heat in underground hard rock mines are virgin rock temperature, machinery, auto compression, and fissure water. Other small contributing factors are human body heat and blasting.

1.2 Background

This report will summarize the information gathered from the literature review thus far. The economics of any mining project is fundamental to its success and is the main driver in applying new technologies and processes. Therefore, one needs to take cognizance of the following:

- Expert knowledge of the orebody and its characteristics.
- The designated mining and processing methods are a consequence of orebody characteristics and technology "fit".
- Technology selection defines Capex and Opex profiles.
- Ensure superior performance through competent leadership and operational excellence.

In any fiscal analysis, one needs to understand the same production output.

- The CAPEX requirement.
- The OPEX requirement.
- Production ramp-up.
- Tail management.
- The overall ROI.

Finally, it is clear to summate that the deeper the mine, the more pronounced is the Safety, Productivity, and Project risk. This phenomenon is directly translated into ventilation and cooling complexities and costs, both in terms of OPEX and CAPEX. Some factors affecting the mining method which need to be taken into consideration are (Table 1).

Table 1: Geology influences on mining methods (Anglo Platinum Investor Presentation,)

Underground Methods	Unsupported					Supported		Caving		
Factor	Narrow Tabular	Room & Pillar	Stope & Pillar	Shrinkage Stoping	Sublevel Stoping	Cut & Fill Stoping	Square Set Stoping	Longwall Stoping	SubLevel Caving	Block Caving
Ore Strength	Moderate /Strong	Weak/ Moderate	Moderate/ Strong	Strong	Moderate/ Strong	Moderate/ Strong	Weak	Any	Moderate/ Strong	Weak/ Moderate
Rock Strength	Strong	Moderate/ Strong	Moderate/ Strong	Strong	Fairly Strong	Weak	Weak	Weak / Moderate	Weak	Weak / Moderate
Deposit Shape	Tabular	Tabular	Tabular / Lenticular	Tabular / Lenticular	Tabular / Lenticular	Tabular / Irregular	Any	Tabular	Tabular / Massive	Massive / Thick
Deposit Dip	Low/ Moderate	Low / Flat	Low / Moderate	Fairly Steep	Fairly Steep	Fairly Steep	Any	Low/ Flat	Fairly Steep	Fairly Steep
Deposit Size	Large / Thin	Large / Thin	Any	Thin / Moderate	Thick / Moderate	Thin / Moderate	Usually Small	Thin / Wide	Large Thick	Very Thick
Ore Grade	High	Moderate	Low / Moderate	Fairly High	Moderate	Fairly High	High	Moderate	Moderate	Low
Ore Uniformity	Uniform	Uniform	Variable	Uniform	Uniform	Variable	Variable	Uniform	Moderate	Uniform
Depth	Shallow / Deep	Shallow / Moderate	Shallow / Moderate	Shallow / Moderate	Moderate	Moderate/ Deep	Deep	Moderate/ Deep	Moderate	Moderate

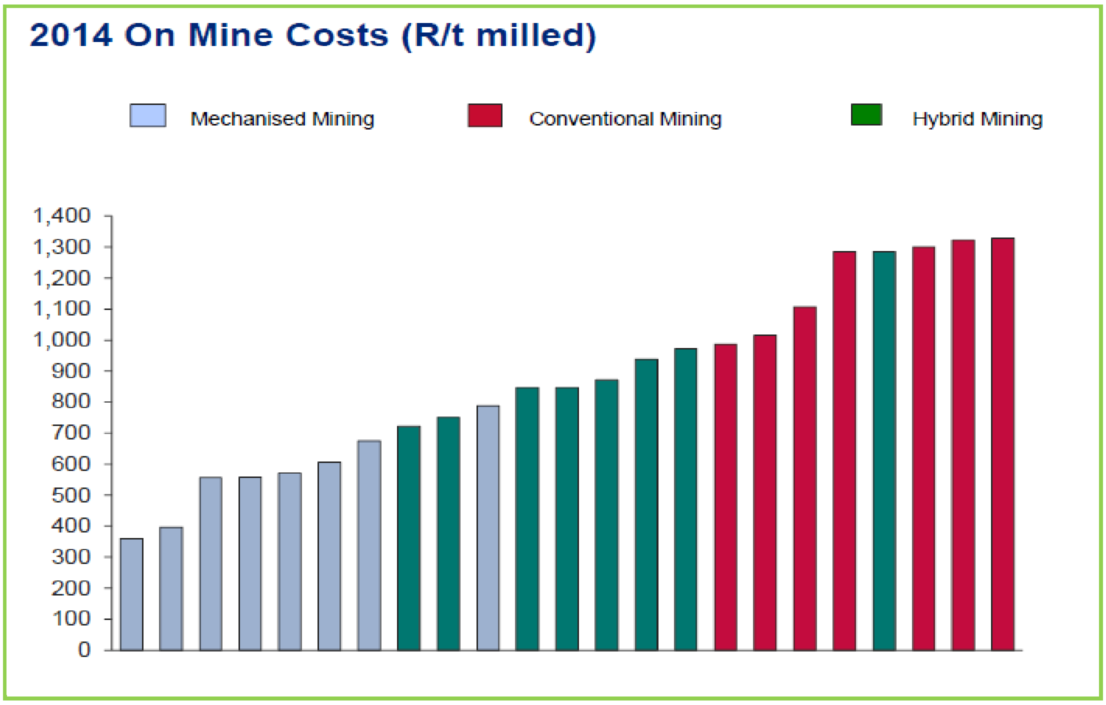

Figure 1: Costs Influencing Mining Method (Anglo Platinum Investor Presentation)

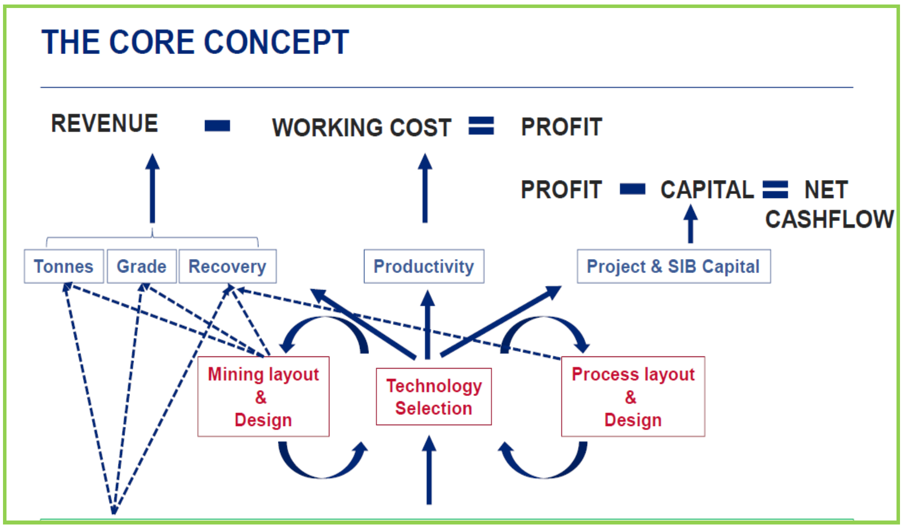

Figure 2: Core Concept (Anglo Platinum Investor Presentation,)

From the above analysis (Figure 2) it is clear that mechanised mining or hybrid mining should be the obvious area of focus.

Of importance, albeit that ventilation plays a pivotal role in the mining method chosen, it is not the dominant factor in the selection of the mining method to be deployed. It is therefore of paramount importance that the ventilation engineer is part of the whole mining design to integrate practical fit for purpose ventilation designs early on in the mining design process.

1.3 Study Objectives

Table 2 shows the objectives of Work Package 4.3.2.

Table 2: Work Package 4.3.2 Objectives

Deliverable Product	Milestones		Start Month	End Month
	No	Activity		
Guideline to the application of Ventilation Design in an underground mining environment for - Maximising Ventilation utilisation - Mechanised Ventilation Strategy	4.3.2.1	Literature review on existing Vent designs for every mechanised mining method with specific measure to: - Vent system utilisation	May-2020	Jun-2020
	4.3.2.2	Industry workshops **Day 1:** Learnings of failures and successes and establish criteria and guidelines for future ventilation design and strategy specifications and requirements **Day2:** Challenge Engineers and OEM's to conceptual design ventilation designs according to criteria, guidelines and requirements	Jul-2020	Aug-2020
	4.3.2.3	Draft guideline for Best Practice applications of mechanised ventilation strategy	Sep-2020	Nov-2020
	4.3.2.4	Approval of Guideline by TSC	Dec-2020	Feb-2021

2 LITERATURE REVIEW

2.1 Mining Methods

The current mechanised mining practice for narrow reef hard rock mines are explained in detail under Work Package 3: Narrow reef hard rock mines Concept Designs. The following is a brief overview of the basic concepts.

2.1.1 Current Mining Systems for Mechanised mining

The following publication, UNDERGROUND MINING METHODS, AND EQUIPMENT by S. Okubo and J. Yamatomi (Okubo, 2015), is an excellent rendition of the main mining methods available and affirms that a deep understanding of the geology is one of the main drivers in mining method selection.

Taking cognisance of the importance of ground support, underground mining methods are categorized into three classes based on the extent of support required: unsupported, supported, and caving.

2.1.2 Unsupported Methods

Unsupported methods are essentially naturally or self-supported and require no major artificial system of support to carry super-incumbent loads, instead of relying on the natural competence of the walls of the openings and pillars. This definition of unsupported methods does not exclude the use of rock/roof bolts or light structural sets of timber or steel, provided that such artificial supports do not significantly alter the load-carrying ability of the natural structure. The followings are considered unsupported methods:

- Room-and-pillar mining.
- Shrinkage stoping.
- Sublevel stoping.

Of the unsupported methods, room-and-pillar mining is employed for the extraction of flat-dipping and tabular deposits, whereas shrinkage and sublevel stoping is applied to vertical or steeply inclined ore bodies. However, with rising costs, this method has been largely displaced by sublevel stoping and cut-and-fill.

2.1.3 Supported Methods

Supported methods require substantial amounts of artificial support to maintain stability in exploitation openings, as well as systematic ground control throughout the mine.

Supported methods are used when production openings (stopes) are not sufficiently stable to remain open during operation, but the opening is required to be held open to prevent caving or surface subsidence. In other words, the supported class is employed when the other two categories of methods, unsupported and caving, are not applicable. The supported class of mining methods is intended for application underground conditions ranging incompetency from moderate to incompetent. The design of artificial support systems to provide varying degrees of controlled wall closure and ground movement and evaluation of the load-carrying capacity of the natural rock structure is a prerequisite. The most satisfactory forms of artificial support are backfilling/stowing, timbers/stulls, cribs/packs, and hydraulic/frictional props.

There are three specific methods in the

- Cut-and-fill stoping.
- Stull stoping.
- Square-set stoping.

Cut-and-fill and stull stoping is intended for moderately competent rock, whereas square-set stoping is suitable for the least competent rock.

2.1.4 Caving

Caving methods are defined as those associated with induced, controlled, massive caving of the ore body, the overlying rock, or both. The exploitation workings in caving methods are designed to collapse, with intentional caving of the ore and/or host rock. The three major caving methods are:

- Sublevel caving.
- Block caving.

Because the exploitation openings are intentionally destroyed in the progress of mining, the caving class is truly unique. Rock mechanics principles are applied to induce caving rather than to prevent the occurrence of caving. Moreover, development openings have to be designed and located to withstand moving and caving ground. Surface subsidence is inevitable and must be allowed for in the case of sublevel and block caving. Production must be maintained at a steady and continuous level to avoid disruptions or stoppages in the caving activity. Highly advanced mining technology, as well as experienced management, is indispensable to a successful caving operation.

2.2 Optimisation of Ventilation Designs

2.2.1 Shaft Designs and Diameter

The progression shafts are indicated in

Figure 3: The progression of shafts (Anglo Platinum Investor Presentation,). This indicates the evolution of access to the orebody starting where the reef outcrops.

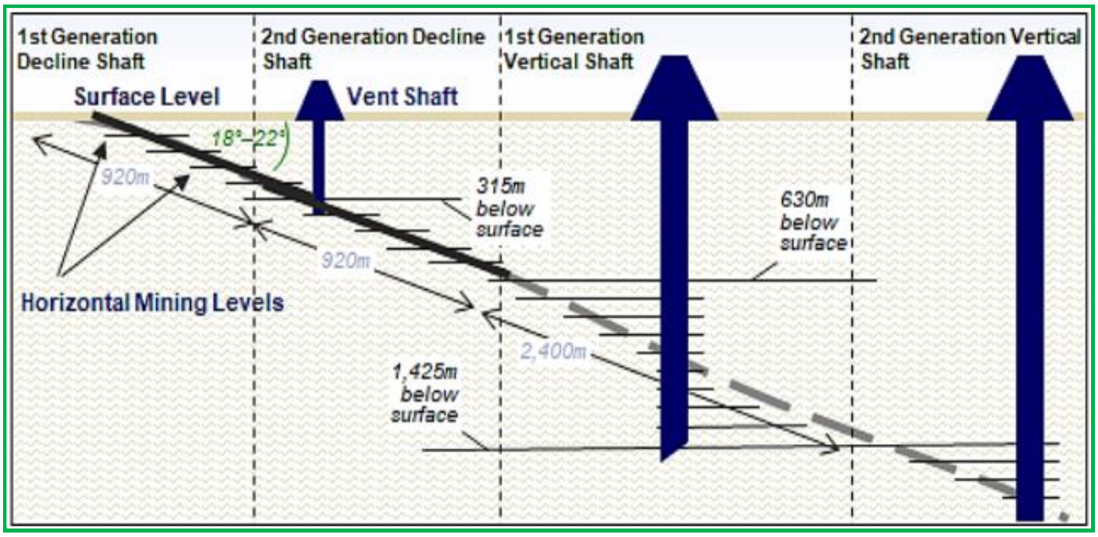

Figure 3: The progression of shafts (Anglo Platinum Investor Presentation,)

There is a myriad of factors affecting the shaft designs. The ventilation requirements normally supersede excavation sizes required for people and material. The size of any excavation should be subject to an economic evaluation, which fits into the design criterion as recorded in Appendix 1. These design parameters are based on safety factors where people travel or work, and on economic factors in other areas.

For every airway in a mine, there is optimum air velocity. This velocity is essentially based on a trade-off between the mining cost and the power cost. The power cost is, in turn, proportional to the air quantity flowing through the airway and the resistance to airflow in the airway. The resistance to airflow is dependent on several factors such as the dimensions, length, and friction factor. The friction factor (also termed 'Atkinson factor') is a measure of the "roughness" of the tunnel and is variable depending on the mining method used and the type of support employed.

It may be desired to limit the air velocity in an airway for reasons other than economic (i.e. minimising airborne dust).

A typical optimisation analysis of airways assumes a fixed air quantity that is required to flow in an airway. Calculation of the mining cost for various sizes is done and plotted as well as a representation of the power cost (generally a present value figure for the life of the airway is used). Adding these two costs leads to a curve that has a minimum value (cost) at some value for the size or area. A graphical representation of this type of analysis is shown in Figure 4 and Figure 5.

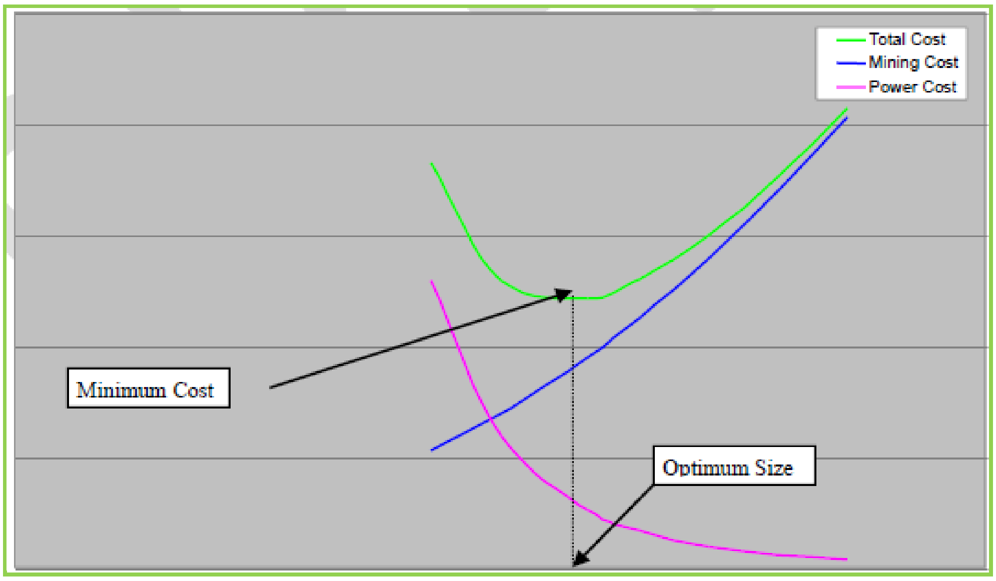

Figure 4: Optimisation of Shafts

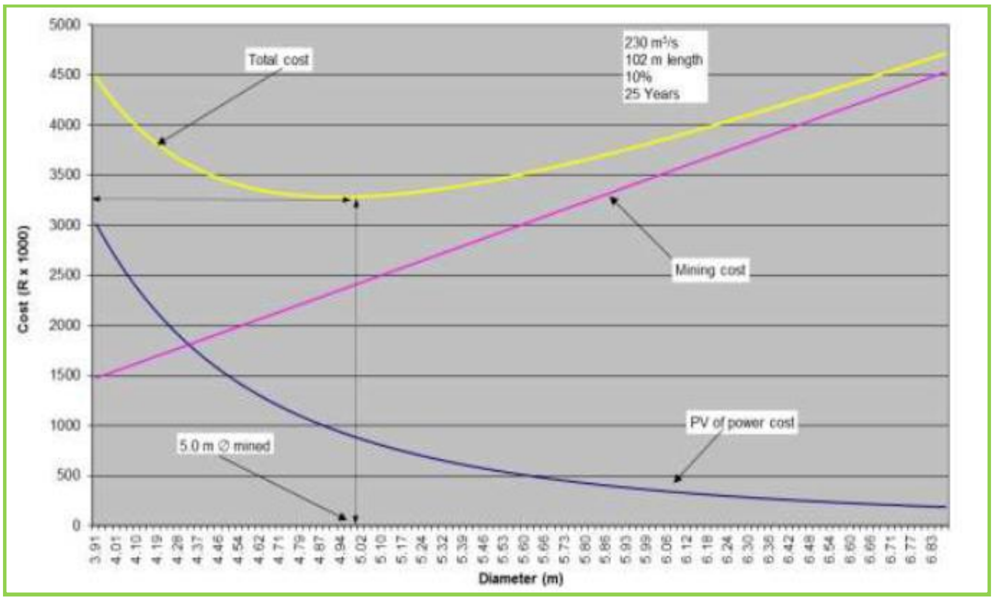

Figure 5: Cost versus diameter

2.2.2 Critical Velocity Zone in Up-cast Shafts

It is generally accepted that in mine ventilation the pressure loss in an airway is proportional to the square of the air volume flowing, except at very low Reynolds numbers which rarely occur in practice.

The air which has passed through the working areas of a mine is usually saturated with water vapour by the time it reaches the bottom of the upcast shaft. As the air rises in the shaft, the barometric pressure to which it is subjected diminishes, and consequently the temperature of the air decreases. This results in water being condensed out of the air. In a deep up-cast shaft carrying a large volume flow rate of air, several thousand liters of water can be condensed per hour.

The water condenses as very small droplets which give the air a foggy appearance. As the air rises, more water condenses onto these small droplets and they gradually grow to larger drops. The terminal velocity of large drops of water, i.e. drops of over 3 mm diameter, is about 8 m/s. This means that if the air travels up the shaft at much less than 8 m/s, these drops will fall whereas if the air is travelling much faster than 8 m/s, they will be carried up the shaft.

If the velocity is about 8 m/s the drops will tend to stay suspended in the air until they strike the sidewall and run down it as a stream, or until they become still larger and fall through the air. Smaller drops will tend to remain suspended in the air up-casting at, say 7 m/s, but will fall out when they grow larger.

The condensed water drops cause only a very slight increase in shaft resistance due to their mass and to the obstruction they create to airflow. However, if the air velocity is such that drops of certain sizes are suspended in the air or move very slowly up or down the shaft, the concentration is sometimes increased to such an extent that a very considerable increase in shaft resistance and pressure results.

The position can be even more serious in cases where water is “made” in the shaft, i.e. where water issues from the rock.

It has been shown by experiment that the most dangerous air velocity is about 8 m/s and this is called the critical velocity. However, this is not an exact figure and it is affected by various factors.

Furthermore, the air velocity in a shaft varies inversely as the density of the air at any particular point in the shaft, and if the velocity at the top of a deep shaft is 10 m/s it may well be 8 m/s at some point near the bottom of the shaft. The whole range of air velocities from 7 m/s to 12 m/s is therefore regarded as a critical range for up-cast shafts and when designing a shaft it is advisable to design it either for a velocity of less than 7 m/s or for more than 12 m/s so that the water will either fall or be carried up the shaft and will not remain suspended in the air. (Stanton 2020).

2.2.2.1 Advantages and Disadvantages of Fans running in Force/Exhaust Mode

In designing the main ventilation infrastructure of a mine, a primary decision is whether to connect the main fans to the up-cast shafts, i.e. an exhausting system or to connect the main fans to the downcast shaft to provide a forcing or blowing system. These choices are illustrated in the figures below.

From the time of the shaft bottom furnaces of the nineteenth century, the up-cast shaft has, traditionally, been regarded as associated with the means of producing ventilation. Most mines are ventilated using the exhaust system. An examination of the alternatives continues to favor a primary exhaust system in the majority of cases. The choice may be based on the following four concerns.

2.2.3 Gas Control

Air pressure in the subsurface is depressed by the operation of an exhausting main fan but is increased by a forcing fan. The difference is seldom more than a few kilopascals. As strata gases are, typically, held within the rock matrix at gauge pressures of 1 000 kPa or more, it is evident that the choice of an exhausting or forcing system producing a few kilopascals will have little effect on the rate of gas production from the strata.

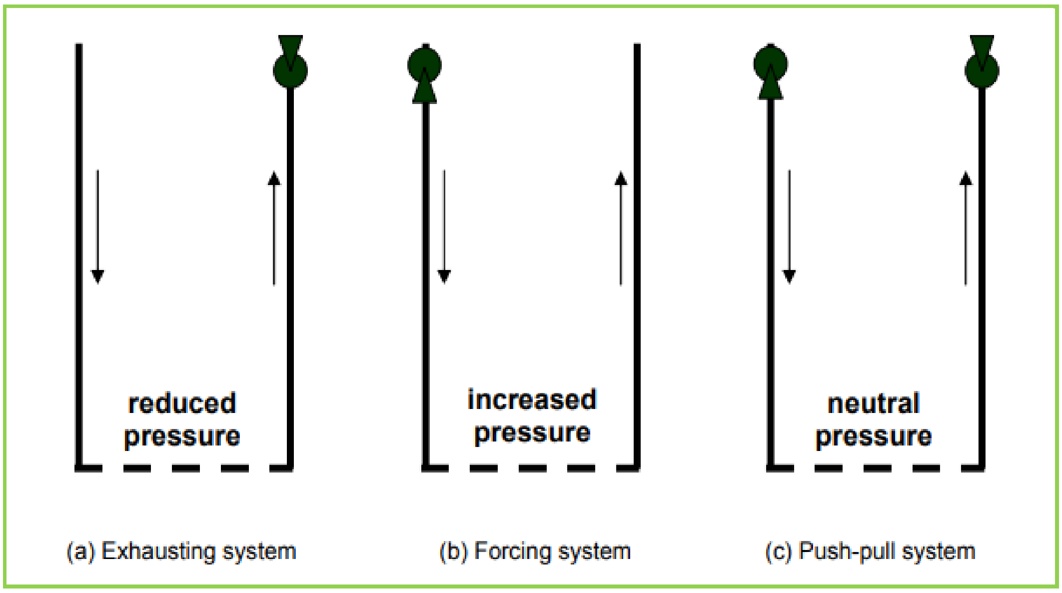

Figure 6: Ventilation Systems

Steady-state operation of either exhausting or forcing fans will produce no changes in air pressure in the subsurface. However, consider the situation of the stoppage of a forcing fan. The barometric pressure throughout the ventilation system will fall rapidly. Accumulations of voidage gas will expand and flood into the workings at the worst possible time i.e. when the airflow is considerably diminished, causing a peak concentration of gas. Conversely, when a main exhausting fan stops, air pressure in the system increases, compressing accumulations of gas. Hence, no peak of general body gas concentration occurs within the airstream.

It is true that when the main exhaust fan restarts, the sudden reduction in barometric pressure will then cause the expansion and emission of accumulated gas. However, this occurs at a time of full ventilation and the peak of gas concentration will be much less than that caused by the stoppage of a forcing fan. A consideration of strata gas control favors a primary exhausting system.

2.2.4 Transportation

The choice between main forcing and exhausting systems should take into account the preferred routes for the transportation of minerals, personnel, and materials. Ideally, conveyors, locomotives, or other modes of moving broken rock should not be required to pass through airlocks. Hence, a mine design that has mineral or rock transportation routes in the main intakes and rock hoisting in a downcast shaft will favor an exhausting system. Alternatively, if there are good reasons to transport mineral in the returns and up-cast shaft then a forcing system may be preferred. This could be necessary, for example, in evaporite mines producing potash or halite where the hygroscopic nature of the mineral could give ore handling problems if transported within the variable humidity of intake airways.

2.2.5 Fan Maintenance

An exhausting fan will pass air that carries dust, water vapour, perhaps liquid water droplets, and is usually at a higher temperature than that of the air entering the mine. The combined effects of impact and corrosion on impeller blades are much greater on main exhaust fans. Forcing fans to handle relatively clean air and require less maintenance for any given duty. On the other hand, corrosive air passing up through the headgear of an up-cast shaft can cause much damage. This can be prevented by drawing the air out the shaft into a near-surface fan drift through a low-pressure high volume fan.

2.2.6 Fan Performance

A forcing fan normally handles the air that is cooler and denser than that passing through an exhausting fan. For any given mass flow, the forcing fan will pass a lower volume flow at reduced pressure. The corresponding power requirement is, therefore, also lower for a forcing fan. However, the effect is not great and unlikely to be of major significance.

A counteracting influence is that forcing fans must be fitted with inlet grilles to prevent the ingress of birds or other solid objects. These grilles necessarily absorb available energy and result in an additional frictional pressure drop. Furthermore, the expanding evasé fitted to the main exhaust fan recovers some of the kinetic energy that would otherwise be lost to the surface atmosphere.

2.2.7 Heat

When air is compressed through a fan its temperature is increased. The rise in temperature through a forcing fan will be reflected by an increase in average temperature in the intake airways. However, heat exchange with the strata is likely to dampen the effect before the air reaches the work areas. It is noted that the total input power to a fan is converted into heat which is added to the air entering the mine if in force mode.

Table 3: Heat

Advantages		Disadvantages	
Force Fan	**Exhaust Fan**	**Force Fan**	**Exhaust Fan**
Adds additional heat during winter	The heat generated due to input power not increasing air temperature in summer	Adds additional heat during summer	The heat generated due to input power not captured requiring additional heating in winter
Slight less power use due to density	Regain in static pressure due to evasé	Additional friction drop due to inlet grills	Slightly more power due to density
Less maintenance due to non - corrosive environment			Increase maintenance due to corrosive environment
	Favored for Strata Gas emissions i.e. methane	Not favored for gas strata emissions	

The above are the broad advantages and disadvantages of the Main Fan operating configuration.

2.2.8 Main Fan Damping Efficacy Systems and the Effect of the System Resistance with Overall Fan Efficacy

2.2.8.1 Inlet Guide Vane Control

The motor and fan run at a fixed speed. A solid gear may be used, since fan speed may be lower than motor speed. Flow is adjusted with the inlet guide vane position. The guide vane directs the air into the same direction of rotation as the fan impeller, which reduces the fan flow. Inlet guide vane control is more efficient than inlet dampers due to reduced friction in creating the pre-swirl movement.

2.2.9 Inlet Damper Control

The motor and fan run at a fixed speed. Flow is adjusted with the inlet damper position. The inlet damper directs the air into the same direction of rotation as the fan impeller, which reduces the fan flow. Inlet damper control is less efficient than an inlet guide vane due to increased friction in creating the pre-swirl movement.

2.2.10 Outlet Damper Control

Motor and fan run at a fixed speed. The flow is adjusted with the outlet damper position. Outlet dampers are the least efficient of all methods. They throttle the airflow to remove the power supplied by the fan. As outlet dampers close, the system curve becomes steeper, intersecting the fan curve at the required lower flow rate, and a point below the fan's best efficiency point.

2.2.11 Adjustable Gear Control

The motor runs at a fixed speed. The hydraulic gear or eddy-current clutch changes the speed of the fan. The flow is adjusted with the fan speed. The hydraulic gear includes significant hydraulic friction which can be observed as waste heat at the hydraulic oil cooler. Hydraulic friction has its lowest value at full load (5 %) and increases as the load goes down (>20 %). The eddy-current clutch transmits the motor torque and allows the slower speed of the fan. The lower the fan speed, the higher the losses.

2.2.12 The Use of Variable Speed Drives (VSD's)

The VSD changes the speed of the motor. The motor and fan are connected directly or via a solid gear. In applications requiring variable flow and pressure, VFDs are the most efficient method of control. Varying the speed of the fan adjusts the flow rate to the system requirements without the need for additional mechanical devices, and at high efficiency.

However: Many engineers do not take cognizance of the current system operating point. Invariably we find fans running at 40% efficiency or lower, normally due to excessive leakage, or due to mining not following the original design.

The system resistance with the fan's operational efficiency is crucial and should be the first thing looked at before the purchase and installation of a VSD. In these scenarios, you achieve a very expensive damping device at an unacceptable fan efficiency operating point. One needs to consider the fan's current operating point before the expensive purchase of a VSD. (Stanton. 2020).

As shown in Figure 7. A VSD tends to preserve the efficiency at the original operating point. (So, if your fan is currently running at 40% efficacy, by installing a VSD, no to very little improvement in fan efficacy will be realized.

Therefore, if your fan efficiency is 40% due to the current system resistance irrespective of what damping system is deployed your efficiency will tend to remain the same. (Figure 7).

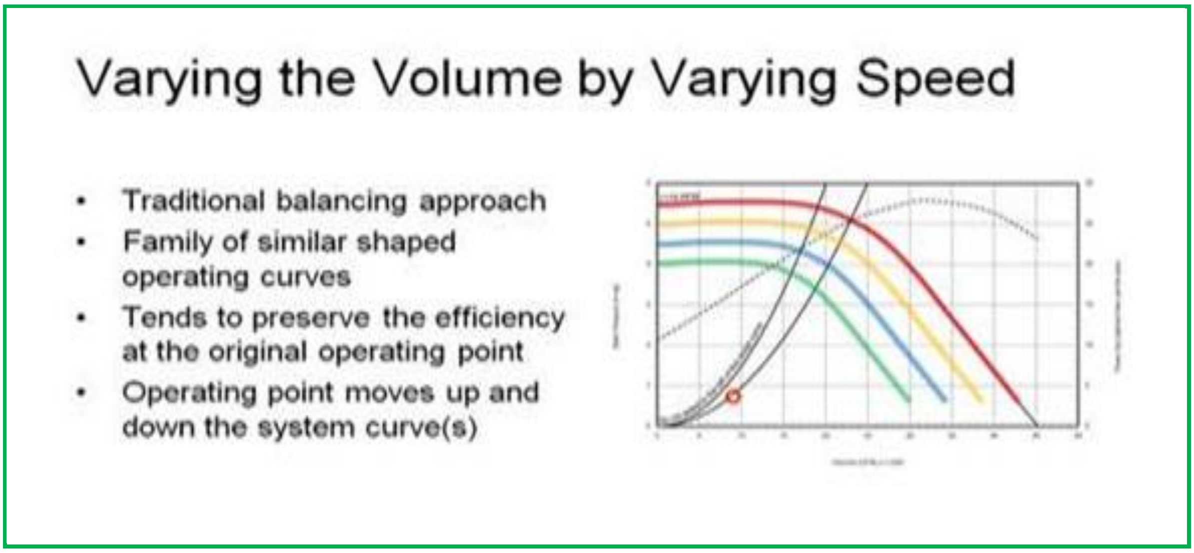

Figure 7 Fan curve

To explain the above scenario in a bit more detail, the following graph depicts the various parameters of a fan curve, note the System Resistance Curve meets the fan curve called system operating point at virtually max efficiency. I then drew in another system resistance curve B note the very low efficiency in this scenario (Figure 8).

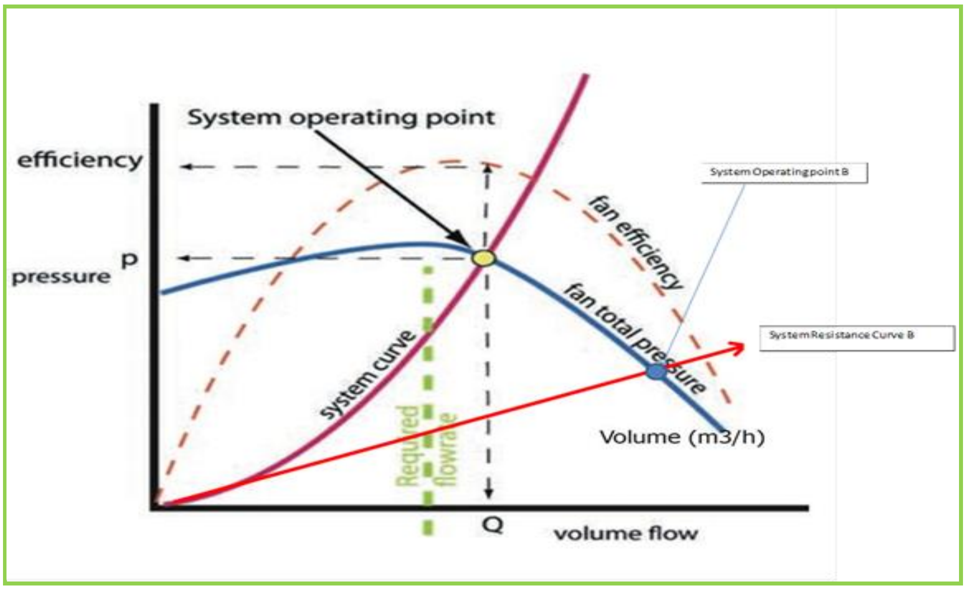

Figure 8: System operating point

This is what engineers have missed and there is a huge cost-saving potential if we can match the fan system resistance intersection point with the fan curve at its most efficient portion of the curve.

In Figure 9, the two blue fictitious system resistance curves, the top one will operate on 80% fan efficiency and the bottom one will be 40 % fan efficiency. <u>Installing a VSD or inlet guide vane control cannot rectify this</u>. (Stanton. 2020).

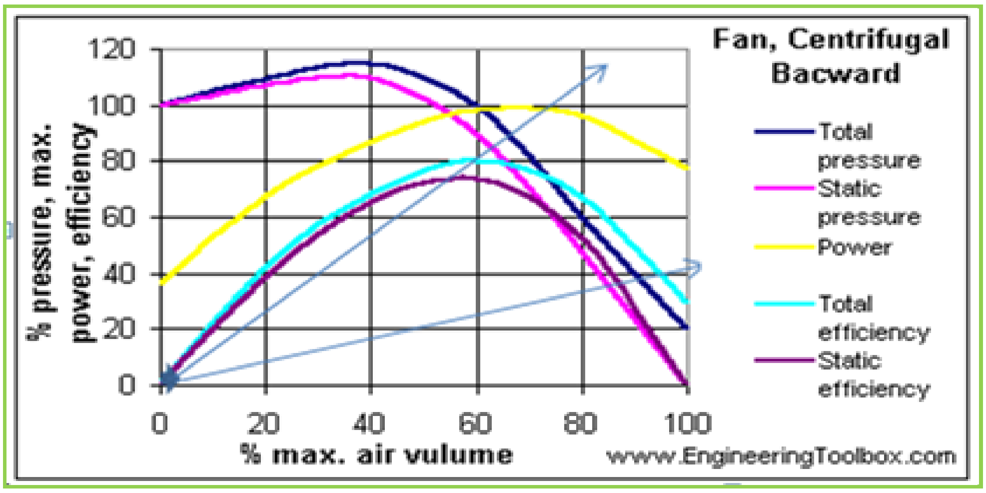

Figure 9: System operating point

There to be a major opportunity in terms of overall energy savings on main fan installations, firstly by determining the current efficacy of the installations, and then determining and addressing the root cause. In some instances, it may be advantageous to change the fan, or the impellor to achieve the desired outcome.

The fan-selected must be able to meet the system resistance curve over the life cycle of the mine. In most instances, this results in selecting an axial flow fan with variable pitch blade settings and driven through a Variable Speed Drive (VSD). This aspect of optimisation should always be pursued with gusto. (Stanton 2020).

2.2.13 Controlled air Recirculation

Controlled air recirculation is the re-introduction of a portion of the exhaust air from a working area into the intake air of the same area. In such a system, the recirculated air is always in addition to the 'fresh' intake air normally supplied to the area. The use of recirculation in mines is not a new concept. Several authors (Aldred and others, 1984; Bakke and others, 1964; Pickering and Aldred, 1977) have considered its application for temperature, dust, and methane control since the first use of recirculation was recorded (Lawton, 1932). A paper by Allan (1983) gave a comprehensive review of the development and use of recirculation in British collieries, where 61 sites were using controlled recirculation by January 1983.

A description of the theoretical effects of recirculation as applied to gold mines may be found in a recent paper (Burton and others, 1984), which also gives details of the Loraine field trial. Until this field trial, there had been no large-scale investigation of controlled recirculation in South Africa. Two major practical benefits are resulting from the introduction of recirculation. Firstly, increased airflow results in increased air velocities. This has two effects: slightly improved air-cooling powers, and better 'scouring' of pollutants. Secondly and most importantly, increases in airflow combined with bulk cooling of the air and possibly dust filtration provide a convenient and economic means of controlling temperatures and dust within working areas.

2.2.14 Leakages (Air Utilization)

The largest cost aspect in mine ventilation is the power costs of running the ventilation fans and refrigeration plants, which can reach as high as 50 percent of mines' entire electrical power cost. The need to optimise these costs by utilizing new and innovative technology makes it an attractive undertaking. Needless to say, proper design, planning, installation of the right equipment and controls, monitoring, and maintenance are crucial, if a mine is to come even close to optimizing its ventilation systems.

Poorly designed ventilation systems not only mean greater operational costs but can also impair a mine's safety and endanger the lives of the miners. The environment created by proper ventilation systems must be able to clear dust, gases from both the orebody and underground machinery, and lower temperatures to comfortable levels. Improper ventilation reduces productivity greatly by lowering the output of workers in stressful temperature conditions.

Stoppings and doors are the primary ventilation control system used by mines to course ventilation air through a mine. Since stoppings separate fresh intake air from the return air that may contain dust, contaminants, or potentially explosive mixtures, it is important to keep leakage to a minimum through stoppings to keep personnel both healthy and safe. The number of stoppings being constructed each year requires the mining industry to devote considerable resources and time for the construction and maintenance of these structures.

Due to costs, the qualities of these stoppings have deteriorated through the years, wherein effect mainly temporary stoppings or poor-quality stoppings are installed which require constant maintenance. The cost of electrical power has however increased to such a level that it now is feasible and cost-effective to install permanent robust stoppings and controls. Also, the traditionally accepted leakage figures can now no longer be accepted.

As alluded to above air utilization is of paramount importance and needs to be addressed during the initial mine planning stage.

The volume of air circulated directly affects both CAPEX and OPEX. Ventilation shafts and roadway dimensions are in most cases the result of the air which needs to be drawn into and out of the mine. This is further exacerbated by set velocities specifically where men and machinery travel. With the drastic increase in electricity over the last 15 years, leakages must be kept to a minimum. Where planned leakages of 50% were acceptable in the past due to the relatively low cost of power, this is no longer tolerable. Leakage factors as low as 30% are now possible. (Stanton 2020).

2.2.15 Prevention

Leakage prevention must be part of the initial ventilation strategy. Mine designs can be "leakage friendly" thus stressing the importance of an integrated approach to mine planning where the Ventilation Engineer gives early and ongoing input into the mine design. The major factors that should be incorporated into the ventilation design to prevent leakages are:

- Low-Pressure Circuit.
  - This has a direct impact on the leakages due to the differential pressure between intake and return circuits, and on OPEX due to required fan power.
- Effective Controls
  - Effective fit for purpose seals and stoppings must be installed to prevent leakage. Ventilation `controls should where reasonably practical be incorporated within the rock engineering support requirements wherever possible. This results in a robust system, cost-saving, and assurance that it will be installed.

During the planning and within producing mine, cognizance of the following areas of preventing air wastage and associated costs are:

- Reduction of all leakages to acceptable levels and the maintenance thereof.

- Ensuring the optimum amount of air is coursed to each working place.
- Ensuring refrigerated air and water is used effectively.

The above can be achieved by:

- Numerous Vuma/VentSim modelling scenarios to ascertain the art of the possible.
- A level by level and mine wide volume and leakage analysis including the inspection of all existing stoppings and controls.
- Review of each working place Air Utilisation Factor [AUI].
- The review and update of existing mine standards:
    - Footwall controls
    - In stope strike controls and bratticing
    - Accessing white areas
- Installation of effective ventilation stoppings and ventilation controls, both in the footwall and reef plane
- The installation of backlog controls
- The curtailment of airflow to non-working areas
- The use of refrigerated air and chilled water only to the areas where it is required.
- Implementation of an integrated ventilation and cooling on-demand strategy.

Prevention of ventilation leakages and costs is not only a planning issue but more importantly the constant checking and maintenance of existing infrastructure and controls to ensure an optimised ventilation strategy in terms of efficacy and costs (Stanton 2020).

2.2.16 Cost Association

Normally main fan power is the largest user of power in a mechanised mining layout where compressed air use is not significant.

Power (P, kW) varies as the square to the ratio of the rotational speed (RPM, u/min) of the impeller.

The cubic nature of this relationship between power and the rotational speed demonstrates how even for small volume gain, large amounts of additional power are needed as per the following fan law:

$$\mathrm{kW}_2 = \mathrm{kW}_1 \left(\frac{\mathrm{U}_2}{\mathrm{U}_1}\right)^3$$

- P1: Power, kW2.
- P2: Power, kW1.
- U1: RPM 1, u/min.
- U2: RPM 2, u/min.

Also, main and auxiliary fans run 24/7 and therefore make up a large portion of the Mines OPEX costing.

It remains therefore of utmost importance that leakages are kept to a minimum and that the correct amount of air is circulated to the respective working places continually. This is required not only to save electric energy but more importantly to ensure that the environment meets the mental and physical health requirements of the worker and creates an environment conducive to safe profitable production.

It is therefore imperative to ensure that not only is the design conducive to low pressures and unnecessary leakages, but that fit for purpose sealing mechanisms are introduced to maximise the air on the face, thus reducing costs improving on face ventilation conditions and re-entry period. (Stanton 2020).

2.2.17 Diesel Driven Equipment

There are three fundamental contaminant types associated with the operation of diesel driven equipment underground. These are Gases (NOx, SOx, and CO), all three being toxic.

Fumes and vapours, e.g. poly-nuclear aromatic hydrocarbons (PAHs), which are considered potentially carcinogenic as well as volatile organic compounds (VOC's), such as benzenes, benzidines, and numerous other organic combinations, some of which are also considered to be potentially harmful.

Fumes and vapours are essentially very fine carbon particles, which by themselves do not constitute significant risk. However, as these particles tend to coagulate and absorb a number of the fumes and vapours mentioned above, these become carriers. Typically, these particles are less than two μm in aerodynamic diameter, implying the potential for deep lung penetration and transference via the inner alveolar lining into the bloodstream, thus carrying the previously mentioned noxious compounds into cells and other organs.

Diesel driven equipment gives rise to heat emissions. This is due to under optimum efficiencies, where diesel engines convert approximately 35% of the calorific value of diesel fuel into mechanical power, the balance appearing as heat. This implies that a simple calculation can be effected to determine the heat produced by diesel-driven equipment. This factor is generally accepted as being 1.8.

In addition to the foregoing, it is also accepted that diesel-driven equipment is only partially effectively used. Typically, LHD's and haul trucks are partially utilised concerning their full available capacity (typically 60%) in relatively well-managed mines (and less in poorly managed mines). Similarly, roof bolters and drill rigs will only use their diesel driven engines 10 to 15% of the time to travel from one site to another. When generically applying these values to a fleet, it is possible to determine the overall heat generated.

A second method that may be applied is to determine the expected rate of diesel fuel consumption (typically referring to historic data from other shafts on the same mine or similar mines). In essence, the fuel consumption rate is multiplied with the calorific value of the fuel being used and then divided by the shift time that the equipment is to be used in seconds, to give a value in joules per second (J/s) (x 1,000 = kilowatt). This method, however, results in generic values and does not take cognizance of localised, transient, or time-dependent heat effects. It may also adversely affect the determination of the heat flux value from the rock mass, as it may skew the temperature difference depending on where the generic diesel heat value is applied. (Marais 2020).

2.2.18 The Effect of Virgin Rock Temperature

A Publication by M.Q.W. Jones in the J. S. Afr. Inst. Min. Metall. vol.118 n.7 Johannesburg Jul. 2018 about Virgin rock temperatures and geothermal gradients in the Bushveld Complex.

Knowledge of the in-situ virgin rock temperature (VRT) is essential for planning refrigeration and ventilation requirements of deep mines. Geothermal studies in the goldfields of the Witwatersrand have been in progress for approximately 80 years, with the result that a very extensive rock temperature database is available. However, it is only in the last three decades that deep-level platinum mining in the Bushveld Complex, north of the Witwatersrand Basin, has made mine refrigeration an important issue.

This paper presents temperature profiles in 31 boreholes in the Bushveld Complex that were surveyed as part of a project, conducted between 1985 and 2005, aimed at establishing the geothermal characteristics of the Complex. Most of the boreholes are located in platinum mining areas or prospects situated around the perimeter of the Complex. The geothermal gradient in rocks of the Main Zone of the Complex, which immediately overlie the platinum reefs, is remarkably constant at 20.7±1.3 K/km. Data from the Upper Zone and the Bushveld granites yield lower gradients, 16.5±1.1 K/km, and 16.4±2.4 K/km respectively. Geothermal gradients in the Bushveld Complex are approximately double the thermal gradients in the Witwatersrand.

The geothermal heat flux in the platinum mining areas, calculated from the thermal gradients and thermal conductivity data measured on samples of borehole core, is also remarkably uniform at 45±4 mW/m2; this is somewhat less than the average for Witwatersrand gold mining areas, 51±6 mW/m2. The main reason for the higher gradients in the Bushveld Complex is the low thermal conductivity of the rocks. Bottom-hole temperature measurements in boreholes in the Northam mining area of the Complex yield the highest virgin rock temperatures (up to 70°C at 2.2 km depth). This is 30°C hotter than the temperature at the same depth in mines in the Carletonville area of the Witwatersrand Basin. The surface temperature data and heat flow data, together with an extensive thermal conductivity database, make it possible to predict VRTs in new platinum mining areas as well as chromium and vanadium mines if such mining proceeds to substantial depths.

Increased mining depth means an increase in virgin rock temperature (VRT), which results in increased heat loads on underground workings (e.g. Rawlins, Phillips and Jones, 2002; Jones, 2003a). This is particularly relevant in the goldfields of the Witwatersrand, where mining approaches 4 km in-depth, and in the Bushveld Complex, where platinum mines exceed 2 km depth. Because it is necessary to control the working environment, mine refrigeration and ventilation are important considerations when planning such deep-level mining. This planning requires knowledge of the VRT as well as the thermal properties of the rocks surrounding underground workings.

The thermal gradients listed in Table 3 are least-squares fits the temperature versus depth data in the specified depth intervals. A range of gradients is given in cases where boreholes pass through variable lithologies with different thermal conductivities. The data confirm the early results of Carte and van Rooyen (1969), which indicated that the thermal gradient in the Bushveld Complex is relatively high.

Because of the great depth of some platinum mines, geothermal gradients above these mines are most pertinent. The gradient in individual boreholes or range of values if more than one borehole was used, for different segments of the platinum mining areas or prospects around the perimeter of the Bushveld Complex are listed in Table 6. In most cases, the measurements were made in rocks constituting the Main and upper Critical Zones of the Complex, which overlie the main platinum reefs. The thermal gradient is remarkably uniform and averages at 20.7±1.3

Table 4: Geothermal Gradients and Heat-flow in the Bushveld Complex

Geothermal gradients and heat flow in platinum mining areas of the Bushveld Complex (after Jones, 2017)

Area	dT/dx (K/km)	q_0 (mW/m²)
Marikana	20.4–21.1	44–48
Rustenburg	19.3–24.5	46–51
Amandelbult	19.9–21.2	41–44
Northam	20.2	45
Vila Nora	22.6	42
Mokopane	18.2–20.9	43–47
Zebediela	17.7–19.9	40–44
Umkoanesstad	21.2	47
Steelpoort	21.2	43

There is also a significant change vertically in the thermal gradient within the Bushveld Complex (Table 4). One measurement is the Lower Zone yielded a gradient of 16.0 K/km (NG1). Eight measurements in the Upper Zone yielded 16.5±1.1 K/km, and three in Bushveld granite yielded 16.3±2.4 K/km.

Table 5: Mean Geothermal Gradients

Mean geothermal gradients in rock units above the main gold mining areas of the Witwatersrand Basin and platinum mining areas of the Bushveld Complex

Rock unit/sub-unit	Rock type	dT/dx±s.d. (K/km)
KAROO SUPERGROUP		
Ecca Group	sandstone, shale*	25.3±5.1
BUSHVELD COMPLEX		
Bushveld granite	granite	16.3±2.4
Upper Zone	gabbro, norite	16.5±1.1
Main–Critical Zone	norite, anorthosite	20.7±1.3
Lower Zone	dunite	16.0
TRANSVAAL SUPERGROUP		
Chuniespoort Group	dolomite*	8.8±1.6
VENTERSDORP SUPERGROUP	lava*	14.5±1.6
WITWATRSRAND SUPERGROUP		
Central Rand Group	quartzite*	9.3±1.0
DOMINION GROUP	lava#	9.8±0.8

Figure 10 depicts the bottom hole temperature data from boreholes north and northeast of Northam in the Bushveld Complex and virgin temperature data from the Carletonville area in the Witwatersrand Basin. The least-squares regression line for the Northam data is T = 21, 6 + 20, 5 x, and for the Carletonville area T = 12.5 + 11.7x.

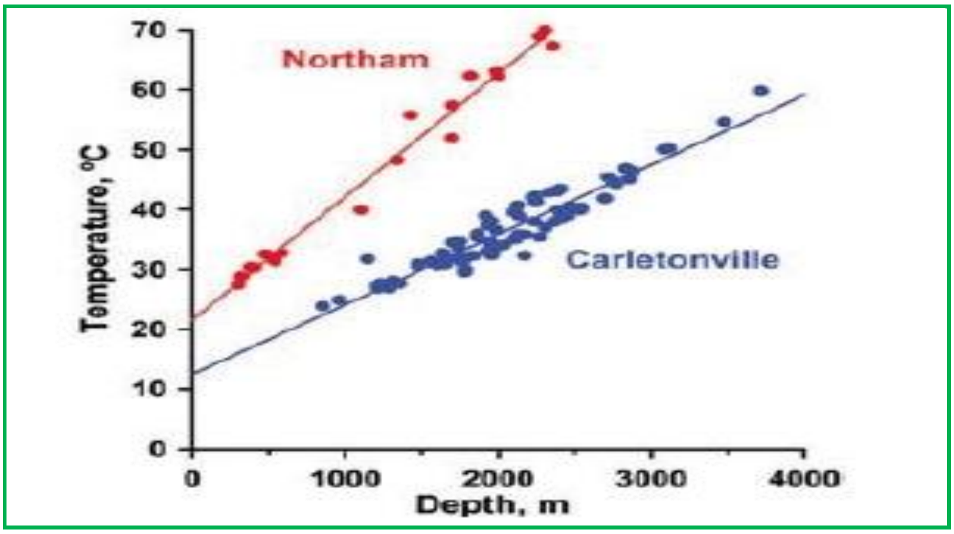

Figure 10 Geothermal gradients in the platinum mining areas of the Bushveld Complex

Geothermal gradients in the platinum mining areas of the Bushveld Complex (17.7-24.5 K/km) are approximately double the gradients in rocks overlying gold reefs of the Witwatersrand Basin (9.6-12.9 K/km). The geothermal heat flux in platinum mining areas of the Bushveld Complex (45 mW/m2) is lower than that in the Witwatersrand goldfields (51 mW/m2). The main reason for the high thermal gradients in the Complex is the relatively low thermal conductivity of the constituent rocks compared with the Witwatersrand Basin. The VRT in the Northam area, the deepest area investigated in the Bushveld Complex, is as much as 30°C higher than the VRT at equivalent depths in the Carletonville area, where the deepest gold mining takes place; this is due both to elevated surface temperatures and thermal gradients in the Bushveld. The Bushveld thermal gradient, heat flux, and thermal conductivity database make it possible to predict the VRT in new potential mining areas for platinum and other ores that may be extracted from the Bushveld Complex.

From the above, Virgin Rock temperatures are pivotal in deciding at what depths diesel mechanised equipment can be effectively introduced before incurring additional cooling costs. Within the Bushveld Complex, Diesel vehicles can be introduced without refrigeration up to a depth of circa 650m. It is also considered uneconomic to install Diesel vehicles at depths greater than circa 1300 m due to the copious amount of costly refrigeration required to ensure an acceptable environment. Within the Witwatersrand basin, these numbers would be circa 1200m and 2500m (Stanton 2020).

2.2.19 Alpine (High Altitude) Environments

Mining operations located at high altitudes come with many unique challenges, which include in no particular order; a greater amplitude in diurnal and seasonal temperature fluctuations, reduced oxygen content [Not percentage] in the ambient air, altered fan performance, and different diesel engine performance characteristics. It also has a considerable effect on the physiology of humanoids.

2.2.19.1 Fans

Most manufacturer's fan curves are given at standard density (1.21 kg/m3) and are useful only for those inlet conditions. To accurately predict the fan operating point(s) at varying air densities the universal fan laws can be used to predict the performance of a fan at corresponding altitudes.

It's not enough to make fan performance adjustments based on density corrections. The designer must also consider what effect the variables that are influencing the fan air density might have on the structural components of the fan. Temperatures other than 21°C can cause an alloy to become too pliable or brittle. Speed adjustments can exceed the limits of the wheel, shaft, and bearings. Gases, other than air, that change the inlet density may also be corrosive to vital structural components. All these variables must be considered when making fan inlet density adjustments.

Fan pressure (P) and power (H) vary directly with the ratio of the air/gas density at the fan inlet to the standard density; however, fan air volume (flow kg/s) is not affected by the air density. Fans are constant volume machines that, when operating at a constant speed will deliver the same flow (kg/s) at 1.2 kg/m3 density air as they will with lower density air or higher-density air.

It is imperative that during the tender phase that the suppliers are requested to tender on the prevailing conditions, specifically relating to density, temperature, and barometric pressure. (Stanton 2020).

2.2.19.2 Diesel Engines

At high altitudes where the ambient air density is reduced, the performance of diesel engines also suffers if not properly adjusted to meet the appropriate inlet conditions, often resulting in increased emissions and eventually, damage. Most diesel engine manufacturers provide engine derate curves for high altitude operations for each of the engine models or series.

Where exact ambient conditions are unknown, there is a general rule for derating engine power at approximately 3% per 300m in elevation above sea level where the equipment will be operating. This recommendation is commonly applicable across all modern diesel equipment utilized by the mining industry (but should only be used when engine-specific data is not available).

Of further importance is that Diesel engines do not self-derate enough so that the fuel setting can be left unchanged. If they are not reset to appropriate power levels, naturally aspirated engines may smoke badly and turbocharged engines may suffer excessive thermal and mechanical loading, resulting in internal damage, without giving an external indication of distress.

As with the fan specification, it is imperative that during the tender phase the suppliers are requested to tender on the prevailing conditions, specifically relating to density, and barometric pressure, and be requested to supply specific performance figures for the prevailing environmental conditions.

2.2.19.3 Human Physiology Effects

The effects of high altitude on humans are considerable. The percentage of oxygen saturation of hemoglobin determines the content of oxygen in the blood. After the human body reaches around 2,100 m (7,000 feet) above sea level, the saturation of oxyhemoglobin begins to plummet. However, the human body has both short-term and long-term adaptations to altitude that allows it to partially compensate for the lack of oxygen.

The human body can perform best at sea level, where the atmospheric pressure is 101,325 Pa (or 1 atm, by definition). The concentration of oxygen (O_2) in sea-level air is 20.9%, so the partial pressure of O_2 (pO_2) is 21.136 kPa. In healthy individuals, this saturates hemoglobin, the oxygen-binding red pigment in red blood cells.

Atmospheric pressure decreases exponentially with altitude **while the O_2 fraction [Percentage] remains constant to about 100 km**. It is about half of its sea-level value at 5,000 m (16,000 ft.),

Mountain medicine recognizes three altitude regions that reflect the lowered amount of oxygen in the atmosphere:

- High altitude = 1,500–3,500 meters (4,900–11,500 ft.)
- Very high altitude = 3,500–5,500 meters (11,500–18,000 ft.)
- Extreme altitude = above 5,500 meters (18,000 ft.)

The following graph depicts the relationship between mean arterial oxygen saturation (%) and altitude for several performance tests in un-acclimatized subjects.

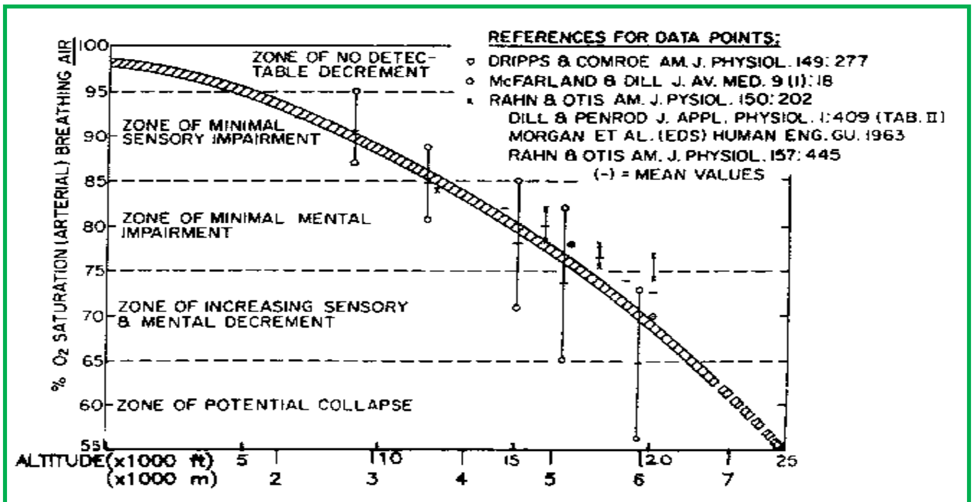

Figure 11 Altitude Zone of Working

One measure of the amount of oxygen available for use within the body is arterial oxygen saturation Sao_2, the percentage of binding sites of hemoglobin molecules that are carrying oxygen. This quantity can be easily measured using a finger or ear oximeter. Within a minute of exposure to altitude, Sao_2 begins to drop. Typical values for Sao_2 as a function of altitude for un-acclimatized individuals are shown in Figure 11. Figure 11 also indicates the general level of human performance impairment expected at high altitude but note that the boundaries between the different levels of impairment are very approximate and vary between individuals. Over a few days at altitude, by the adjustments mentioned below, the body will acclimatize, and it can be expected that at 5000 m Sao_2 will rise from an initial value of about 75% to about 85%. This compares with about 90% measured.

2.2.19.4 Occupational Health of Miners at Altitude

Both mining and work at altitude have independently been associated with several adverse health effects. Careful selection of workers, appropriate acclimatization, and on-site surveillance can help control most health risks.

Current literature regarding adverse health effects and toxic exposures that may be associated with mining operations conducted at altitude is summarized below. (Vearrier, David & Greenberg, Michael. (2011) Occupational Health of Miners at Altitude).

2.2.19.5 Cardiovascular Effects

High altitude is associated with an increased sympathetic tone that may result in elevated blood pressure, particularly in workers with pre-existing hypertension. Workers with a history of coronary artery disease experience ischemia at lower work rates at high altitude, while those with a history of congestive heart failure have decreased exercise tolerance at high altitude as compared to healthy controls and are at higher risk of suffering an exacerbation of their heart failure.

2.2.19.6 Pulmonary Effects

High altitude is associated with various adverse pulmonary effects, including high-altitude pulmonary edema, pulmonary hypertension, subacute mountain sickness, and chronic mountain sickness. Mining at altitude has been reported to accelerate silicosis and pneumoconiosis. Miners with pre-existing pneumoconiosis may experience an exacerbation of their condition at altitude. Obesity increases the risk of pulmonary hypertension, acute mountain sickness, and sleep-disordered breathing.

2.2.19.7 Neurological Effects

The most common adverse neurological effect of high altitude is acute mountain sickness, while the most severe adverse neurological effect is high-altitude cerebral edema. Poor sleep quality and sleep-disordered breathing may contribute to daytime sleepiness and impaired cognitive performance that could potentially result in workplace injuries, particularly in miners who are already at increased risk of suffering unintentional workplace injuries.

2.2.19.8 Ophthalmological Effects

Adverse ophthalmological effects include increased exposure to ultraviolet light and exophthalmia, which may be further exacerbated by occupational dust exposure.

2.2.19.9 Renal Effects

High altitude is associated with a protective effect in patients with renal disease, although it is unknown how this would affect miners with a history of chronic renal disease from exposure to silica and other renal toxicants.

2.2.19.10 Hematological Effects

Advanced age increases the risk of erythrocytosis and chronic mountain sickness in miners. Thrombotic and thromboembolic events are also more common at high altitudes.

2.2.19.11 Musculoskeletal Effects

Miners are at increased risk for low back pain due to occupational factors, and the easy fatigue at altitude has been reported to further predispose workers to this disorder.

2.2.19.12 1.8.12 Toxic Exposures

Diesel emissions at altitude contain more carbon monoxide due to increased incomplete combustion of fuel. Also, a given partial pressure of carbon monoxide at altitude will result in a larger percentage of carboxyhemoglobin at altitude.

Once again, when going out to tender where Mining contractors are to be used, they need to take cognizance of the prevailing environmental conditions and submit their strategy about selection, pre-placement screening, acclimatization issues, and on-site surveillance strategies.

2.3 Conclusion

In terms of the occupational environment, cognizance of the zone of influence as depicted in Figure 15 must be taken. It must further be noted that this is for un-acclimatized workers. With careful selection, pre-placement screening, acclimatization, and worker surveillance, coupled with good engineering control the adverse health effects and toxic exposures can be reduced.

The correct sizing of electrical equipment and diesel machinery is an engineering function and poses no risk if fit for purpose engineered designed equipment is offered which meets the requirements about the prevailing environmental conditions.

2.4 Main Results of Poor/Inadequate Ventilation

2.4.1 Heat Stress

Impaired performance may result in unsafe acts and heat may also tend to promote accidents due to sweaty palms or impairment of vision through fogging of safety glasses.

Heat may be classified into two areas:

- Heat Stress - which is the burden or load of heat that must be dissipated if the body is to remain in thermal equilibrium.
- Heat Strain - is the normal physiological or abnormal pathological change resulting from heat stress? The physiological condition referred to as heat strain is characterised by increases in deep body temperature, heart rate, blood flow to the skin, and water, and salt loss due to sweating.

Most adverse effects arise from a failure of the body's cooling mechanisms or because of overloading the system. Normally, several physical and physiological mechanisms assure the transfer of excess body heat to the environment. Even when the body is at rest, heat is generated by normal metabolism. With exercise, the heat produced by muscle activity rises rapidly. This generated heat is moved to the skin by the blood to transfer body heat to the environment. Heat may then be lost through convection, evaporation of sweat, radiation, and conduction.

To maintain the appropriate body temperature three issues are essential:

- The metabolic heat produced must be transferred to the skin via the circulation for dissipation.
- The sweat glands must be able to produce the necessary amount of sweat.
- The sweat must be able to evaporate. Failure in any of these mechanisms for heat transfer may cause the body core temperature to rise, leading to heat strain and subsequent heat illness.

Additionally, for the successful maintenance of the thermoregulatory system, adequate fluids must be consumed to prevent dehydration.

When the air temperature is above skin temperature (around 36°C), evaporation of sweat is the main mechanism for the body to lose heat.

2.4.2 Heat Stress Factors

Six factors are influencing a person's capacity for heat exchange with the environment:

1. Air temperature (dry bulb). Above 36°C, the body can gain heat from the environment.
2. Absolute humidity (wet bulb temperature). When the absolute humidity is high, the evaporation of sweat is reduced, thereby reducing the body's opportunity to lose its heat.
3. Radiant heat from objects such as the sun, furnaces, and other hot surroundings. The direction of heat transfer depends on the absolute temperature difference between the body and the surrounding surfaces. It is not affected by air temperature or humidity.
4. Air movement. This can influence both convection and evaporation and can have a marked effect on heat exchange at the exposed skin surfaces (face, arms, and legs). Convective heating or cooling does depends on the air temperature. Air movement assists with the evaporation of sweat from the skin and hence cooling capacity.
5. Muscular activity. This is the most significant as it imposes a variable heat load. Work rates may increase heat production up to ten times the resting level and can cause a rapid body heat rise if this cannot be lost to the surroundings.
6. Clothing. This can have a major effect on the amount of heat transfer from the body. Clothing may limit convective exchange and may interfere with the body's capacity to lose heat through the evaporation of sweat.

2.4.3 Methods of Reducing Heat

Excessive heat load can be due to radiation, convection, unsuitable clothing, or, body metabolism. Consistent with the hierarchy of control measures generally applied to health and safety hazards, the employer should ensure that exposure to heat is limited by:

- not exposing employees to heat so far as is practicable.
- isolating sources of heat, so far as is practicable.
- providing engineering controls, such as ventilation, to reduce heat loads.
- adopting safe work practices and appropriate administrative procedures such as job rotation.

2.4.3.1 Minimising the Potential for Heat Strain

The following are some factors to be considered in high-temperature environments:

- Ensure appropriate water consumption.
- Sweat rates can be as high as 2 litres/hour for those performing heavy physical labour in the heat.
- Therefore, water must be readily available and should be consumed before the shift, and then subsequently at regular intervals thereafter (such as half-hourly).
- Thirst indicates that moderate dehydration is already established. The water must be palatable by being cool (6-15°C).

2.4.3.2 Heat Acclimatisation

Through acclimatisation, employees can increase tolerance to work in the heat. Full acclimatisation takes 7-14 days with 3 hours of activity per day. Acclimatisation usually increases water requirements as it increases sweating, but reduces salt loss:

- A good physical condition will reduce the likelihood of heat strain.

- Those that are more than 20% overweight are more prone to developing heat illness symptoms. Those that are fit will most readily acclimatise and have some 'protection'.
- Clothing that is both loose-fitting and made from cloth that "breathes" may be appropriate.
- Artificial fibre cloth such as nylon is not recommended in heat stress situations. It is important not to obstruct evaporation from the skin. Protective covering such as hats, long-sleeved shirts, and shoes are recommended in situations where radiant heat is likely to be a problem.

2.4.3.3 Work Rates and Physical Activity.

Sustained physical activity can cause a rapid rise in body core temperature which may exceed the body's capacity to dissipate this heat to the environment. It may be necessary to provide adequate and regular rest periods to minimise heat production, or to provide for self-paced work. The provision of air-conditioned retreats and cooled fluids may also assist in maintaining appropriate body temperature.

2.4.4 Signs/Symptoms and Treatment of Heat Disorders

Table 6: Heat fatigue

Types	Signs/Symptoms		Treatment
Heat Fatigue	Takes place when workers have not acclimated to the environment or physical demands.	•Decrease in performance •Lack of good judgment	•Increase water/electrolyte intake •Rest in shade/cool environment
Heat Rash	Appears when the skin starts to waste away because sweat cannot evaporate from the skin.	•Red blisters (neck, upper chest, groin, under breasts, and in elbow creases)	•Loosen clothing •Dry skin often •Use drying powders
Heat Collapse	This occurs when the blood pools in the extremities instead of returning to the heart.	•Fainting •Reduced movement	•Rest in shade/cool environment •Wait for the normal colour to return to the victim’s face
Heat Cramps	Caused by too many or too few electrolytes. Affects people who sweat a lot.	•Painful muscle spasms (abdomen, arms, legs, back) •Heavy sweating	•Increase water/electrolyte intake •Rest in shade/cool environment
Heat Exhaustion	Happens when workers fail to replenish water and electrolytes lost during sweating.	•Pale and clammy skin •Headache •Weakness, fatigue •Nausea •Normal body temperature •Dizziness •Heavy sweating	•Lie down in the cool environment •Increase water/electrolyte intake •Loosen clothing •Call ambulance once in a shade/cool environment.
Heat Stroke	**Life-threatening.** Arises when the body loses the ability to sweat causing the body temperature to rise.	•Cessation of sweating •Skin hot and dry •High body temperature •Unconsciousness •Collapse	**•Medical Emergency – Call an ambulance** •Move victim to shade/cool environment

Types	Signs/Symptoms	Treatment
	•Convulsions •Confusion or erratic behaviour •Rapid pulse	•Cool the victim by any means (loosen clothing, spray with water, immerse in cold water while massaging skin)

2.4.5 Optimal Working Temperatures

2.4.5.1 Heat Effect on Productivity and Safety

Working in high heat environments can put workers at risk of impaired performance, heat illnesses, and heatstroke.

Impaired performance may result in unsafe acts and heat may also tend to promote accidents due to sweaty palms or impairment of vision through fogging of safety glasses.

The following Figures 12 and 13, emanated from studies conducted in South African Mines, and indicate the delirious effect heat has on both productivity and safety.

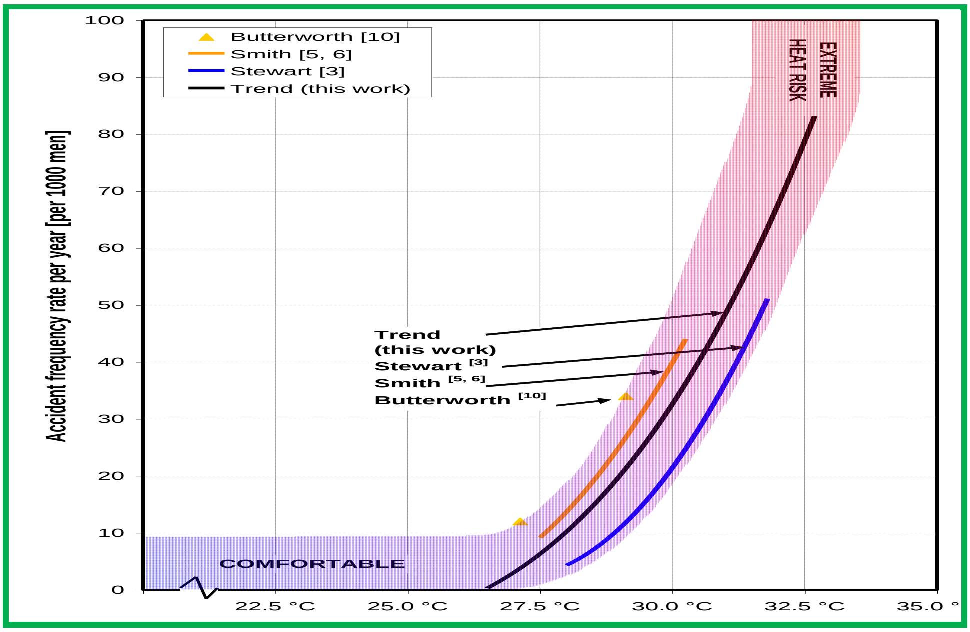

Figure 12: Effect of Temperature on Safety Performance

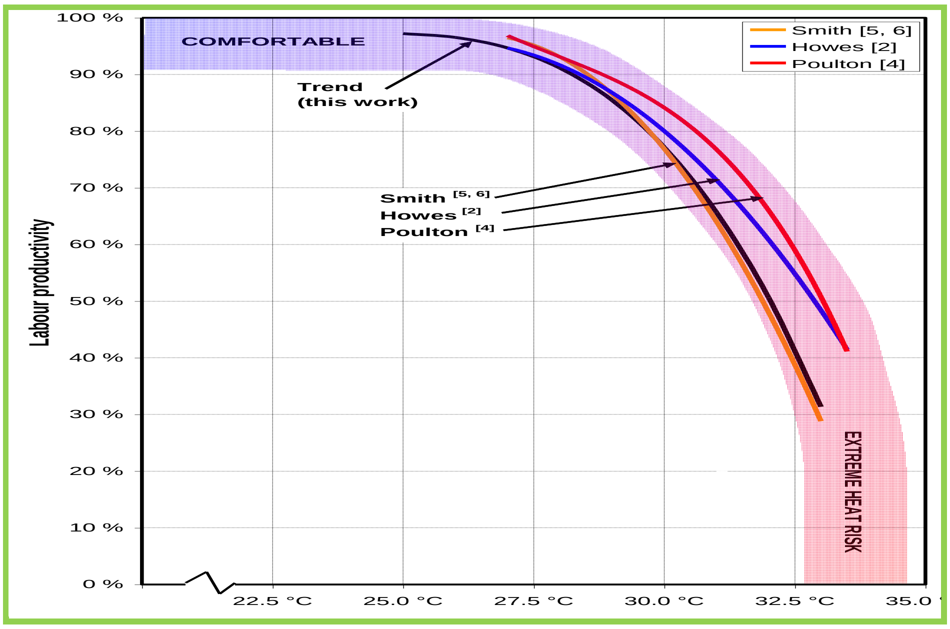

Figure 13: Effect of Temperature on Labour Productivity

Studies have shown that the optimum ventilation temperature in terms of minimising the above effect in terms of financial constraints and safety implications is 29.5 ° C Wet Bulb. This is considered the benchmark for Deep South African mines where acclimatization is practiced.

If one would plan for comfort conditions, i.e. Maximum face temperature of 27, 5°C, where acclimatization is not required, one would have to plan for an average temperature of circa 24°C Wet Bulb (Stanton 2020)

2.4.5.2 Pitfalls/Dangers of Recirculation

Recirculation can be defined as any portion of mine airflow that travels through the same area more than once. Recirculated air has several undesirable and possibly dangerous consequences.

Unfortunately, in a remarkably high portion of mines, recirculation is very prevalent. In some cases, mine personnel is not even aware of it. In response to the poor ventilation conditions caused by recirculation, a common response is to install more fans or larger fans, which can often make conditions even worse.

The negative environmental effect of recirculation is inter alia:

- A build-up of heat and humidity – As air recirculates, it repeatedly picks up increasing heat from machines, rock strata, and ventilation fans. Moisture and humidity are increased by groundwater and mining activities.
- Build of fumes and dust – Mining activities need fresh air to clear out noxious gases and dust. Recirculated air prevents this and allows fumes and dust to stay in suspension.
- Recirculated blasting fumes and dust may often prevent re-entry into blasted areas for extended periods, delaying production, and other activities.
- The gas build-up, particularly in gaseous mines can create a dangerous environment, prone to explosion or poisoning of personnel.

The vast majority of recirculation in mines is caused by two aspects of mine ventilation design.

2.4.5.3 Underground Booster Fans.

Booster fans are normally designed to 'push' air through a mine, usually to assist surface mounted fans to circulate air into further reaches of the mine. This configuration creates a high-pressure zone through the region in front of the fans. ANY connection back to the mine behind the fans (drives, declines, shafts, mined out voids, and stopes) provides an opportunity for air to leak back into the mine and recirculate. Even closed doors and other ventilation control may allow for unacceptable recirculation, particularly if high pressures are present.

Solution – Use booster fans only when necessary and limit or eliminate pathways for boosted air to re-enter the mine. If possible, place booster fans near intake or exhaust shafts to limit re-entry points. Ensure any doors or controls to prevent recirculation are of high quality and regularly maintained.

Underground development fans are another source of recirculated air regularly encountered in mines. In many cases, the auxiliary fan consumes more air than it receives, resulting in used air being redrawn back through to feed the fan intake.

Solution – Any free-standing (or hanging) auxiliary fan MUST have more air feeding past the inlet than it consumes. As a rule of thumb, try to ensure at least 0.25m/s or more of excess air moves past the fan when running to prevent air from being drawn back from the working face.

Test installed fans using smoke tubes or similar to ensure air is not drawn back through the fan.

Finally, avoid using multiple inline auxiliary fans to extend duct length, unless the duct is solid, low leakage duct, and cannot draw air through gaps under negative pressure. Do not use open flexible duct feeding into downstream fans and duct, as recirculation will be significant and inevitable.

2.4.6 Ventilation strategy - Underground ventilation challenges in narrow reef hard rock mining

The mining industry is at a phase where there is a depletion of easy-access reserves, hence most of the metal mines are going deeper below the surface, the health, and safety of workers is a concern and the mining operations are becoming more mechanized and/ or automated. This phase has raised several challenges about underground ventilation and cooling. This section will focus on ventilation challenges due to depth increase, mine health and safety requirements, and implementation of technology in the mining industry.

2.4.6.1 Increase in Depth

According to Hardcastle, 2004 there are three ways in which depth can affect the economics of ventilation: firstly, an increase in depth will have a linear increase in associated capital and operating costs due to an increase in pressure and power of the main fan. Secondly, depth increase is associated with high air leakages within the system. Looking at large ventilation systems, if a mine must supply an additional airflow of 10% to account for leakages as compared to a smaller mine, the resultant power-to-cost will be 33% higher. This then shows the need to optimize the quantity of air sent underground.

Thirdly, air temperatures increase with an increase in depth. An increase in air temperatures is a result of auto compression and additional heat transfer from the virgin rock as it gets closer to the earth's molten core. This is something that cannot be avoided, but certain optimizing measures may be taken. To deal with this heat gain and provide the same capacity to remove heat produced by machines, the airflow in deep mines must increase with depth and cooling methods may be employed accordingly. The selection of the optimum cooling system depends on design reject temperature, surface design temperature, depth of mining (VRT), and electricity costs (Figure 14) (Mackay, 2012).

Figure 14 Generic selection of optimum cooling system as a function of depth (Mackay M. K., 2012)

2.4.6.2 The Impact of Mechanized and/or Automated Mining Operations

The mining industry has gone from hand-tool equipment to electrical and diesel-powered equipment, and it is now heading to semi-automation and full automation machines. Mechanization of mining operations has also challenged ventilation in deep metal mines. Initially, only a few numbers of diesel equipment were used at the mines and it was quite small with engines of less than 75 KW. Since that time, the diesel equipment at the mines has larger engines of 260 to >550 KW and the number of these machines has dramatically increased. Increased mechanization and workforce mobility has effects on heat and required mines to more air quantities underground for the dilution of diesel fumes. An increase in air quantities will then result in an increase in pressure and power, which will drastically raise the cost associated (Kocsis, 2004). Heat production of a diesel engine at full load is about 3 kW of heat/rated kilowatt while heat production of an electric motor at full load is 1 kW of heat/rated kilowatt. Even though electrical equipment comparatively produces less heat and no fumes, mines still prefer to use diesel equipment due to practical requirements such as freedom of movement. Developments on improving the quality of diesel fuel and engine efficiency are being made, but these factors are still significant driving factors in planning the levels of ventilation and cooling for mine design (Mackay, 2012).

2.4.6.3 Health, Environmental and Safety challenges

One of the requirements for ventilation is to dilute and remove pollutants from the air so to provide a safe atmosphere for workers underground. The most common contaminants are (Kocsis, 2004):

- Strata gases: methane, radioactive, and thoron.
- Mining process gases: By-products of combustion from diesel engines and fumes from explosives.

- Mineral dust: Dust and attrition of the rock liberated during blasting and material handling practices.
- Non- mineral dust: Soot (by-pass of combustion from diesel engine).

Strata gases are not that much of a concern to metal mines and dust from blasting and material handling processes are controlled by wetting practices and other mechanical methods. On the other hand, fumes from the explosives are released when the working area is evacuated and by the time workers return to the working area the fumes have been diluted. The major issue for metal mines is the by-products of combustion from a diesel engine (e.g. heat and soot) and due to high quantities of air currently supplied to dilute these diesel by-products, all other contaminants are then controlled. When focusing on mine health and safety, there are two types of ventilation requirements: dilution requirement of raw exhaust and regulations concerning personnel exposure stating threshold limit values. These requirements vary according to countries and may be a fixed value for all equipment regardless of engine and fuel type.

With an increase in mechanization and equipment size, the regulations set for diesel exhaust dilution requirements play a significant role in the economics of ventilation. According to Mackay, 2012 diesel engine exhaust is carcinogenic to humans based on sufficient evidence that exposure is associated with an increased risk for lung cancer. This shows the need for a much cleaner environment. This much cleaner environment cannot be addressed by ventilation only but there should be control measures at the source. Another concern is the global environment. The mining industry is responsible for producing greenhouse gases either directly or indirectly. Direct sources of greenhouse gases include diesel engines, heating fuels, explosives, and strata gas, and indirect sources are through electricity generated from carbon-based fuels. Energy requirements for the mining industry have increased since 1996 and will continue to go up through 2020 (Kocsis, 2004). In summary, an increased need for ventilation to remove heat, dilute contaminants from larger diesel equipment and more harsh exposure regulations historically have shown the requirement of more supplied air, increased power and associated cost, and the high volume of greenhouse gas emissions.

2.4.6.4 Design Parameters

Design parameters form the basis of what specification we design to.

2.4.6.5 Controlled air Recirculation

Underground controlled recirculation is a method used to reduce the overall airflow into and out of an underground mine, by re-using some of the underground air. To re-use the air, it needs to be cleaned of gases, fumes, and dust, and in most cases (especially in the South African context) it needs to be cooled. Controlled recirculation programmes on South African mines have most often been proposed where the provision of additional ventilation from the surface is not practical or cost-effective, for instance at an old mine where ventilation shaft dimensions are restricted, yet increased production levels or deepening programmes (and increased ventilation air quantities) are required.

The use of controlled recirculation for underground mining is not a new concept and has been practiced on a fairly limited scale for some years, mainly in gold mines. Gold mines are fairly well-suited for recirculation systems, as the main limiting factor for recirculation air quantities at gold mines often becomes dust levels, and the platinum mines tend to have significantly less hazardous dust (lower silica content) than is the case in gold mines.

The concept of underground recirculation should be considered once the ventilation requirements start to dictate the shaft and/or tunnel sizes. This is, in general, not the case for these projects and at this stage, recirculation is not being considered. This will be revisited during the next stage of the study, particularly if the larger options are deemed to be preferred.

2.4.6.5.1 Ventilation on Demand

The Ventilation on Demand (VOD) system continually monitors air quality and adjust ventilation as required. In this way, areas that are being worked in benefit from better, more efficient ventilation, while in areas not being worked the ventilation is reduced. Overall, this leads to significant electricity and other cost savings, and also makes the mine much safer and more productive.

Applying a VOD system requires complete and detailed knowledge of the mine ventilation network, the ongoing processes, and regulatory demands.

To precisely define local air demands, all machinery with their properties and positions must be known in real-time requiring a machinery tracking and identifying system.

Information on machinery and personnel then must be analyzed to define needed volume flows and adequate reactions. Analyzing data and triggering commands can either be conducted by a central control system or decentralised. In both cases, adequate infrastructure is required to transmit information.

Furthermore, ventilation infrastructure is to be installed to change the airflows to the calculated needs. It should be remotely controlled to guarantee short reaction times. Among regulators and doors, especially fans can be subject to variable settings.

To meet regulatory demands, only calculating static demands based on e. g. diesel-powered equipment will not be sufficient.

Monitoring the network with gas detection sensors and measuring devices can be used to analyse air qualities and react e. g. with higher flow rates if certain regulatory demands are not yet met.

Using a monitoring system instead of applying calculated quantities will finally make the system a quality-based VOD rather than a quantity-based system, which is unable to react to spontaneous events. Also, o control air automated damper control systems coupled with vehicle monitoring are required and the specifications and requirements of these need to be determined.

2.4.6.6 Fuel Cell Technology

Most notably, hydrogen fuel cells are used to power cars, buses, and trains as a clean alternative to traditional petrol and diesel engines, which burn fuel to produce the energy they require.

Not only are hydrogen fuel cell vehicles a clean alternative, emitting only water from the tailpipe, these vehicles also refuel quickly with comparable driving ranges to traditional vehicles. This use is evolving with emerging applications to power delivery vans, trucks, and forklifts as well as boats and ships.

From powering engines in cars to forklifts and schools, here’s how hydrogen fuel cells are changing the face of the energy industry:

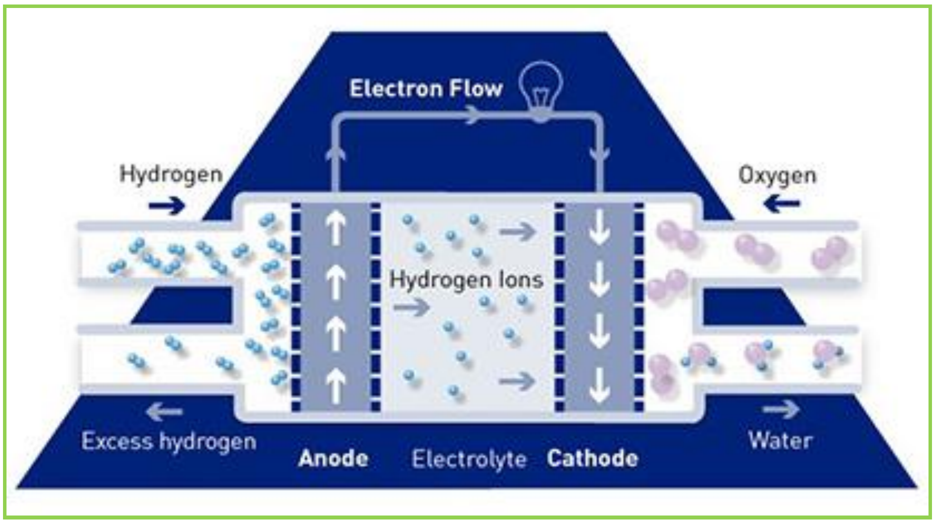

Figure 15: Hydrogen fuel cell (Anglo Platinum FUTURESMART MINING TM)

Hydrogen fuel cells convert chemical energy into electrical energy by converting hydrogen gas and oxygen into the water.

Oxygen is readily available in the atmosphere, so it's only necessary to supply the fuel cell with hydrogen, which happens to be the most common element available on Earth. Beyond its availability, it's also possible to produce more hydrogen from water electrolysis using solar or wind energy. In this way, it's possible to generate hydrogen fuel cell power entirely carbon emission-free.

2.4.6.6.1 How a Fuel Cell Turns Chemical Energy into Electrical Power

To turn hydrogen and oxygen into electricity, every fuel cell needs three components - an anode and a cathode, and an electrolyte membrane. The substance contained in the electrolyte can vary in different types of fuel cells.

Hydrogen enters the fuel cell at the anode, and oxygen at the cathode.

Platinum metal is most often used as part of the anode catalyst. When pressurised hydrogen enters the fuel cell at the anode, the platinum-containing catalyst separates it into protons (H+) and electrons (e-).

The protons travel through the electrolyte membrane towards the cathode where electrons are diverted to an external circuit that generates an electrical current. The electrons then move towards the cathode to combine with the oxygen and protons—forming a water molecule.

The water molecule is the only direct emission of a fuel cell, aside from a small amount of heat.

Fuel Cell Electric Vehicles (FCEVs) are a key part of a low-carbon future and will play an important role in achieving global carbon reduction targets. Global levels of investment in the technology currently surpass billions of dollars annually and many global automotive manufacturers are developing FCEVs, some of which are already available in the market.

By 2021, most leading automotive manufacturers are expected to have launched at least one FCEV globally, demonstrating the real-world application of the technology and increasing demand for the vehicles.

We have worked, in conjunction with Element Energy, to produce an FCEV factsheet to help provide a snapshot of where the industry is and its effects on ventilation demand if diesel driven trackless equipment is replaced with an electrical, fuel cell, or battery-operated fleet.

2.4.6.7 Effect on ventilation demand if diesel driven trackless equipment is replaced with an electrical, fuel cell, or battery operated fleet

Heat generation is a very important factor to consider when dealing with mechanised mines, more so in hot climates. Calculating the heat load and cooling requirements for mechanised mines are similar in approach to any other mine, with the addition of a substantial amount of heat load due to the diesel equipment fleet. Diesel engines are only thermodynamically efficient up to 40%, whilst the remainder is given off as heat when operating at full power. Maurya et al. (2015) go on to concur with this point as it is stated that generally, the efficiency of diesel engines is 33%, the remaining two-thirds are released in the underground mining environment in the form of heat. The internal combustion engines of diesel equipment have an overall efficiency of roughly one-third of the efficiency which can be achieved by electrical units. Hence, diesel equipment will produce approximately three times more heat than electrical equipment of the same mechanical work output. Diesel equipment as an additional heat source increases a mines ventilation requirement in addition to the following factors:

- Geothermal gradient
- Auto-compression
- Explosives and blasting
- Mechanical processes and light.

The main ventilation requirements of mechanised mines are determined by establishing the size of the diesel fleet and then multiplying it by a factor that links the amount of fresh air to the rated power of the diesel engine. These factors are often dictated in the mining legislation of the country in question. The common numerical factor used in mines is often 0.05 to 0.06 m/s^3 per rated kW, while some mines use a factor of up to 0.10 m/s^3 per rated kW to account for leakages and other ventilation requirements throughout the mine. Illustrates this variation of ventilation rates both locally and internationally.

Table 7 Selected ventilation requirements for diesel mining equipment

Location	Statutory Ventilation Rate(s)
Australia	0.06 m^3/s per kW minimum
Canada	Varies by province from 0.045 – 0.092 m^3/s per kW minimum – most commonly 0.06 m^3/s per kW
Chile	2.83 m^3/min per effective brake horsepower minimum (0.063 m^3/s per kW equivalent)
China	0.067 m^3/s per kW
South Africa	0.063 m^3/s per kW minimum (based on "best practice")
USA	Based on MSHA certificate – ventilation required to dilute contaminants to specified levels at the tailpipe

Perhaps the most documented motive to seek alternatives to diesel-powered equipment is improving occupational health conditions. Diesel particulate matter (DPM) is produced by diesel engines due to incomplete combustion and impurities in the fuel. As of June 2012, the World Health Organisation has categorised DPM as a Group 1 carcinogen. This categorisation is based on confirmation that exposure is linked to an increased risk of developing lung cancer.

Additionally, exposure to DPM and diesel exhaust emissions (DEE) puts employees at the risk of health effects which include irritation of the nose and eyes, lung function and respiratory changes, headache, fatigue, and nausea. Chronic exposure is then associated with coughing, excess sputum production, and degradation of lung function. Exposure studies in healthy humans have shown several substantial inflammatory changes in the airways, particularly, before any changes in pulmonary function are detected. These effects may probably be even more harmful in asthmatics and other employees with compromised pulmonary function.

Intuitively, one can conclude that these health risks are more pronounced in a confined underground space. A report by Bugarski et al. (2004) further highlights this notion as it is stated that underground miners are exposed to the highest concentrations of DPM of all occupations.

Jacobs (2013) goes on to explain that although diesel vehicles tend to be more mobile and versatile than their battery electric counterparts, they also suffer from larger operating costs due to fuel, consumables (filters, lubricants), increased ventilation requirements, and regulation checks. These negative factors have sped up the requirement of an alternative to the use of diesel equipment in underground mines.

The main benefits of battery-powered equipment are realised in occupational health and safety, and a reduction in operational costs of the mine. In terms of ventilation, the introduction of a battery-powered fleet has the overall effect of a reduction in ventilation requirements and power consumption. To reduce ventilation power consumption, the ventilation requirement must be reduced, and replacing diesel vehicles with battery-powered ones is an effective means to achieve this. This is due to an electric motor producing zero emissions and only emitting a third of the heat of a comparable diesel engine. This equates to a reduction in ventilation requirements and power consumption as airborne pollutants and heat are now less prominent in the ambient air, subsequently improving the health and safety of mine employees.

The efficiency of conversion from electric energy to wheel drives of the vehicle is much higher than the conversion efficiency from diesel to wheel drives; thus the amount of heat produced is significantly less. This means the effective convection energy required for refrigeration and cooling can be reduced. This results in reduced ventilation requirements of between 30 to 50% and lower energy costs.

Table 8 illustrates the comparison of two underground loaders of the same make, with the first being diesel-powered and the second being a Battery Electric Vehicle (BEV). It can be seen that the BEV does not consume air, whilst the diesel-powered vehicle still requires the use of the exhaust diesel fume factor. Additionally, the aforementioned overall energy conversion rate is more than twice as efficient in the BEV as the diesel vehicle. This means that more energy is used by the BEV as opposed to being converted to heat and dispersed into ambient air, as is the case with the diesel vehicle.

Table 8: ST14 Diesel Scooptram Vs ST14 BEV Scooptram

	ST14 Diesel	ST14 BEV
Min. required ventilation per kW (Exhaust Diesel Fume Factor)	0,063 $m^3/s/kW$	0 $m^3/s/kW$
Overall Energy Conversion Efficiency	30%	60-70%

Additional benefits of the use of BEV compared to diesel vehicles include:

- Diesel engines consume air, which increases the ventilation requirement.
- Elimination of diesel fuel costs, which a variable quantity.
- Reduced maintenance costs; and
- Less noise, vibration, and heat for miners operating the equipment underground.

A typical mechanised mine can have dozens of diesel-powered equipment and it is, therefore, important to note that converting to battery-powered vehicles equates to a substantial up-front cost, primarily due to the cost of the equipment, batteries, and on a smaller scale, the retraining of personnel. The technology to create a diesel-free mine was once not a realistic possibility, although Rycroft (2017) notes that recently this has been made possible due to advancements in the battery storage sector.

In a study conducted by SRK Consulting for a mine in South America, BEV's were used as primary haulage and loading equipment. Considerations were made for heat, dust, and minimum air velocities. Based on these considerations, several ventilation and thermal models were created at key ventilation stages in the life of mine to evaluate ventilation demands and potential savings.

The study showed several advantages of using BEV's. The results of the study showed that the ventilation system demand could potentially be reduced by up to 50% of the original airflow and a potential reduction of total fan power by approximately 80%. This result is seen as very successful as it did not include modifications to the original mine infrastructure other than the redistributing of airflow to meet various mining demands. Additionally, with less airflow demand, the size and number of raises/shafts could be reduced, resulting in major development cost savings. Even when considering the raise/shaft size reduction which results in a higher overall mine resistance to airflow, a main fan power savings of up to 60% was calculated.

While BEV's have no tailpipe emissions, they contribute to the production of greenhouse gases (GHG), criteria pollutants, and fine particulates such as:

- Nitrogen oxides (NOx);
- Volatile organic compounds (VOC);
- Particulate matter of between 2.5 and 10 micrometers;
- Carbon monoxide
- And sulphur dioxide

These emissions are mainly determined by the upstream emissions, defined as the emissions from the energy used to charge batteries. Also, it is well documented that lead-acid batteries release hydrogen gas that can be potentially explosive (when above a concentration of 4%) and become a direct hazard to the health and safety of mine employees. Due to this, it is recommended that the concentration of hydrogen never exceeds 1% of the available volume of a battery bay. Even when taking the upstream emissions into account, the emissions associated with BEV's are generally lower than emissions of conventional vehicles.

To date, only a small number of mines have started to employ significant use of BEV's, so limited data is available for actual savings. The additional concerns with BEV's are the capacity of the battery, the ability to work a complete shift without a recharge, battery degradation, potential production losses due to charging and/or battery swap-outs, and power grid requirements. Despite these potential issues, BEV's provide a promising alternative, which may save significantly on ventilation, power costs, and result in a cleaner mining environment for employees.

2.4.6.8 Battery-Powered Equipment

According to Mike Rycroft, EE Publishers (September 28th, 2017, Published in Articles) Battery electric vehicles are changing the face of mining. Battery-powered mining vehicles were introduced in the 1980s, but it is only in recent years that large-scale adoption of the technology is being considered. A recent news report states that the market for underground mining machines is still in the beginning stages of a paradigm shift that will ultimately see battery-powered equipment make its diesel competition obsolete. The tipping point where everyone has decided that, in the future, they will use battery-driven zero-emissions equipment underground has not yet been reached. It is anticipated that all major mining companies will only purchase zero-emission equipment for the underground.

Battery technology is ideally suited for underground mining and the speed of adoption will be driven by the mines' comfort level with the technology and the OEMs' ability to deliver a solid product that will operate for a full shift A broad range of benefits driving the battery electric vehicle transition are:

- Elimination of diesel fine particular matter and other exhaust gas components in the underground environment, requiring less ventilation and therefore lower costs, as well as improved health for miners.
- The efficiency of conversion from electric energy to wheel drives is much higher than the conversion efficiency from diesel to wheel drive, so the amount of heat that an electric vehicle produces is much less. This results in reduced ventilation requirements (30 to 50% less) and lowers associated energy costs.
- Diesel engines consume air, which increases the ventilation requirement. BEVs do not consume air.
- Elimination of diesel fuel costs, a variable quantity.
- Reduced maintenance costs (some 25% fewer parts on EV propulsion versus diesel propulsion systems).
- Less noise, vibration, and heat for miners operating the equipment underground.

In addition to these advantages, there is an increasing move towards automation of mine machinery, and the use of remotely controlled mining robots, which favour the use of electric drives and battery-driven vehicles.

Most underground mining operations currently use diesel-powered trackless mobile machines. BEVs are far more energy-efficient than their internal combustion engine counterparts. As an additional benefit, they can further increase efficiency by using regenerative braking to convert kinetic energy into potential energy, which can then be re-used when accelerating. Mining operations could save a considerable amount of their operational expenditure when using electric equipment instead of a diesel-driven fleet [Atlas Copco, 2007]. Battery-powered machines, unlike their power cord-tethered or trolley-connected cousins, have an unlimited range of motion, the freedom to work in developing areas without outlets, and few exposed fragile parts.

Figure 16 A battery powered Scooptram (Atlas Copco).

2.4.6.8.1 Cost Issues

One of the biggest problems with switching from diesel-driven equipment to a new electric fleet is the significant capital investment required. In an economy dealing with lowered commodity prices, this places pressure on new purchases. While most mines have slowed down on their spending, the long-term benefits of investing in a clean, green, and modern range of electrically driven underground equipment may outweigh the short-term cash outlay. Directly driven mine machinery (i.e. power from an AC feed) has advantages, but there is a serious disadvantage in areas where mobility is required. It is in these areas specifically where battery-driven and hybrid units come to the fore/

With the cost of batteries and other storage systems being driven down by other sectors, the cost of converting to BEVs in underground mines is reducing. Also, the electric vehicle market is developing and producing batteries with increased energy density and of the size and shape suitable for low profile mining traction units. The cost of batteries specifically designed for transport is decreasing rapidly and charging regimes have been developed which allow rapid recharge of batteries. Further development is the use of hybrid mining propulsion units, which can be adapted to a wide variety of underground operations.

2.4.6.8.2 BEV Equipment Range

Most people are aware of BEVs being used for transport in underground mines, but the range is being expanded to other vehicles and machinery as well. It is estimated that 80% of the fuel burned in an underground mine is burned by loaders or trucks [3]. Since these machines are commonly used in underground mining operations, they were the first obvious choice for conversion to battery operation, and most of the mining BEVs today fall in this category. BEVs are confined to personnel transport, load haul dumpers (LHDs), and trucks, but several companies are intending to extend the battery-powered option over the full range of equipment powered by diesel engines (Anglo American Platinum, 2012. FUEL CELL TECHNOLOGY IN UNDERGROUND MINING).

2.4.6.8.3 Load Haul Dumpers

Tried and tested, operational and available, battery-powered load haul dumpers (LHDs) primarily face one obstacle to widespread use in underground mining. Both manufacturers and academics say the equipment is largely proven, but its market share will remain limited until the perception improves. A few examples are:

- Scooptram loader: A front-end loader produced by Atlas Copco. The performance matches that of the company's diesel-powered version. It is powered by a 165 kWh, 630 V DC LiFePO4 battery.
- Artisan's 3-mt 153: This LHD offers a total power of 214 kW. It is powered by a 600 V DC 88 kWh lithium-ion phosphate battery. The unit is claimed to outperform the equivalent sized diesel-powered unit.
- The GE Fairchild: It is powered by a 240 V, 930 Ah (214, 8 kWh) battery.

Figure 17 A Battery Powered Load Haul Dumper (Artisan).

2.4.6.8.4 Battery Powered Haul Trucks

GE and others are offering battery powered underground haulage trucks, which are similar to LHDs but are used for ore haulage only.

2.4.6.8.5 Battery Tramming: Drills and other Equipment

Tramming is the movement of machinery from one site to another. Usually accomplished using diesel engines, units using battery-driven motors are now available to perform the function. The battery unit has several other advantages over diesel:

- The battery can be recharged during drilling.
- The battery can boost the mine AC supply during drilling.
- The unit can recharge when tramming downhill.

The Sandvik DD422iE is an example of a battery tramming driller. The unit is powered by a 160 kW battery and is claimed to be more energy-efficient than the diesel version.

2.4.6.8.6 Personnel Carriers

These are light vehicles designed to transport people and light equipment in the mine. There is a wide variety of battery-powered versions, but all are designed for steep gradients and rough roads, and the batteries are required to withstand this type of abuse. The batteries were originally automotive or small industrial types, and required several hours to recharge. More modern designs use LiFePO4 batteries for safety reasons. The personnel carrier is not expected to have a high duty cycle and is suited to slow charge methods. Designs may change with the advent of cheaper batteries for normal electric vehicles. The battery-powered mine personnel carrier has been in use for many years.

2.4.6.8.7 Future Battery Powered Ranges

MacLean's fleet electrification programme aims to offer customers a battery tramming/operating option on all units across the company's product range. GE also aims to produce battery-powered options for all of its diesel-powered mining equipment in the future. It is expected that other mining equipment manufacturers will follow suit.

Figure 18 The DD422iE tramming driller (Sandvik).

2.4.6.8.8 Hybrid Solutions

Hybrid diesel/battery electric propulsion systems are quite common in mine vehicles, offering a reduction in fuel consumption as well as better controls over the operation of the vehicle. Most hybrid versions also make use of regenerative energy recovery. There is a wide variety of hybrid configurations in use, making use of both batteries and super-capacitors [Louw, L: "Time to go electric"].

2.4.6.8.9 Regenerative Energy Recovery

Regenerative braking is a well-known technique of converting kinetic energy into electricity. In an EV or train, for instance, the movement is slowed down by reversing the motor to act as a generator. Regenerative braking is used extensively in mining BEVs, especially those operating on a fixed route with significant gradients. Where a BEV is operated over a fixed route, the regenerative energy could be calculated accurately, which would allow accurate sizing of the battery and recharge cycles.

2.4.6.8.10 Battery Technology

Battery-driven mine equipment has been around for almost 30 years. Earlier models used valve-regulated lead-acid batteries but the technology of choice today seems to be lithium-ion phosphate. Technologies in use include:

- Lead-acid: Lead-acid industrial batteries are an established technology, mainly the VRLA or valve regulated variety. Advantages are lower cost compared to other technologies, but the power density is lower and rapid recharge is usually not possible. The technology is falling out of favour except for smaller applications where weight is not critical.
- Lithium-ion phosphate (LiFePO4): A well-developed technology offering a very rugged battery with long service life and reasonably short recharge time. LiFePo4 batteries have the least probability of bursting into the flame of all the lithium-based batteries and are chosen for this reason.
- Lithium titanate: A high-performance battery offering a very short recharge time (15 minutes) and long cycle life. The battery was primarily developed for the mobile battery market and is offered by one of the suppliers of LHDs. The single-battery quick recharge system removes the need for backup batteries and a dedicated swap, service, and recharging area, which reduces cost.
- Sodium metal halide (NaMx): These batteries are an emerging technology with performance and longevity compared to those of lithium-ion (Li-ion) batteries, yet require less capital. NaMx technology has been considered for mass transit and industrial applications. One supplier uses a proprietary sodium nickel chloride battery.

The biggest concern with BEVs is the capacity of the battery and the ability to work a complete shift without a recharge. Capacities depend on the type of BEV and prospective usage cycle and range from four to eight hours. With a battery swap-out during the shift break, the four-hour capacity unit could manage an eight-hour shift of continuous operation. The development of batteries is expected to extend this time.

Figure 19 Sodium nickel chloride battery mounted on an LHD (Saminco).

2.4.6.8.11 Charging Regimes

To maintain most units in an operational state requires two sets of batteries: one in the vehicle and one on charge [J Burke: "GMSG recommended practices for battery electric vehicles in underground mines", 2016.]. Units using lead-acid (LA) batteries used three sets per BEV, two on the unit (one operational and one spare), and one on a charge. This was because LA batteries took eight hours to recharge. More advanced units can recharge in less time than it takes the battery to discharge and only two batteries are required per unit. The charging regime may be adopted if the BEV is not operational on a 24-hour basis.

2.4.6.8.12 On-board Charging

In this system, the charger is associated with the BEV, and the charge is accomplished by connection to an AC source. The disadvantage of this method is that extra weight is placed on the BEV. This system is used in tramming vehicles where connection to an AC source during operation is available, and where battery swap out is not used.

2.4.6.8.13 Off-board Charging

In this method, the charger is located at a special charging station and DC is fed to the BEV. The disadvantage is that the BEV is out of service during the charging process. This process only applies to BEVs that run a single shift or multiple shifts with breaks in between, and where swap-out is not anticipated. The battery must be able to power the BEV for the whole shift.

2.4.6.8.14 Off-board Swap Charging

In this method, a spare battery is charged off-board and swapped out with a discharged battery at specific times or the prompting of a charge monitoring system. The battery must have a discharge time longer than the charge time.

2.4.6.8.15 Hybrid Charging

This system is a combination of onboard and off-board. The onboard charger is used for slow charging of the battery, and the off-board when a rapid or boost charge is required.

2.4.6.8.16 Diesel-free Mines

The diesel-free mine option is being considered by several mining companies. Goldcorp, a gold producer based in Vancouver, Canada, recently announced plans to build the world's first diesel-free hard rock mine near Chapleau, Ontario. Going diesel-free is an ambitious goal. A typical mine can have dozens of diesel engines across its heavy equipment fleet. Going electric means enormous up-front cost, and massive retraining. This means embracing the reality that, until recently, the technology to create a diesel-free mine was barely a realistic possibility but has been made possible by developments in the battery storage sector.

2.4.6.9 Ice Plants

One of the existing methods that can be used to cool a mine is to use the latent heat of melting ice. This method was firstly used in 1982 at the East Rand Proprietary Mines in South Africa. Ice has a specific heat changing from 2040 J/ (kg °C) at 0°C to 1950 J/ (kg °C) at -20°C and latent heat of melting of 333.5 kJ/kg. The mass flow of water circulated a mine for cooling purposes can be reduced by a factor of over 5 if it is supplied in the form of ice. Four factors need to be considered when investigating ice plants for mine cooling:

- Manufacturing of ice
- Transporting ice underground
- Incorporation of an ice plant into a mine cooling system
- The benefits of the ice system.

2.4.6.9.1 Manufacturing of Ice

The ice that is used in a mine cooling system may be supplied either as particulate ice at sub-zero temperature or as a slurry of ice crystals within liquid water or brine.

2.4.6.9.2 Particulate Ice

The ice may be in a form of cylinders or tubes of clear ice, cubes, or as ice flakes that can be compressed into pellets for transportation. Water is sprayed or allowed to flow over the surfaces of plates, tubes, concentric cylinders that are cooled on their opposite sides by a refrigerant fluid. In the process of creating ice, additional thermal resistance to heat transfer is being created. This then requires an evaporator temperature of -15 to -30°C giving rise to coefficients of performance in the range 2.3 to 3.5, lower than this might be expected from a well-designed water chiller. In the process of producing flake ice, a thin film of ice is continuously removed from the surface of a rotating drum or metal belt. To remove this ice from the unit, the particles of ice then fall into a hopper that feeds into a screw or belt conveyor.

2.4.6.9.3 Slurry Icemakers

Slurry ice is produced at an earlier stage of development for mine cooling systems. In this case, the microcrystals of ice are formed within a stream of water or brine. Slurry ice has one primary advantage over particulate ice. Every industrial and domestic supply of water has many impurities involving magnesium, sodium, and dissolved salts of calcium. The freezing process favours pure water. This is why if freezing takes place sufficiently slowly or if the ice is continuously washed with water, then the ice crystals will have a greater purity than the water in which they grow. The dissolved salts remain in the liquid and become more concentrated.

In relatively, particulate ice occurs quickly and with a more limited washing action by the water, giving rise to the entrapment of salts within the ice matrix. If the microcrystals, usually less than 1 mm in size, are removed from the ice slurry and washed, then they will be relatively free from impurities. This process is known as freeze desalinization. Providing purified water to a mine cooling system assists greatly in minimizing corrosion and scaling within pipes and heat exchangers.

2.4.6.9.4 Transporting Ice Underground

The mass of ice required for a mine cooling system must be supplied continuously rather than in a batch transportation system. Slurry ice can be pumped through pipes while particulate ice must be transported from the ice-making plant to the shaft by conveying systems or by a hydraulic or pneumatic pipeline. In the process, the supply air temperature should be no more than 8°C to prevent the undue accumulation of the ice particles. Particulate ice falls through the shaft pipeline either as dense or slug flow or dilute flow where the particles are separated and keep their identity. At a later stage, the ice particles form into distinct slugs separated by air spaces. Having a too great ratio of ice to air may increase the risk of pipe blockage.

There are six factors involved in the type of flow through an ice pipeline: ice-to-air ratio, shape, size of the particles, the temperature of the particles, and the type and size of the pipe. Unplasticised PVC (uPVC) is a suitable pipe material for ice lines. But, changes in cross-section or lips at expansion joints should be avoided. Having radii of curvature of 3 m or more at the shaft stations allow the pipelines to be extended horizontally for several hundred meters.

2.4.6.9.5 Incorporation of an Ice Plant into a Mine Cooling System

The return water that is pumped from the mine goes through a surface pre-cooling tower and is further cooled in a water pre-chiller. This may be provided by the coolness from the ice-making refrigeration plant. The particulate ice falls through the shaft pipeline and is discharged into an ice/water mixing silo with a perforated base. Some of the water from the hot water dam is also sprayed into the ice silo. The discharge from the silo enters the cold-water dam at 0°C. This is illustrated in Figure 20.

The ice inside a silo should be kept at a thickness of 1 to 2 m while the supply of ice to each silo must be matched to the required cooling duty at that level. The ice level inside the silo should be monitored. This can be achieved through the use of Position transducers. The transmitted signals may be used to control the ice feed rates. Also, the mine at hand should have sufficient ice bunkering to accommodate any crisis or emergencies regarding the system.

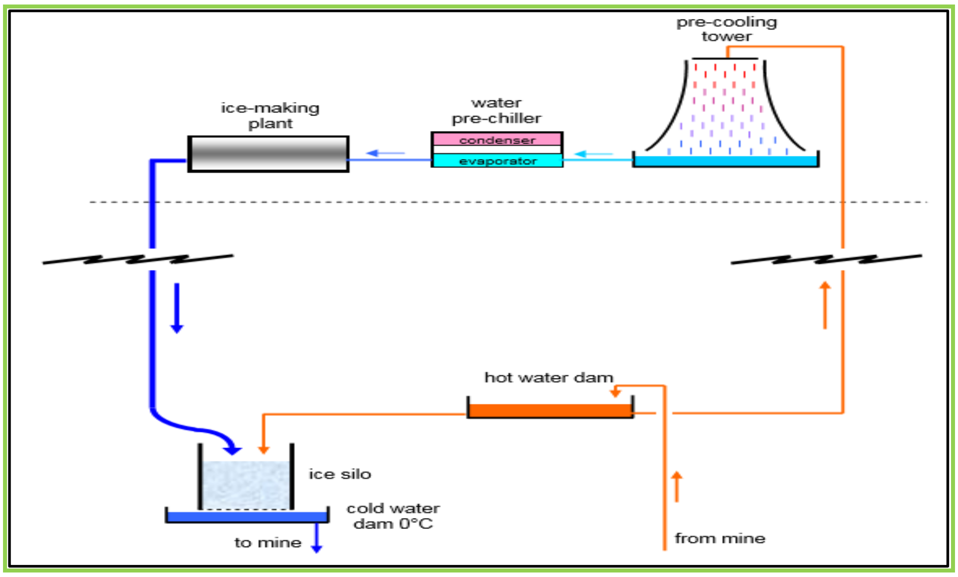

Figure 20 Incorporation of an ice plant into a mine cooling system

2.4.6.9.6 The Benefits of Using an Ice System

The benefits of using an ice plant as a cooling system at the mines have the following benefits:

- The quality of water is improved by ice-making.
- Smaller pipes and lower pumping costs due to a great reduction in water flow in shaft pipelines.
- The ice is stored in ice bunkers and silos to satisfy short term variations in demand.
- The need for turbines is reduced or eliminated which makes the subsurface system to be more simplified.
- Water is available at 0°C underground rather than the 3 to 6°C common with conventional chilled water systems. Therefore, there is less flow and reduced pumping costs in the subsurface circuits. Also, the performance of heat exchangers is improved.
- The ice plant system can be easily upgraded for future increases in cooling load.

2.5 Current mechanised equipment

The following are some examples of the current equipment available from various suppliers for mechanised mining. In effect, full suites of equipment are now available, which negates the use of compressed air underground in its totality.

2.5.1 Drilling

The Boomer S1 L is a low-profile hydraulic face drilling rig and uses well-proven, heavy-duty Epiroc (Atlas Copco) components such as the COP 1838 rock drill, BUT 28 SL boom, and BMH 2837 feed.

Figure 21 Epiroc Boomer S1 L (https://www.epiroc.com/en-za/products/drill-rigs/face-drill-rigs/boomer-s1l)

The Sandvik DD220L low profile drill makes use of the HLX5 rock drill, B26F boom, and a selection of feeds namely TF512, CD12, and CFX6/12.

Figure 22 Sandvik DD220L (https://www.rocktechnology.sandvik/globalassets/products/ underground-drill-rigs-and-bolters/pdf/dd220l-specification-sheet-english.pdf)

2.5.2 Support

For rock bolting, 1.6 m long Swellex bolts are used, in a standard bolting pattern of 1.5 m x 1.2-

1.5 m. The Boltec SL () is equipped with Secoroc Magnum SR28 Tapered Speed rods, with a 38 mm model -27-67 bits for Swellex installation. The tramming height of the Boltec SL is just 1.30 m, with a ground clearance of 0.26 m. It is equipped with a COP 1028HB rock drill and can insert a Swellex bolt of length up to 1.6 m in roof height of 1.8 m

Figure 23 Epiroc Boltec SL (Epiroc, 2013)

There are so many accessible faces near each other in the room and pillar layout and therefore utilization is a key factor for upholding a high level of productivity and efficiency. The required utilization for the drill rigs ranges from 50%-75%, and accessibility is about 90%.

2.5.3 Cleaning

The Scooptram ST600LP (Figure 24) is an extremely robust loader designed specifically for demanding thin seam applications where the roof heights are as low as 1.6 m.

Figure 24 Low Profile ST600LP Load Haul Dumper (LHD) (Atlas Copco, 2019)

The Epiroc Scooptram ST7 battery LHD Figure 24 is the battery equivalent of Epiroc's ST7 diesel LHD. It has a similar load-carrying capacity of 6.8 tons, slightly higher than the rated capacity of 6 tons of the RHAM HD20. It is equipped with a traction drive of 108kW and a hydraulic drive of 76 kW. The battery drive is rated at 165 kWh energy and 160 kW power output. Epiroc indicated that a low-profile model will be available in 2021, pending adequate interest from the industry.

Figure 25 Epiroc Scooptram ST7 Battery (Epiroc, 2016)

2.5.4 Trucking

The Sandvik TH550 hauls 50 tons of ore and is driven by a 515 kW engine. The haulers are driven remotely from the control room, using a high capacity Ethernet LAN (Stone, 2015). Both the loader and the haul trucks use a diesel engine.

Figure 26 Sandvik TH550 haul truck (Sandvik, 2018)

2.5.5 Belts

Fish-bone belts are installed on-strike every fifth ASD; three panels above and two below, which feed the main belt. This method makes use of a mobile crusher fitted with a sacrificial belt that is positioned in the strike belt drive (Figure 27).

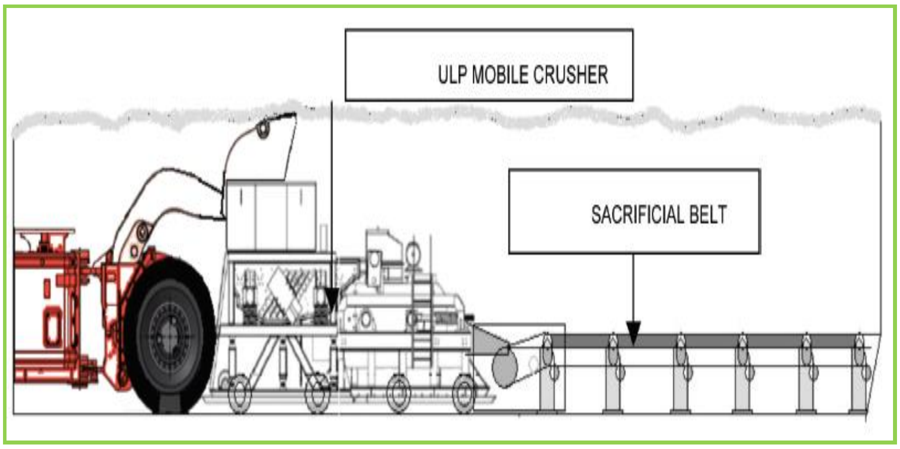

Figure 27 Section view of a typical crusher installation during predevelopment (Anglo American Platinum, 2014)

2.5.6 Development Drilling

The HPE narrow tunnel drilling rig (HPE, 2019) makes use of a monorail system that can be used to transport material and equipment along the horizontal and up to 34˚ in raise, gully, or traveling way. The nominal travelling speed is 0.3 m/s.

To do blast hole face drilling and roof bolt holes to develop travelling ways raises (finger raise and T raise) and gullies, furthermore to transport material and equipment along the horizontal and up to 34° in a raise, gully, or travelling way and to improve on safety whereby the operator is removed from the danger area. The rig is shown in **Error! Reference source not found.** is c apable of developing wide raises (T raise) of up to 8 m wide.

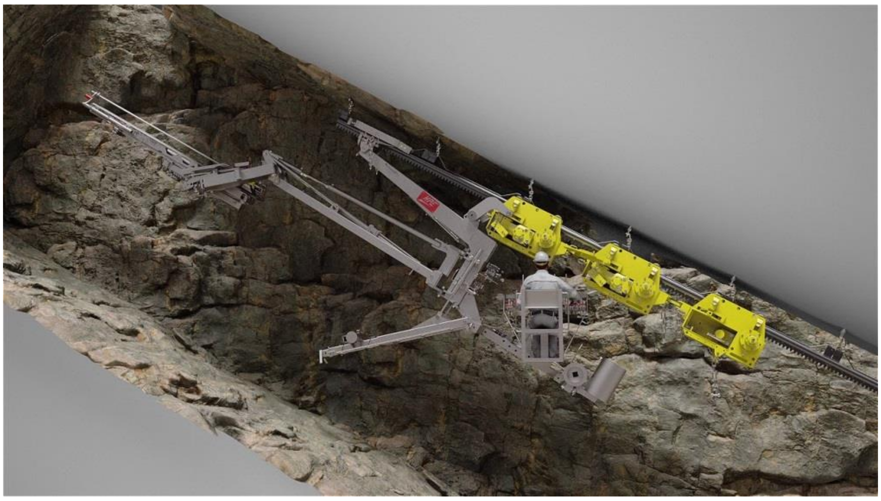

Figure 28 HPE narrow tunnel drilling rig on monorail (HPE, 2019)

2.5.7 Stoping Drilling

The XLP double boom drill rig is 8,396 mm in length, 2,200 mm in width, and a height of 854 mm.

Figure 29 XLP double boom drill rig (Draft Technical Support Document – MCE Mining Area, 2016)

shows the XLP double boom drill rig.

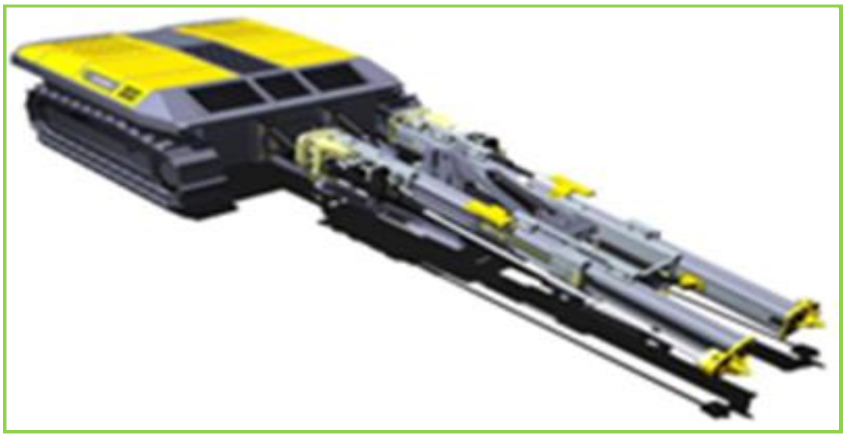

Figure 29 XLP double boom drill rig (Draft Technical Support Document – MCE Mining Area, 2016)

2.5.8 Roof-support

The XLP roof bolter is 4,963 mm in length, 2,198 mm in width, and a height of 854 mm. 0 below shows the XLP roof bolter.

Figure 30 XLP Roof bolter (Draft Technical Support Document – MCE Mining Area, 2016)

2.5.9 Cleaning

XLP dozers are remote-controlled machines suitable for multipurpose tasks and missions.

Table 9 XLP dozer comparison for diesel vs electric (Harrison, 2008)

Machine	Dok-ing MVD XLPD	Sandvik LZ101LE
Overall dimensions with blade	3435 x 1436 x 834 mm	3565 x 1650 x 965 mm
Pushing capacity	-	4000 kg
Speed	5 km/h (travel) 1.2 km/h (working)	4 km/h (tramming)
Power source	3100 m^3 diesel engine	85 kWh batteries
Power train	88 HP (~66kW)	60 kW
Torque	260 Nm	60 Nm
Work capacity (dozing)	5-10 h	5 h
Total weight	4000 kg	5800 kg
Operating principle	Radio remote control	Radio remote control
Productivity	50-120 t/h	-

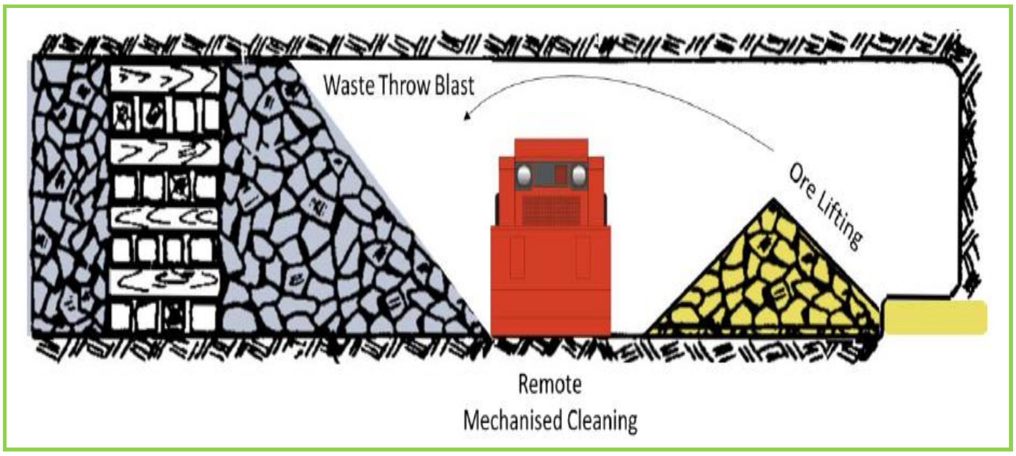

Figure 31 Remote mechanized cleaning equipment used in Resue mining (Minxcon, 2016)

2.5.10 MT1000 Multi-drill

The ability to mechanise conventional tabular orebodies has been a key strategic driver of the Safe Technology and Innovation department (STID) since its inception in June 2014. While the programme is extensive concerning dependencies, maneuverability was identified as the priority in terms of development. 2017 was a landmark year for the stope mechanisation programme as both the initial MT1000 multi-drill and MT100 sweeper and dozer prototypes were completed and deployed for testing.

The MT1000 is a multi-track (Figure 32), electrically driven platform capable of operating in a minimum stoping width of 1,000 mm. The four individual track assemblies are capable of three separate degrees of motion:

- Track rotation (drive).
- Track assembly rotation (lifting, lowering).
- Lateral articulation (steering), which is facilitated by an on-board hydraulic power circuit.

Figure 32 MT1000 Multi-drill during initial commissioning and sub-system testing (Sibanye Stillwater, 2018)

2.5.11 Monorail

Transport systems by FAMUR are designed for continuous haulage and transport of materials as well as people transportation. Complete material and man transport systems such as suspended monorail (Figure 33) or floor rail systems with diesel-powered locomotives, rope winches, track locomotives, and complete rail routes.

Figure 33 FAMUR Suspended monorail system (Mining Technology, 2019)

3 LITERATURE REVIEW FINDINGS

During the study, the following findings were made of the objectives during the work done:

3.1 The Impact of Mechanized and/or Automated Mining Operations

The mining industry has gone from hand-tool equipment to electrical and diesel-powered equipment, and it is now heading to semi-automation and full automation machines. The mechanisation of mining operations has also challenged ventilation in deep metal mines. Initially, only a few numbers of diesel equipment were used at the mines and it was quite small with engines of less than 75 KW. Since that time, the diesel equipment at the mines has larger engines of 260 to >550 KW and the number of these machines has dramatically increased. Increased mechanization and workforce mobility has effects on heat and required mines to more air quantities underground for the dilution of diesel fumes. An increase in air quantities will then result in an increase in pressure and power, which will drastically raise the cost associated (Kocsis, 2004). Heat production of a diesel engine at full load is about 3 kW of heat/rated kilowatt while heat production of an electric motor at full load is 1 kW of heat/rated kilowatt. Even though electrical equipment comparatively produces less heat and no fumes, mines still prefer to use diesel equipment due to practical requirements such as freedom of movement. Developments on improving the quality of diesel fuel and engine efficiency are being made, but these factors are still significant driving factors in planning the levels of ventilation and cooling for mine design (Mackay, 2012).

3.2 Incorporation of an Ice Plant into a Mine Cooling System

The return water that is pumped from the mine goes through a surface pre-cooling tower and is further cooled in a pre-chiller. This may be provided by the coolness from the ice-making refrigeration plant. The particulate ice falls through the shaft pipeline and is discharged into an ice/water mixing silo with a perforated base. Some of the water from the hot water dam is also sprayed into the ice silo. The discharge from the silo enters the cold-water dam at 0°C.

3.3 Ventilation on demand

A Ventilation on Demand (VOD) system continually monitors air quality and adjust ventilation as required. In this way, areas that are being worked in benefit from better, more efficient ventilation, while in areas not being worked the ventilation is reduced. Overall, this leads to significant electricity and other cost savings, and also makes the mine much safer and more productive.

Applying a VOD system requires complete and detailed knowledge of the mine ventilation network, the ongoing processes, and regulatory demands.

3.4 Hybrid Solutions

Hybrid diesel/battery electric propulsion systems are quite common in mine vehicles, offering a reduction in fuel consumption as well as better controls over the operation of the vehicle. Most hybrid versions also make use of regenerative energy recovery. There is a wide variety of hybrid configurations in use, making use of both batteries and super-capacitors [Louw, L: “Time to go electric”].

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3.6 Battery-operated mechanised machines

Battery-driven mine equipment has been around for almost 30 years. Earlier models used valve-regulated lead-acid batteries but the technology of choice today seems to be lithium-ion phosphate. Technologies in use include:

- Lead-acid: Lead-acid industrial batteries are an established technology, mainly the VRLA or valve regulated variety. Advantages are lower cost compared to other technologies, but the power density is lower and rapid recharge is usually not possible. The technology is falling out of favour except for smaller applications where weight is not critical.
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- Lithium titanate: A high-performance battery offering a very short recharge time (15 minutes) and long cycle life. The battery was primarily developed for the mobile battery market and is offered by one of the suppliers of LHDs. The single-battery quick recharge system removes the need for backup batteries and a dedicated swap, service, and recharging area, which reduces cost.
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3.7 Fuel cell operated mechanised machines

Most notably, hydrogen fuel cells are used to power cars, buses, and trains as a clean alternative to traditional petrol and diesel engines, which burn fuel to produce the energy they require.

Not only are hydrogen fuel cell vehicles a clean alternative, emitting only water from the tailpipe, these vehicles also refuel quickly with comparable driving ranges to traditional vehicles. This use is evolving with emerging applications to power delivery vans, trucks, and forklifts as well as boats and ships.

3.8 Main Study Recommendations

3.8.1 New ventilation systems

Ventilation engineering has a pivotal role to play in the innovation of novel mining designs and the future profitability of mining operations.

Mining Engineers should be able to apply their minds to an unrestricted mine extraction philosophy, thereby unlocking the full potential of the ore-body.

Antiquated ventilation and engineering considerations have hampered the ability to really "Sweat the Asset". Taking the idle capital deployed, and equipment efficacy over 24 hours, compels all mining disciplines to "step up to the plate" and design an optimised mine extraction strategy devoid of restrictions, where the entire mining process is honed to maximum proficiency.

In any fiscal analysis and optimisation process, one needs to understand the same production output.

- The Capex requirement.
- The Opex requirement.
- Production ramp-up.
- Tail management.
- The overall ROI.

It is therefore incumbent on the mining and ventilation engineer, to integrate the planning of new mechanised operations to ensure fit for purpose efficient designs.

New ventilation systems that will allow uninterrupted operations, via a short (30-minute re-entry interval) need to be developed in conjunction with the mining engineers.

This will allow for concentrated mining, where the assets are used continuously in a focused operational approach with improved supervision. The aim is to improve efficiency thus reducing the capital required and improving the Return on Investment (ROI)

The ventilation engineer must be part of the entire planning process, giving input into effective, and where possible on reef mine designs, equipment selection, and mining cycle.

The principal contributor to bottom-line mining organisation profits is to maximise the daily extraction ratio per block of ore reserve. To achieve this there are two main fundamental requirements, namely:

- Increase the blasting frequency.
- Implementation of a practically achievable mining cycle.

The capability of achieving the above is predominantly affected by available face time.

Ventilation on Demand (VOD) is an optimal ventilation control system that targets the "Real-Time" ventilation supply to individual mining areas, with the required quantities when they are needed taking full cognizance of ambient conditions at the time. In essence, it can cut ventilation and refrigeration costs dramatically, noting that:

- On average, ventilation accounts for up to 50 % of a mine's energy costs, and up to 15 % of a mine's total costs.

- The introduction of an extensive VOD system has the conservative potential of reducing the overall power expenditure by at least 20 %.

The introduction of a ventilation design that allows for VOD invariably supports the ability to reduce re-entry times and may also allow for variable shift and blasting times, as each ventilation segment is separately ventilated. Furthermore, it has major Capex and Opex benefits as it reduces the main ventilation infrastructure and concomitant operating costs.

Ventilation designs need to incorporate fan control using Variable Speed Drives (VSD) and Variable Pitch Blades (VPB). This is to ensure optimum efficiency through fan total life cycle duties by matching fan performance with increasing system resistance.

This will allow for:

- Optimised fan utilization ensuring peak efficiency.
- Implementation of Ventilation on Demand.
- Reduced re-entry times.
- Reduced Opex.
- Energy savings relating to input power and load shifting. [Time of Use (TOU) capabilities].

The ventilation engineer needs to optimise leakage factors and plan for low-pressure ventilation networks, noting the cubic relationship between volume flow and fan power.

Every effort needs to be taken through the entire design process to reduce the overall pressure drop by introducing an intelligent fit for purpose air supply which leads to a reduction of the total required airflow and pressure requirement within a mine. By reducing the total airflow and pressure, energy can be saved in disproportionately high amounts due to the cubic relationship between volume flow and fan power as shown with the following formula:

- $P = \Delta p \cdot V'$ and
- $\Delta p = R \cdot V'2$ resulting in
- $P = R \cdot V'3$

Finally, robust ongoing management of the designed ventilation system is further required to ensure optimised air distribution with minimal leakages. This will further require a critical review of current acceptable leakage parameters, coupled with the effective fit for purpose sealing and air distribution methodologies.

This will allow for:

- Reduced ventilation infrastructure, main fans, shaft sizes, main intakes.
- Reduced Capex and Opex.

A paradigm shift regarding the replacement of underground diesel equipment with battery alternatives is required to comply with safety and health considerations by ensuring zero-emissions underground equipment. Some of the many benefits are:

- Elimination of diesel fine particular matter and other exhaust gas components in the underground environment, requiring less ventilation and therefore lower costs, as well as improved health for miners.

- The efficiency of conversion from electric energy to wheel drives is much higher than the conversion efficiency from diesel to wheel drive, so the amount of heat that an electric vehicle produces is much less. This results in reduced ventilation requirements (30 to 50% less) and lowers associated energy costs.
- Less noise, vibration, and heat for miners operating the equipment underground, thus assisting in meeting the mental and physical health requirements of the worker.
- Lower carbon footprint, with associated carbon credits.

The implementation of new technologies and monitoring regimes results in countless information submissions. This information needs to be collated, analyzed, and distributed from one hub. This calls for the introduction of an overarching IoT.

Notwithstanding the mining and engineering benefits, the associated ventilation benefits include:

- Managing the entire VOD system.
- Condition monitoring of the occupational environment.
- Real-time monitoring of critical safety systems/ components.
- Real-time alarming/messaging – email, SMS, WhatsApp, etc.

3.8.2 Conclusion

There is no doubt that a step-change in ventilation optimisation in mechanised mining operations is realistic, which will greatly assist the mining engineer in developing an unconstrained mining extraction plan.

The available technologies need to become a focal area of optimisation where both the mining and ventilation engineer combine their respective skill set and challenge the current “self-inflicted” production limitations by “thinking out the box” and developing novel yet feasible mining plans. (Stanton 2020).

4 INDUSTRY WORKSHOP 1

4.1 Workshop Focus

The participants were briefed as to the objective of the workshop which is to share the collective expertise and to put in place ventilation criteria and principles to ensure innovative fit for purpose ventilation engineered designs to augment the new mechanised mining journey by:

- **D**esigning novel ventilation systems for the different types of mining methods for mechanized mines.
- Challenging Mining Engineers and OEM's to innovative ventilation designs.

4.2 Background

The circumstantial reasons for the renewed focus on ventilation optimisation relating to mechanised mining were discussed to stress upon the participants the importance of finding innovative solutions, which were gleaned from the Work package 4 Mechanised Mining Optimisation. The main points of information transfer were:

- Conventional mining methods are very labour intensive, and the ever-increasing distances to working places result in reduced shift time.
- The mines believe that stoping operations in narrow reef mines need to be fully mechanised to negate the conventional mining barriers to safety and production.
- The lack of innovation in the current conventional operations where efficiency is very dependent on the individual team members' physical output.
- Critical stoping activities are time-dependent, therefore mining cycle times are hard-pressed invariably resulting in sub-standard work, manifesting into lost blasts, poor safety performance, and lower profit margins.

This was followed with an extract from the Mechanised Mining Optimisation, Work Package showing typical face time per shift for a conventional mining system as depicted below.

Activity	Duration (hours)
Travel in	1
Waiting Place procedure	0,5
Early entry examination	0,5
Installation of safety nets	0,5
Installation of temporary support	0,5
Drilling in-stope roof-bolts	2
Marking of the panel	0,5
Drilling of panel	4
De-sludge blast holes	0,5
Charging up	0,6
Tamping	0,6
Connecting the round	0,5
Removing of temporary support	0,5
Travel out	1
Total	**13,2**

The above table highlighted the dire situation mining engineers are facing, thus adding impetus to the quest of pursuing a mechanised mining ore extraction strategy.

This is further entrenched by the following additional factors:

- With the current Covid 19 pandemic which may be prevalent for a long time, it is virtually impossible to integrate "social distancing" with the conventional mining labour intensive practice. This will inevitably lead to zero harm challenges and ultimately the viability of a company.
- Stoping operations need to be fully mechanized where possible, to negate the conventional mining barriers, to safety and production.

Ultimately to negate the negative factors affecting conventional mining methods, innovative mining layouts that are coupled to fit for purpose ventilation engineered designs are urgently required.

It was further noted that Novel mining and ventilation designs will unlock additional mining reserves that are currently not feasible, thereby increasing work opportunities.

4.3 Ventilation Research Findings

A literature search about optimised ventilation designs and newly available technology was carried out, was captured and shared with the workshop participants. The following are the salient findings including personal recommendations.

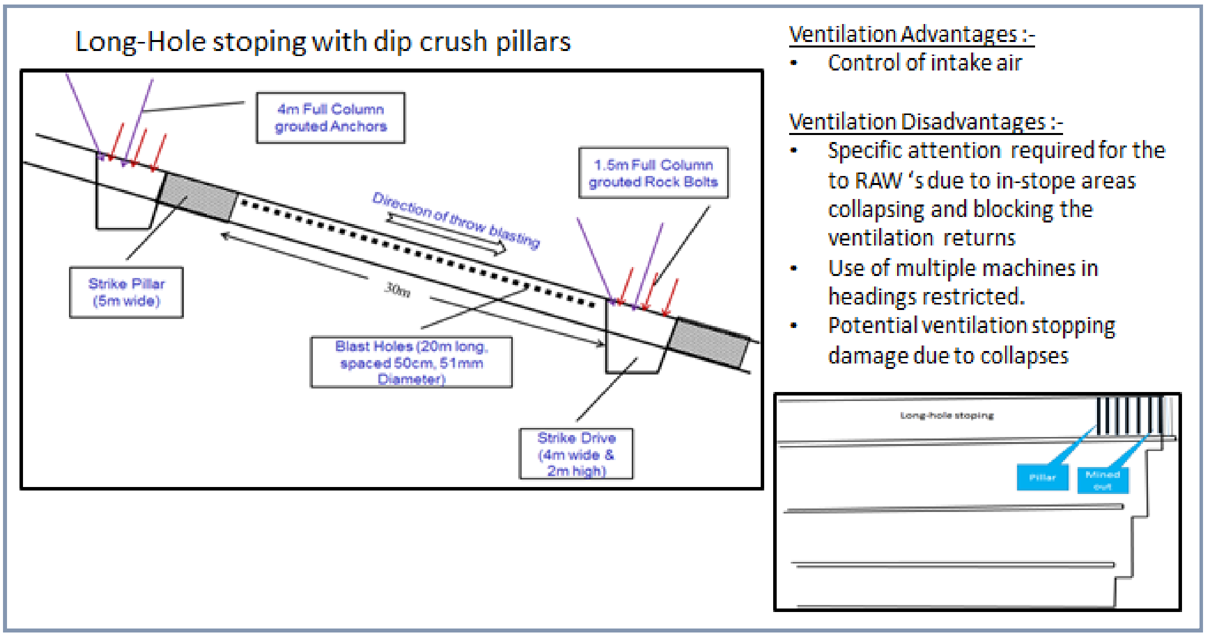
- It is incumbent on the mining and ventilation disciplines, to integrate the planning of new mechanized operations to ensure fit for purpose efficient designs
- New ventilation systems that will allow uninterrupted operations, via a short (30-minute re-entry interval) or hot seat handover, need to be developed in conjunction with the mining engineers
- The ventilation benefits of concentrated mining, where the assets are used continuously in a focused operational approach with improved occupational data management are required. The aim is to drastically improve the ventilation efficacy thus reducing both Capex and Opex requirements and improving Return on Investment (ROI)
- The ventilation engineer must be an integral part of the entire planning process, giving input into effective fit for purpose designs, equipment selection, and mining cycle.
- Stoping operations in narrow reef mines need to be fully mechanized to negate the conventional mining barriers to safety and production.
- The ventilation engineer must also take cognizance of existing infrastructure making use of it where reasonably practical taking due care to resistances and potential leakages
- Every effort needs to be taken through the entire design process to reduce the overall pressure drop by introducing an intelligent fit for purpose air supply which leads to a reduction of the total required airflow and pressure requirement within a mine.
- By reducing the total airflow and pressure, energy can be saved in disproportionately high amounts due to the cubic relationship between volume flow and fan power as shown with the following formulas:
  - $P = \Delta p \cdot V'$ and
  - $\Delta p = R \cdot V'2$ resulting in
  - $P = R \cdot V'3$
- Robust ongoing management of the designed ventilation system and the occupational environment is further required to ensure optimised air distribution with minimal leakages. This will further require a critical review of current acceptable leakage

parameters, coupled with the effective fit for purpose sealing and air distribution methodologies.

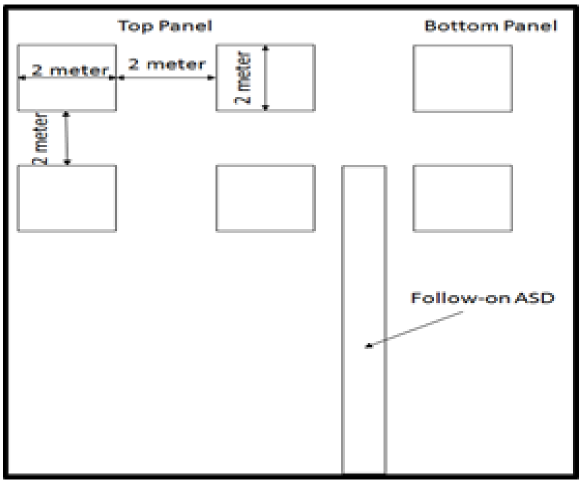
- There are many innovative opportunities with proven technology available for implementation i.e.
    - Ventilation on Demand
    - Variable Speed Drives
    - Variable Pitch Blades
    - Introduction of Battery or Fuel cell trackless equipment
- An industry expert review into generic ventilation design criteria is required to review and optimise existing standards and to formally support new novel technologies and ventilation systems.

4.4 Mining Methods

Various promising mechanised mining methods that are being scrutinised as part of the Mining Optimisation Work Package was discussed in detail to sensitize the participants regarding current opportunities. The following figures, depict the possible mining methods and include high-level ventilation advantages and disadvantages.



Small Bord-and-Crush Pillar



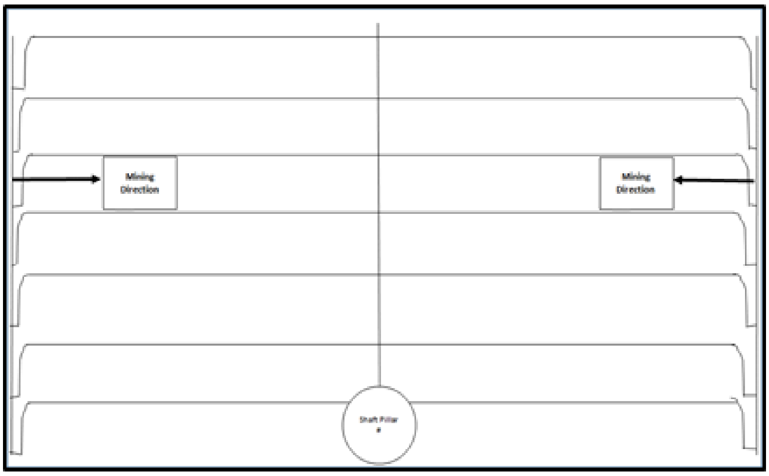
Ventilation Advantages :-

- Low pressure system

Ventilation Disadvantages :-

- Large area requiring ventilation
- Poor ventilation in headings
- Many seals - accumulating ventilation leakage losses

Retreat mining with caving



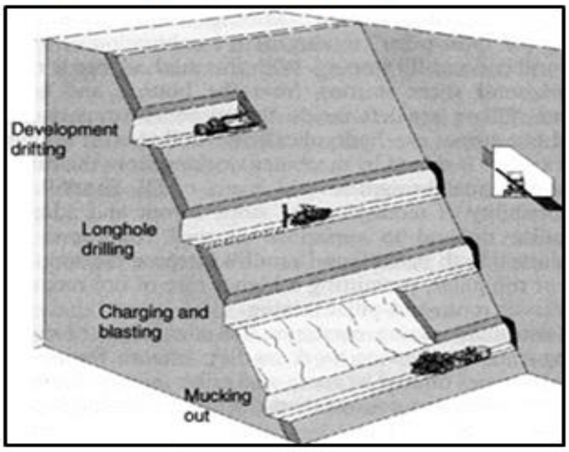
Ventilation Advantages :-

- Reducing area requiring ventilation

Ventilation Disadvantages :-

- Moderate - high pressure system
- Irregular ore extraction can complicate ventilation.
- Possible blockages of RAW

Narrow vein steep dipping mining with Long hole stopping



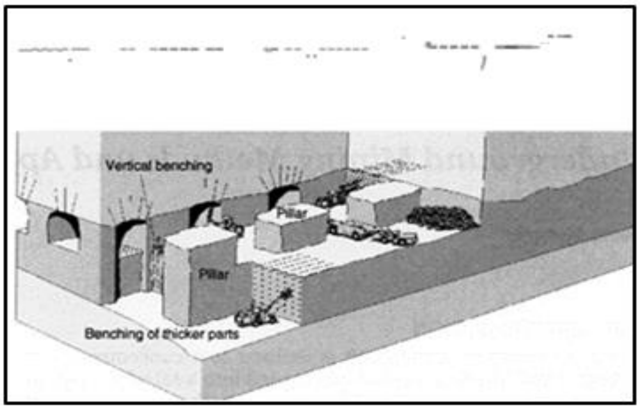
Ventilation Advantages :-

- Control of intake air

Ventilation Disadvantages :-

- Specific attention required for the to RAW 's due to in-stope areas collapsing and blocking the ventilation returns
- Use of multiple machines in headings restricted.
- Long strike seals with increasing leakage losses

Classic Bord-and-Pillar – Flat dipping reef applies to flat deposits having moderate-to-thick beds and to inclined deposits with thicker beds



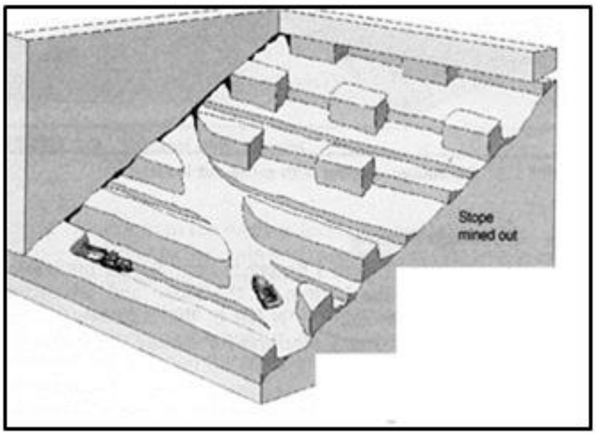
Ventilation Advantages :-

- Low pressure system

Ventilation Disadvantages :-

- Large area requiring ventilation
- Poor ventilation in headings
- The larger openings require larger fans
- Network of roadways can complicate air distribution
- Vertical benching can complicate ventilation.
- Potential blast damage to existing seals
- Difficult ventilation seal installation due to final excavation height

Step room-and-pillar mining applies to tabular deposits with thicknesses from 2 to 5 m and dips ranging from 15 ° to 30°.



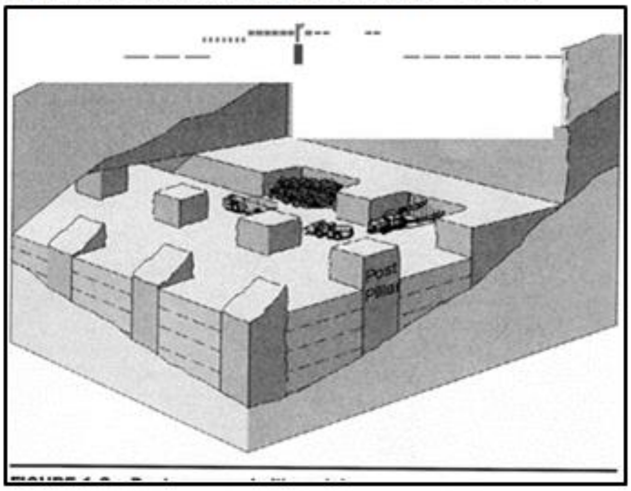
Ventilation Advantages :-

- Low pressure system

Ventilation Disadvantages :-

- Large area requiring ventilation
- Poor ventilation in headings
- The larger openings require larger fans
- Network of roadways can complicate air distribution
- The irregular mine plans can complicate ventilation.
- Multiple seals result in increased ventilation leakage losses

Post room-and -pillar mining applies to inclined ore bodies with dip angles from 20° to 55°.



Ventilation Advantages :-

- Low pressure system

Ventilation Disadvantages :-

- Large area requiring ventilation
- Poor ventilation in headings
- The larger openings require larger fans
- The irregular mine plans can complicate ventilation.

4.5 Mining Method Grouping

The mining methods were further expounded on by explaining the following table which classifies the variant mining methods into depth zones and different reef dip angles.

Depth (m)	Classification	Reef Dip° 0 -10	Reef Dip° 11 - 34	Reef Dip° 35 - 90
0 -500	Shallow	Classic Bord-and-Pillar	Step room-and-pillar	*Post room-and - pillar mining*
500 – 2 200	Intermediate	XLP/ULP	Small Bord-small-pillar	Narrow vein steep dipping mining with Long hole stoping
2 200 – 3 500	Deep	Small Bord-small-pillar	Long hole stoping with dip crush pillars	Long hole stoping with dip crush pillars
3 500 -	Ultra Deep	Small Bord-small-pillar	Long hole stoping with dip crush pillars	Long hole stoping with dip crush pillars

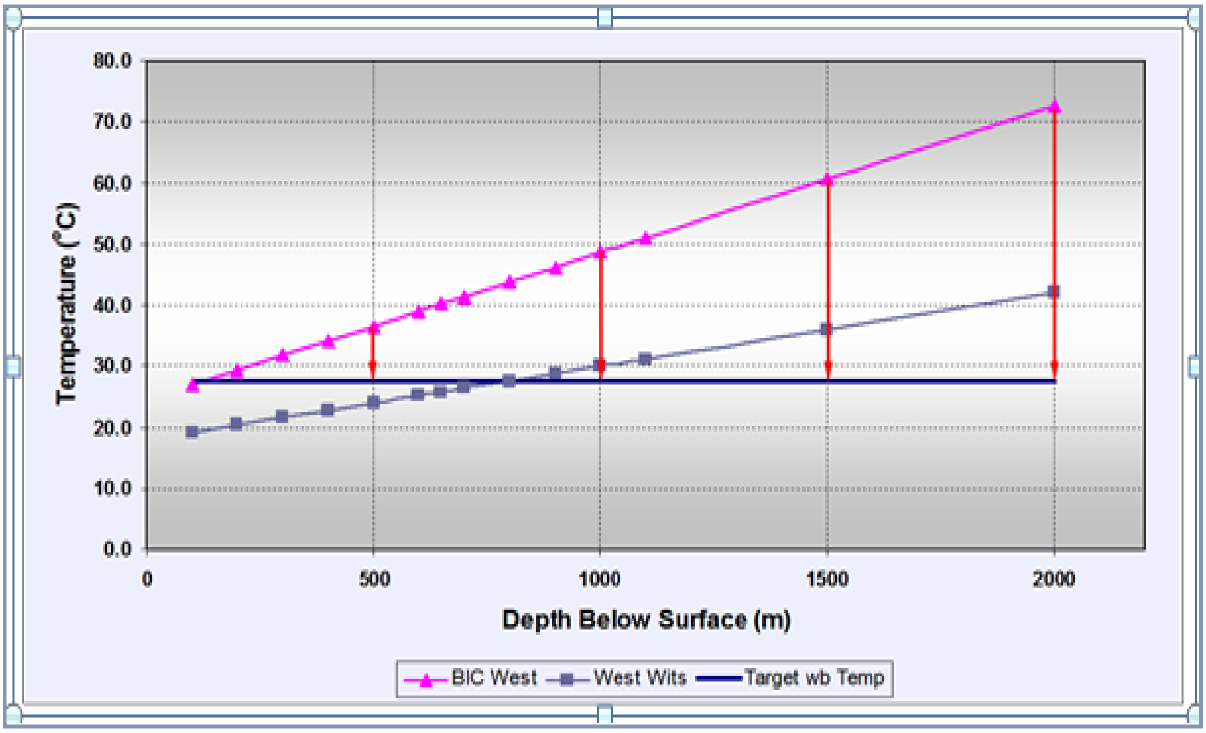
4.6 General Recommendations

A discussion ensued about recommendations made emanating from the literature survey and personal inputs which revealed that the development of specific ventilation designs will be dependent on the mining area, and the mine extraction strategy.

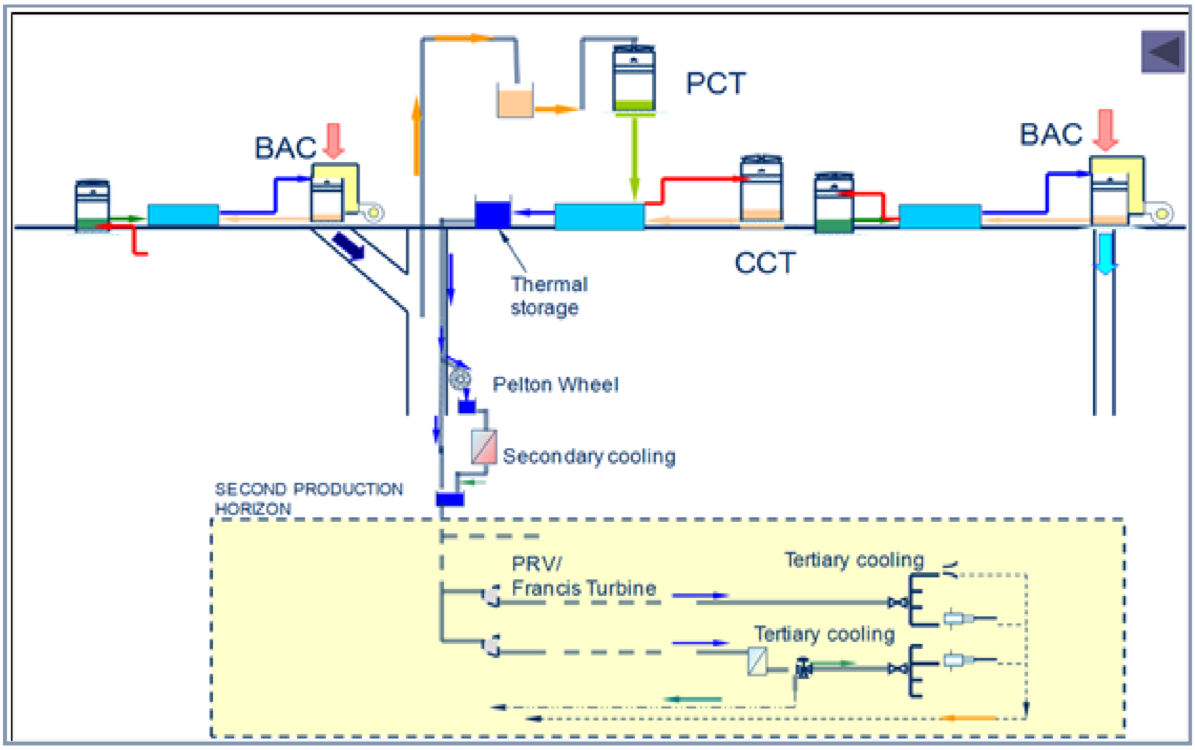
The following are areas where improvements via the implementation of the following criteria would have a marked positive impact on ventilation optimisation. It would therefore be expedient to support ventilation engineers in the field by revising the current design criterion for planning to focus on:

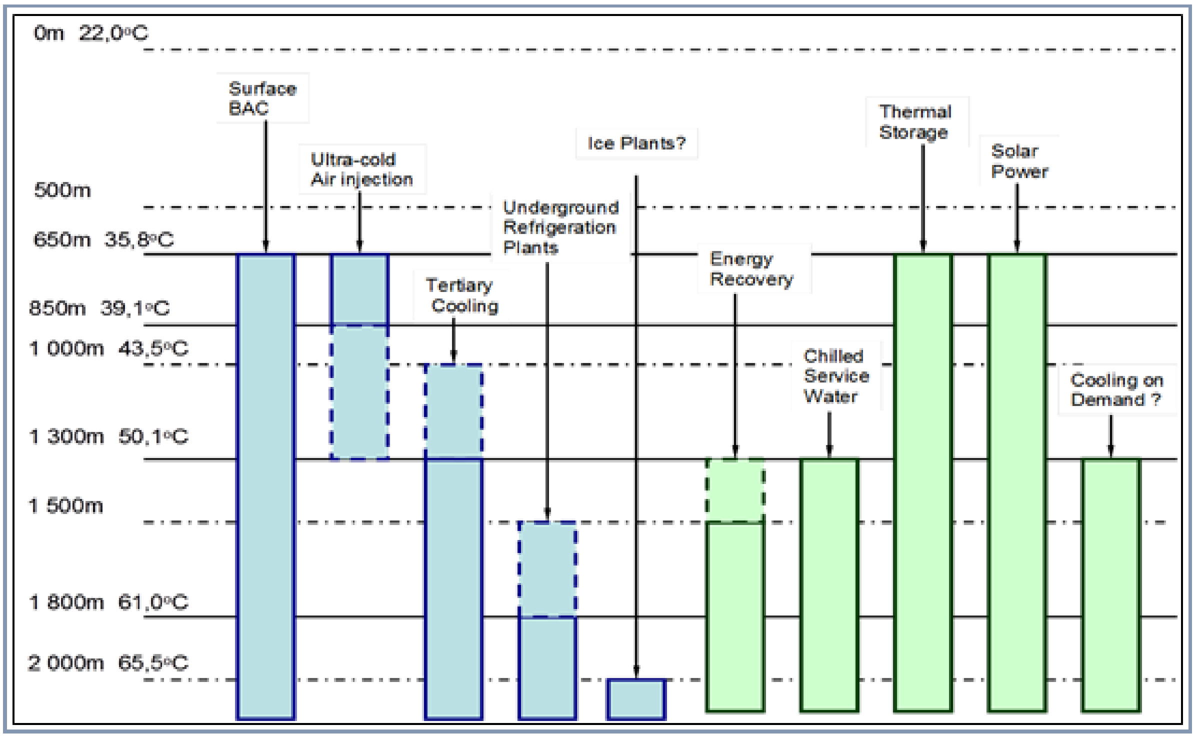
- Reduction of air leakage factors
- Design new mines in such a way as to incorporate systems for faster re-entry times (integrated systems)
- Challenging in older operations because of their existing infrastructure
- Implementation of Ventilation on Demand (VOD)
- Replacement of Diesel machinery – Battery or Fuel cell
- Fan control using Variable Speed Drives (VSD) and Variable Pitch Blades (VPB) ensuring optimum efficiency through fan life cycle duties.
- Industry-focused cooling strategies
- Energy recovery
- Thermal storage
- Introduction of Ice
- Hot ground fissure water to run absorption chillers to provide underground cooling
- Solar-powered refrigeration
- Sustainability and reduction in carbon footprint
- Real-time monitoring of the occupational environment and critical safety components/systems through the implementation of an Internet of Things (IoT) analytical system coupled with real-time alarming, email, SMS, WhatsApp, etc.

In terms of cooling strategies, there is a need to develop specific ventilation frameworks for the various mining areas and concomitant Virgin Rock Temperatures (VRT). A "one fits all" scenario does not apply to ventilation engineering. The following figure depicts some of the variant VRT gradients relating to depth, requiring designs to meet in-situ temperatures. Based on the work that has been done and, looking at the Bushveld Igneous Complex (BIC) and the West Wits the target temperature should be around about 29.5°C.



The following two slides presented and discussed depicts graphically the various technologies available and can be used as a guideline of potential application in new mines. These were developed specifically for the platinum industry, but require review and update to ensure all new technologies have been incorporated, giving the ventilation engineer a blueprint of available optimisation opportunities. Similarly, this information should be updated for the variable mining areas specifically relating to depth and corresponding VRT.

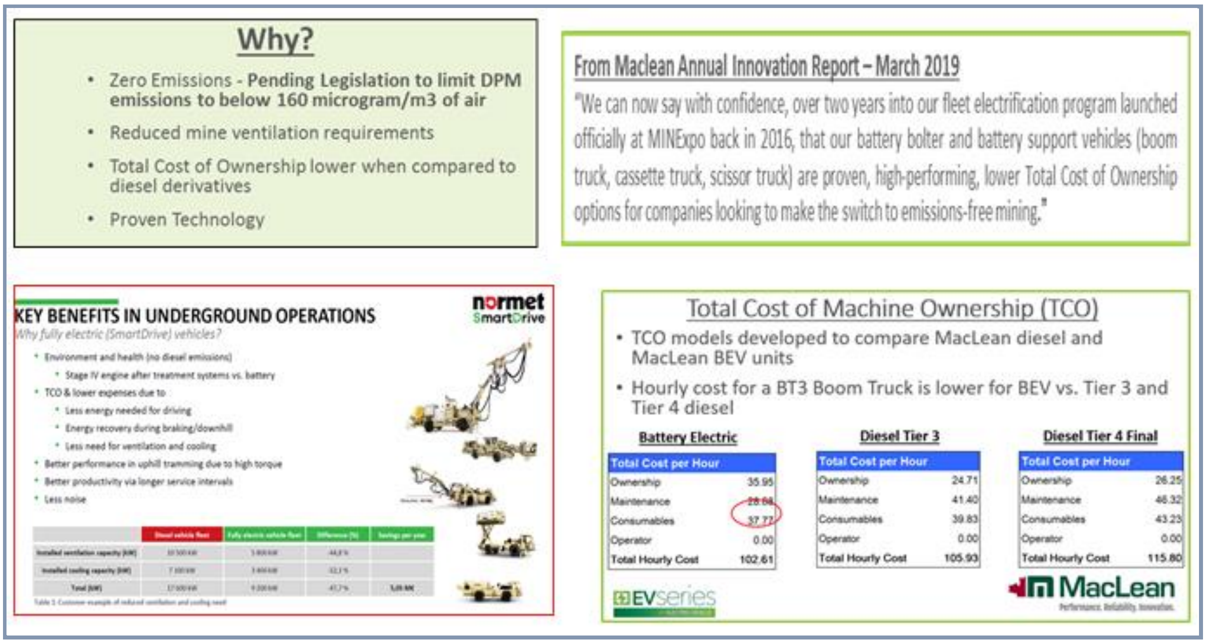


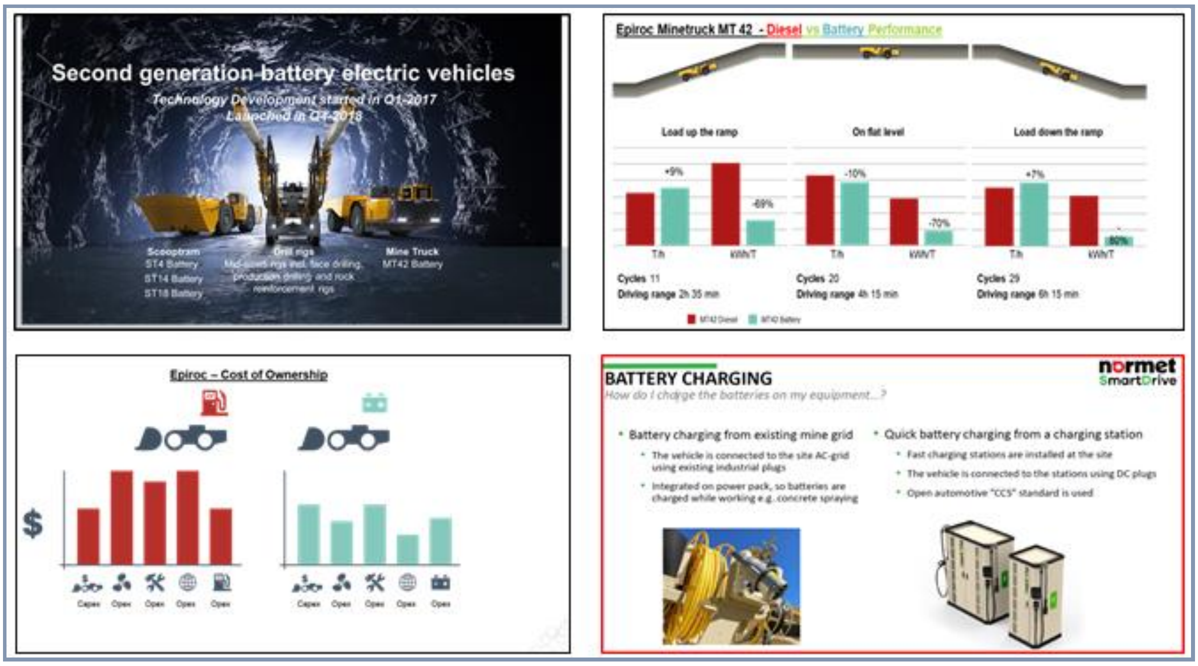


4.7 Battery Electric Vehicles (BEV)

Battery or fuel cell vehicles have developed to the stage where they are comparative with the diesel alternative. There are manifold occupational health benefits and ventilation/cooling benefits about the implementation of these units.

The following slides were discussed which highlighted the benefits of BEV, where some suppliers claim that their equipment's total owning costs are better than the diesel alternative.





4.8 Brainstorming Focal Areas

Unfortunately, time did not allow to brainstorm all the possible optimisation interventions, therefore six areas with the most promising prospects of assisting in the question "Designing novel ventilation systems for the different types of mining methods for mechanized mines" were debated:

4.8.1 Develop ventilation designs to ensure “Multi Blast” stoping operations

Participant’s response

The focal point was fully accepted, however, the request was to change the wording “Multi Blast” to blasting more than once in 24Hours. This was fully accepted noting this required early re-entry (30min) or virtual hot seat handover. This would require ventilation engineers to plan accordingly should the mining extraction plan call for this. It was further noted that to “sweat the asset” mining engineers within the Mining Optimisation work package are contemplating two 10 hour shifts with a blast at the end of each shift.

4.8.2 Design ventilation fan control using Variable Speed Drives (VSD) and Variable Pitch Blades (VPB), to ensure optimum efficiency through fan total life cycle duties by matching fan performance with increasing system resistance.

Participant’s response

The benefits of the system were expounded and accepted pending demonstration of the financial benefits for the specific project. It was however felt that automated variable pitch blades were problematic and that the manually adjustable option was the preferred selection. This was endorsed by the participants.

4.8.3 Optimise leakage factors and plan for low-pressure ventilation networks

Noting:

- The cubic relationship between volume flow and fan power
- The omission that increased leakages due to higher system resistance is not taken into account in our simulations and CAPEX/OPEX evaluations.

Participant’s response

The debate around this factor led to the reintroduction of effective controls. It was accepted that the cost of energy has changed the focus as the cost of reducing leakages can now be justified by introducing more effective ventilation control installations which do come at a premium. It was also felt that this aspect could be further addressed during ventilation modelling to optimise this factor.

4.8.4 Introduction of full-scale Ventilation on Demand (VOD) systems.

- Understanding the barriers to implementation
- Proposed approaches of attaining management “Buy-In"

Participant’s response

VOD although proven technology remains problematic for full-scale implementation. Many lesser VOD systems are deployed daily with success, however, the full-scale implementation has as yet to be accepted by senior mining engineers and mine management. The ensuing discussions focussed on the barriers experienced and remedies to negate the current status quo. It was however very apparent that connectivity to monitoring systems with real-time streaming was the major stumbling block to this innovative cost-saving initiative becoming the standard.

Also, it was mooted that this facet of ventilation required dedicated staff to monitor, adjust and control the overall efficacy of the system and that this normally would be an added responsibility for *the ventilation engineer. Therefore it was the consensus of the meeting that to effectively implement full-scale VOD, it would be critical to have:-*

- *Real-time monitoring coupled to an analytical Internet of Things (IoT)*
- *Dedicated ventilation engineers driving and owning the system*
- *On hand instrument technicians under the auspices of the ventilation, engineer to ensure the effectiveness of the system, and to undertake the remedial work required with maximum despatch.*

4.8.5 The full-scale roll-out of the Internet of Things (IoT) with built-in analytics

To monitor and tweak the ventilation system continuously in terms of:

- Managing the VOD system
- Condition monitoring of the occupational environment
- Real-time monitoring of critical safety systems/ components
- Implementation of smart mining, thereby creating a safer more productive occupational environment that meets the mental and health requirements of the workers.

Participant's response

IoT was determined to be the silver thread that is required to implement the majority of the current innovative systems available to optimise the ventilation system and to assist in achieving the planned mechanised mining optimisation required.

IoT is pivotal to the effective implementation of novel ventilation systems and needs to be addressed as a separate focused area, failing which many innovative systems will fail.

4.8.6 Replacement of Diesel machinery

Participant's response

The benefit both from occupational exposure to harmful substances, as well as the cost of additional ventilation and cooling, is well understood and quantified by the ventilation engineers.

We however need a common front to engage with the mining and mechanical engineers to ensure the replacement of diesel-powered units with the green zero-emission alternatives.

It was further noted by the participants, that advances in BEV and Fuel Cell technologies are well developed and now offer comparable or better alternatives in terms of TOC, power, and efficiencies.

4.9 Conclusion

The workshop was well attended and a good exchange of ideas took place. The brainstorming areas were all accepted and comments were made to improve the focus. The participants were further encouraged to engage with the facilitator regarding any additional sharing of information or ideas.

We all ended the workshop with the following inspiring words "Never Adapt – Own It" This will assist us in rising to the challenge and achieving the optimised ventilation solution for the Mechanised Mining Optimisation program.

All the participants were reminded of the second workshop to be held on 15 September 2020.

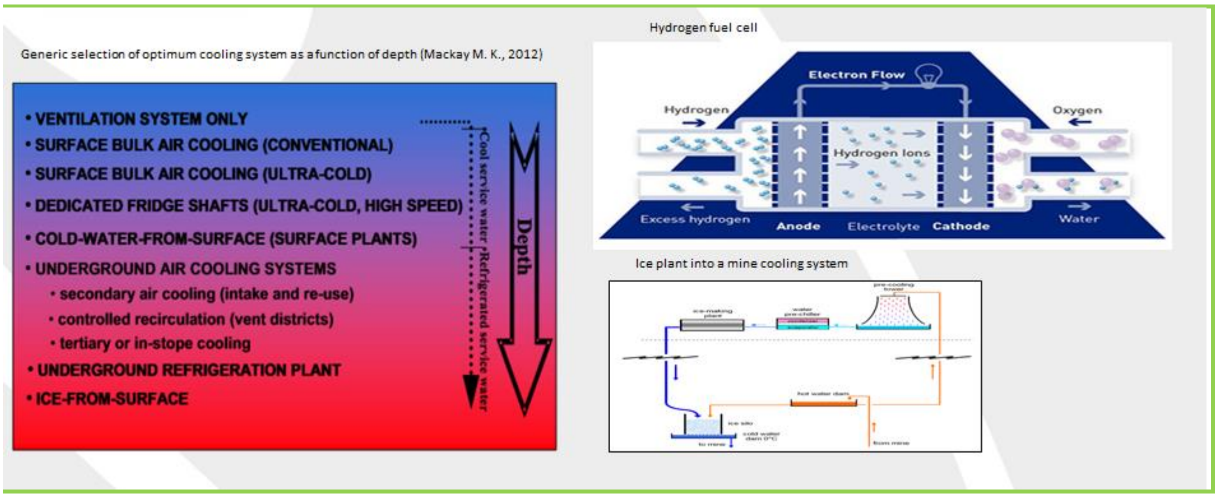
5 INDUSTRY WORKSHOP 2

5.1 Introduction

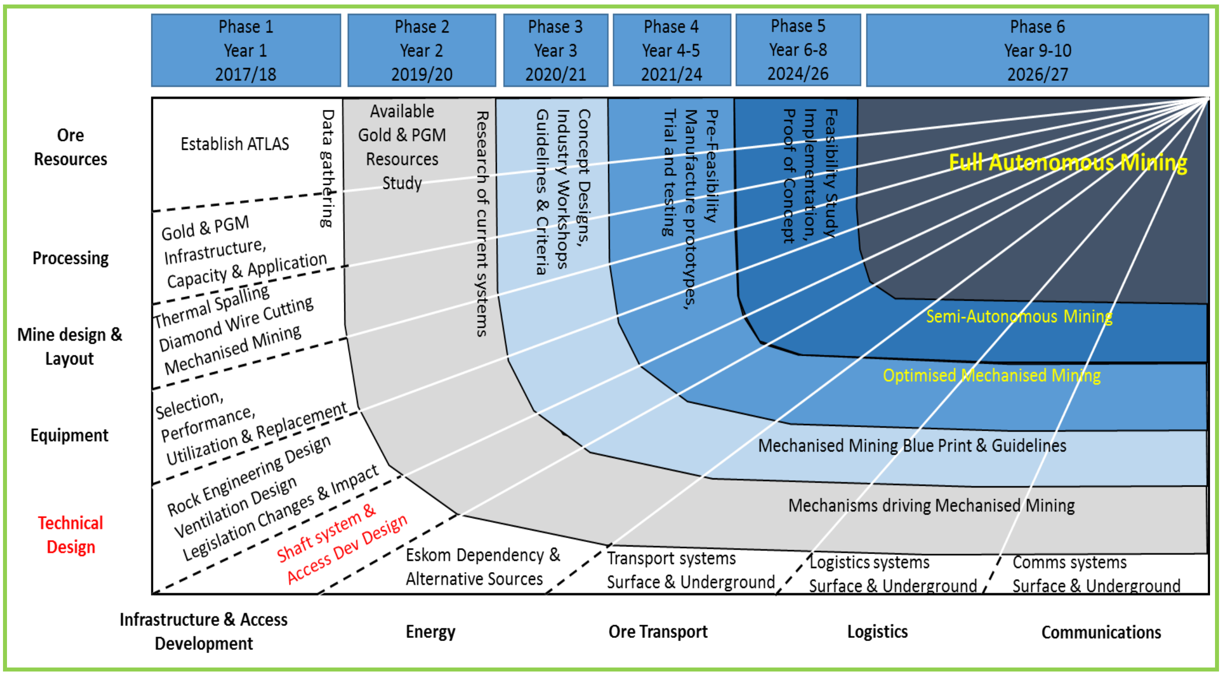
Mr. Pretorius opened the workshop and after welcoming all the participants stated that this workshop is a follow on from the initial workshop held on the 18th of August, which focused on optimizing ventilation engineering practices specific to mechanized mines. He further explained that today's workshop deals with current innovative technologies where Original Equipment Manufacturers will be sharing some of the available novel systems and requested all present to participate freely, as the contributions are highly esteemed and add value to the process

Mr. Pretorius went on discussing in detail the following three slides, of which the main thrusts are captured here.

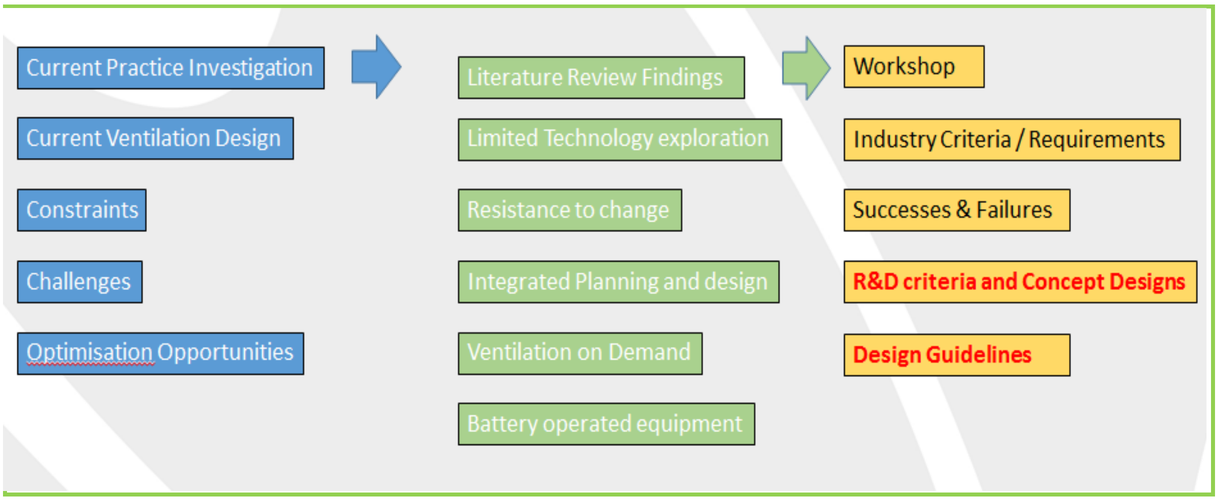
The slide I depict the current generic cooling systems available for optimising ventilation and cooling of the underground environment, including the introduction of Ice in high thermal underground loading, and the advanced novel use of hydrogen fuel cell technology as an alternative energy source.



Slide 2 depicts the Mandela Precincts detailed six-stage roadmap to full autonomous mining by the year 2027



Slide 3 depicts the process underway specifically within the focused Ventilation Area of engineering of the Work Package 4.3.2 Ventilation Design Optimisation which will culminate in a design guideline.



5.2 Workshop Focus

In this workshop which includes Original Equipment Manufacturers (OEM's), the objective is to share current innovative technologies available to aid fit for purpose criteria and requirements for ventilation engineered designs and to set the bar in novel ventilation systems thus enhancing new mechanised mining designs.

The main focus of this workshop will be presentations from leading OEM's within the following arena:

1. Introduction of full-scale Ventilation on Demand (VOD) systems.
   - ✓ Understanding the barriers to implementation
   - ✓ Proposed approaches of attaining management "Buy-In"

2. Design ventilation fan control using Variable Speed Drives (VSD) and Variable Pitch Blades (VPB), to ensure optimum efficiency through fan total life cycle duties by matching fan performance with increasing system resistance.
3. Personnel Safety and Environmental Monitoring
4. Replacement of Diesel machinery, with battery suites
5. The full-scale roll-out of the Internet of Things (IoT) with built-in analytics to monitor and tweak the ventilation system continuously.
    - ✓ Manage the VOD system
    - ✓ Condition monitoring of the occupational environment
    - ✓ Real-time monitoring of critical safety systems/ components
    - ✓ Implementation of smart mining, creating a safer more productive occupational environment

5.3 Re-Cap on Initial workshop

The circumstantial reasons for the renewed focus on ventilation optimisation relating to mechanised mining were discussed to stress upon the participants the importance of finding innovative solutions, which were gleaned from the Work package 4 Mechanised Mining Optimisation.

The initial workshop focused on some of the areas with the most promising prospects of Designing Novel Ventilation Systems. The following are the main aspects.

Ventilation engineering has a pivotal role to play in the innovation of novel mining designs and the future profitability of mining operations.

Mining Engineers should be able to apply their minds to an unrestricted mine extraction philosophy, thereby unlocking the full potential of the ore-body.

Antiquated ventilation and engineering considerations have hampered the ability to really “Sweat the Asset”. Taking the idle capital deployed, and equipment efficacy over 24 hours, compels all mining disciplines to “step up to the plate” and design an optimised mine extraction strategy devoid of restrictions, where the entire mining process is honed to maximum proficiency.

In any fiscal analysis and optimisation process, one needs to understand the same production output:

- The Capex requirement
- The Opex requirement
- Production ramp-up
- Tail management
- The overall ROI

It is therefore incumbent on the mining and ventilation engineer, to integrate the planning of new mechanised operations to ensure fit for purpose efficient designs.

New ventilation systems that will allow uninterrupted operations, via a short (30-minute re-entry interval) need to be developed in conjunction with the mining engineers.

This will allow for concentrated mining, where the assets are used continuously in a focused operational approach with improved supervision. The aim is to improve efficiency thus reducing the capital required and improving the Return on Investment (ROI)

The ventilation engineer must be part of the entire planning process, giving input into effective, and where possible on reef mine designs, equipment selection, and mining cycle.

The principal contributor to bottom-line mining organisation profits is to maximise the daily extraction ratio per block of ore reserve. To achieve this, there are two main fundamental requirements, namely:-

- Increase the blasting frequency
- Implementation of a practically achievable mining cycle.

The capability of achieving the above is predominantly affected by available face time.

Ventilation on Demand (VOD) is an optimal ventilation control system that targets the "Real-Time" ventilation supply to individual mining areas, with the required quantities when they are needed taking full cognizance of ambient conditions at the time. In essence, it can cut ventilation and refrigeration costs dramatically, noting that:

- On average, ventilation accounts for up to 50 % of a mine's energy costs, and up to 15 % of a mine's total costs
- The introduction of an extensive VOD system has the conservative potential of reducing the overall power expenditure by at least 20 %.

The introduction of a ventilation design that allows for VOD invariably supports the ability to reduce re-entry times, and may also allow for variable shift and blasting times, as each ventilation segment is separately ventilated. Furthermore, it has major Capex and Opex benefits as it reduces the main ventilation infrastructure and concomitant operating costs.

Ventilation designs need to incorporate fan control using Variable Speed Drives (VSD) and Variable Pitch Blades (VPB). This is to ensure optimum efficiency through fan total life cycle duties by matching fan performance with increasing system resistance. This will allow for:

- Optimised fan utilization ensuring peak efficiency
- Implementation of Ventilation on Demand
- Reduced re-entry times
- Reduced Opex
- Energy savings relating to input power and load shifting. [Time of Use (TOU) capabilities]

The ventilation engineer needs to optimise leakage factors and plan for low-pressure ventilation networks, noting the cubic relationship between volume flow and fan power. Every effort needs to be taken through the entire design process to reduce the overall pressure drop by introducing an intelligent fit for purpose air supply which leads to a reduction of the total required airflow and pressure requirement within a mine. By reducing the total airflow and pressure, energy can be saved in disproportionately high amounts due to the cubic relationship between volume flow and fan power as shown with the following formula:

- $P = \Delta p \cdot V'$ and
- $\Delta p = R \cdot V'2$ resulting in
- $P = R \cdot V'3$

Finally, robust ongoing management of the designed ventilation system is further required to ensure optimised air distribution with minimal leakages. This will further require a critical review of current acceptable leakage parameters, coupled with the effective fit for purpose sealing and air distribution methodologies. This will allow for:

- Reduced ventilation infrastructure, main fans, shaft sizes, main intakes
- Reduced Capex and Opex

A paradigm shift regarding the replacement of underground diesel equipment with battery alternatives is required to comply with safety and health considerations by ensuring zero-emissions underground equipment. Some of the many benefits are:

- Elimination of diesel fine particular matter and other exhaust gas components in the underground environment, requiring less ventilation and therefore lower costs, as well as improved health for miners.
- The efficiency of conversion from electric energy to wheel drives is much higher than the conversion efficiency from diesel to wheel drive, so the amount of heat that an electric vehicle produces is much less. This results in reduced ventilation requirements (30 to 50% less) and lowers associated energy costs.
- Less noise, vibration, and heat for miners operating the equipment underground, thus assisting in meeting the mental and physical health requirements of the worker.
- Lower carbon footprint, with associated carbon credits.

The implementation of new technologies and monitoring regimes results in countless information submissions. This information needs to be collated, analyzed, and distributed from one hub. This calls for the introduction of an overarching IoT.

Notwithstanding the mining and engineering benefits, the associated ventilation benefits include:

- Managing the entire VOD system
- Condition monitoring of the occupational environment
- Real-time monitoring of critical safety systems/ components
- Real-time alarming/messaging – email, SMS, WhatsApp, etc.

5.4 Industry Original Equipment Manufacturers (OEM) Presentations

Dave Stanton, the project facilitator has added a brief overview in greyscale italics into the various presentations emanating from the previous workshop held in August and from intricate knowledge of the systems. The actual OEM presentations are attached under each heading for completeness.

5.4.1 BEV - Alan Main - Epiroc

Battery or fuel cell vehicles have developed to the stage where they are comparative with the diesel alternative. There are manifold occupational health benefits, and ventilation/cooling benefits about the implementation of these units, also Battery technology is ideally suited for underground mining and the speed of adoption will be driven by the mines' comfort level with the technology and the OEMs' ability to deliver a solid product that will operate for a full shift

A broad range of benefits driving the battery electric vehicle transition are:

- *Elimination of diesel fine particular matter and other exhaust gas components in the underground environment, requiring less ventilation and therefore lower costs, as well as improved health for miners.*
- *The efficiency of conversion from electric energy to wheel drives is much higher than the conversion efficiency from diesel to wheel drive, so the amount of heat that an electric vehicle produces is much less. This results in reduced ventilation requirements (30 to 50% less) and lowers associated energy costs.*
- *Elimination of diesel fuel costs, a variable quantity.*
- *Reduced maintenance costs (some 25% fewer parts on EV propulsion versus diesel propulsion systems).*
- *Less noise, vibration, and heat for miners operating the equipment underground*

5.4.2 VOD - Stephan Berg - Howden

The Ventilation on Demand (VOD) system, continually monitors air quality and adjusts ventilation as required. In this way, areas that are being worked in, benefit from better, more efficient ventilation, while in areas not being worked the ventilation is reduced. Overall, this leads to significant electricity and other cost savings, and also makes the mine much safer and more productive.

- *Applying a VOD system requires complete and detailed knowledge of the mine ventilation network, the ongoing processes, and regulatory demands.*
- *To precisely define local air demands, all machinery with their properties and positions must be known in real-time requiring a machinery tracking and identifying system.*
- *Information on machinery and personnel then must be analyzed to define needed volume flows and adequate reactions.*
- *Analyzing data and triggering commands can either be conducted by a central control system or decentralised. In both cases, adequate infrastructure is required to transmit information.*
- *Ventilation infrastructure is to be installed to change the airflows to the calculated needs. It should be remotely controlled to guarantee short reaction times. Among regulators and doors, especially fans can be subject to variable settings.*
- *To meet regulatory demands, only calculating static demands based on e. g. diesel-powered equipment will not be sufficient.*
- *Monitoring the network with gas detection sensors and measuring devices can be used to analyse air qualities and react e.g. with higher flow rates if certain regulatory demands are not yet met.*
- *Using a monitoring system instead of applying calculated quantities will finally make the system a quality-based VOD rather than a quantity-based system, which is unable to react to spontaneous events.*
- *To control air automated damper control systems coupled with vehicle monitoring is required and the specifications and requirements of these need to be determined.*

5.4.3 Use of Variable Speed Drives (VSD) and Variable Pitch Blades (VPB) – Eduard von Moltke - Zitron Fans

A VSD changes the speed of the motor. In applications requiring variable flow and pressure, VFDs are the most efficient method of control. Varying the speed of the fan adjusts the flow rate to the system requirements without the need for additional mechanical devices, and at high efficiency.

The system resistance to the fan's operational efficiency is crucial and should be the first thing looked at before the purchase and installation of a VSD. In these scenarios, you achieve a very expensive damping device at an unacceptable fan efficiency operating point. A VSD tends to preserve the efficiency at the original operating point. (So if your fan is currently running at 40% efficacy, by installing a VSD, no to very little improvement in fan efficacy will be realized.

In addition to a VSD, It is therefore important to install VPB's, to ensure that the fan efficacy is maintained throughout the whole spectrum of the fan curve.

5.4.4 Safety and Environmental Monitoring – Garth Nelson – Barnel

Ventilation condition monitoring and personnel safety plays a crucial role in mine optimisation and control. Workplace thermal environmental monitoring

- *Real-time data available and stored centrally*
- *Electronic report generation*
- *Proactive identification of sub-standards/ sub-legal*
- *Improve underground working conditions*
- *Less labour required*
- *Eliminate Section 54/55*

Electronic Asset tracking

- *Gas instrument tracking*
- *SCSR*
- *Cap lamp*
- *People tracking*
- *Reduce the risk of theft /loss*
- *Ensure compliance with standards*
- *Immediate exception report generation/notification*

Workplace thermal environmental monitoring

- *Prevent workers from entering into a hazardous environment or working place*
- *Direct and manage workers to follow the best extraction or avoidance of hazard*
- *Early warnings or indications –saves lives*

Real-time data available and stored centrally

- *What you measure you can control*

- *Automated responses safes time and eliminates possible human error*
- *Real-time monitoring allows us to safely adjust, correct, manage and enhance the lives of all our mine employees every second*

5.4.5 Internet of Things (IoT) – Chris Nel - BBAnalytics

IoT is the silver thread that is required to implement the majority of the current innovative systems available to optimise the ventilation system and to assist in achieving the planned mechanised mining optimisation required.

Also, IoT is pivotal to the effective implementation of novel ventilation systems and needs to be addressed as a separate focused area, failing which many innovative systems will fail such as:

- *Managing the VOD system*
- *Condition monitoring of the occupational environment*
- *Real-time monitoring of critical safety systems/ components*
- *Implementation of smart mining, thereby creating a safer more productive occupational environment that meets the mental and health requirements of the workers.*

5.4.6 General Discussion - Participants

The presentations were very well received but did not elicit any discussions.

5.4.7 Conclusion

The workshop was well attended and the presentations from the OEM's were of extremely high quality through which they imparted the current technologies available to aid ventilation engineers in achieving the optimised ventilation solution for the Mechanised Mining Optimisation program.

6 VENTILATION ENGINEERING DESIGN GUIDELINE

6.1 Foreword & Overview

A design criterion contains specific standards or systems required to complete a project. Some of the standards can also be as constraints or minimum requirements to meet acceptable ventilation engineering practice of legal requirements. What gets built will generally embody the best intentions of the design engineers to meet creditable design guidelines.

This guideline sets forth current best ventilation engineering practice, and provides general guidance, with the intent is that it be used by practicing ventilation and mining engineers, tasked with mine design to improve health and safety, by ensuring an occupational environment that meets the physical and mental health requirements of the worker.

The guideline provides general mine ventilation planning guidance that should be applied with the appreciation that circumstances associated with specific mines and ventilation arrangements may vary widely, requiring mine specific information as noted in the text.

At the time of writing the guideline met with all applicable legal requirements, however, one needs to ensure that it is consistent with the mandate of the Mines Health and Safety Act. No 29 0f 1966 and all directives issued by the Department of Mineral Resources (DMR)

The guideline is to be used as a tool to ensure that the correct exactitude has been exercised and that current novel ideas have been tested in the design to ensure the outcome fits for purpose.

6.1.1 Keywords

Ventilation Engineering, Guideline, Environmental Engineering, Mechanised Mining. Best Practice, Mine Design, Fit for Purpose.

6.1.2 Introduction & Background

Ventilation engineering has a pivotal role to play in the innovation of novel mining designs and the future profitability of mining operations. Mining Engineers should be able to apply their minds to an unrestricted mine extraction philosophy, thereby unlocking the full potential of the orebody.

As alluded to above, antiquated ventilation and engineering considerations have hampered the ability to really "Sweat the Asset". Taking the idle capital deployed, and equipment efficacy over 24 hours, compels all mining disciplines to "step up to the plate" and design an optimised mine extraction strategy devoid of restrictions, where the entire mining process is honed to maximum proficiency. In any fiscal analysis and optimisation process, one needs to understand the same production output.

- The Capex and Opex requirement.
- Production ramp-up.
- Tail management.
- The overall return on investment (ROI).

To this end, the following six themes are put forward for consideration as the ventilation engineering contribution to this process:

- Mining Optimisation.
- Ventilation on Demand.

- Variable Pitch Blades and Variable Speed Drives.
- Air Leakage Factors and Low-Pressure Networks
- Introduction of Battery Machinery.
- The full-scale roll-out of the Internet of Things (IoT) with built-in analytics.

These themes are briefly discussed on the pages that follow in order the place the guideline into the correct context.

6.1.3 Mining Optimisation

The principal contributor to bottom-line mining organisation profits is to maximise the daily extraction ratio per block of ore reserve. To achieve this there are two main fundamental requirements, namely:

- Increase the blasting frequency.
- Implementation of a practically achievable mining cycle.

The capability of achieving the above is predominantly affected by available face time. Invariably the archaic ventilation systems, requiring a four-hour re-entry period after the blast has precluded mining engineers from designing differently due to the time taken to clear the area of noxious gasses and dust. This drastically reduces the available face time. In recent years, some operations have reduced this to two hours. This however still leaves room for improvement, and a thirty-minute re-entry period is fully feasible and should be the order of the day where conventional explosives are used.

This will allow for concentrated mining, where the assets are used continuously in a focused operational approach with improved supervision. The aim is to improve efficiency thus reducing the capital required and improving the ROI. The introduction of a two or three-shift system where each shift has the capability of fulfilling the entire mining cycle is a requirement for an optimised future mine. The ventilation engineer has a crucial role to play in aiding this quest.

6.1.4 Ventilation on Demand (VOD)

VOD is an optimal ventilation control system that targets the “Real-Time” ventilation supply to individual mining areas, with the required quantities when they are needed taking full cognizance of ambient conditions at the time. In essence, it can cut ventilation and refrigeration costs dramatically, noting that:

- On average, ventilation accounts for up to 50 % of a mine's energy costs, and up to 15 % of a mine's total costs.
- The introduction of an extensive VOD system has the conservative potential of reducing the overall power expenditure by at least 20 %.

The introduction of a ventilation design that allows for VOD invariably supports the ability to reduce re-entry times and may also allow for variable shift and blasting times, as each ventilation segment is separately ventilated. Furthermore, it has major capital expenses (Capex) and operational expenses (Opex) benefits as it reduces main ventilation infrastructure and concomitant operating costs.

6.1.5 Variable Pitch Blades and Variable Speed Drives

Ventilation designs need to incorporate fan control using Variable Speed Drives (VSD) and Variable Pitch Blades (VPB). This is to ensure optimum efficiency through fan total life cycle duties by matching fan performance with increasing system resistance.

This will allow for:

- Optimised fan utilization ensuring peak efficiency.
- Implementation of Ventilation on Demand.
- Reduced re-entry times.
- Reduced Opex.
- Energy savings relating to input power and load shifting. [Time of Use (TOU) capabilities].

6.1.6 Air Leakage Factors and Low-Pressure Networks

The ventilation engineer needs to optimise leakage factors and plan for low-pressure ventilation networks, noting the cubic relationship between volume flow and fan power.

Every effort needs to be taken through the entire design process to reduce the overall pressure drop by introducing an intelligent fit for purpose air supply which leads to a reduction of the total required airflow and pressure requirement within a mine. By reducing the total airflow and pressure, energy can be saved in disproportionately high amounts due to the cubic relationship between volume flow and fan power as shown with the following formula:

$P = \Delta p \cdot V'$ and

$\Delta p = R \cdot V'^2$ resulting in

$P = R \cdot V'^3$

Where:

P	=	Pressure
Δp	=	Delta Pressure
V'	=	Volume
V'^2	=	Volume Squared
V'^3	=	Volume Cubed
R	=	Resistance

Finally, robust ongoing management of the designed ventilation system is further required to ensure optimised air distribution with minimal leakages. This will further require a critical review of current acceptable leakage parameters, coupled with an effective fit for purpose sealing and air distribution methodologies.

This will allow for:

- Reduced ventilation infrastructure, main fans, shaft sizes, main intakes.
- Reduced Capex and Opex.

6.1.7 Introduction of Battery Machinery

A paradigm shift regarding the replacement of underground diesel equipment with battery alternatives is required to comply with health and hygiene considerations by ensuring zero-emissions underground equipment.

Some of the many benefits are:

- Elimination of diesel exhaust emissions, heat, and moisture associated with diesel-powered equipment in the underground environment, requiring less ventilation and therefore lower costs, as well as improved health for miners.

- The efficiency of conversion from electric energy to wheel drives is much higher than the conversion efficiency from diesel to wheel drive, so the amount of heat that an electric vehicle produces is much less. This results in reduced ventilation requirements (30 to 50% less) and lowers associated energy costs.
- Less noise, vibration, and heat for miners operating the equipment underground, thus assisting in meeting the mental and physical health requirements of the worker.
- Lower carbon footprint, with associated carbon credits.

6.1.8 The full-scale roll-out of the Internet of Things (IoT) with built-in analytics

The implementation of new technologies and monitoring regimes results in countless information submissions. This information needs to be collated, analyzed, and distributed from one hub. This calls for the introduction of an overarching IoT.

Notwithstanding the mining and engineering benefits, the associated ventilation benefits include:

- Managing the entire VOD system.
- Condition monitoring of the occupational environment.
- Real-time monitoring of critical safety systems/ components.
- Real-time alarming/messaging – Email, Instant Messaging, etc.

6.1.9 Summation

There is no doubt that a step-change in ventilation optimisation in mining operations is realistic, which will greatly assist the mining engineer in developing an unconstrained mining extraction plan.

The available technologies need to become a focal area of optimisation where both the mining and ventilation engineer combine their respective skills set and challenge the current "self-inflicted" production limitations by "thinking out the box" and developing novel yet feasible mining plans which allow "sweating the asset" from tonnage build-up through to an optimised mining cycle to final tail management.

6.1.10 Conclusion

The guideline covers a structured approach to ventilation engineering design and provides the general ventilation parameters to be used during the various design phases. It also allows for mine specific data to be incorporated as needed. This allows the ventilation engineer to specify specific requirements for sign-off by the client, which then be used in developing the ventilation component of a Mine.

The guideline covers recommended ventilation engineering planning parameters, an introductory position on core optimisation opportunities, and includes guidance on amongst others, gas and explosions, fire engineering, emergency and response, digital control and environmental monitoring, and occupational stressors.

6.1.11 Acknowledgments

The project team wishes to acknowledge the following individuals/organisations for their involvement and/or contribution to the project:

- The Mandela Mining Precinct
- Martin Pretorius, Mechanised Mining Programme Manager at the Mandela Mining Precinct.

- The Department of Science and Innovation for funding the project.
- Individuals and organisations that engaged with the team and shared valuable information.

6.1.12 Application of this Guideline

This guideline is not an exhaustive rendition of all criterion which should be considered but gives a broad selection of standards and current best practice, including current novel opportunities, which may be incorporated into ventilation engineered design.

The results of this guideline should be the documented roadmap of specific design criterion which has been selected for a specific mine ventilation system and which has been approved by the client for further ventilation engineering design, through interactive Vuma/VentSim modeling on the following page provides an overview of the layout of the draft guideline document.

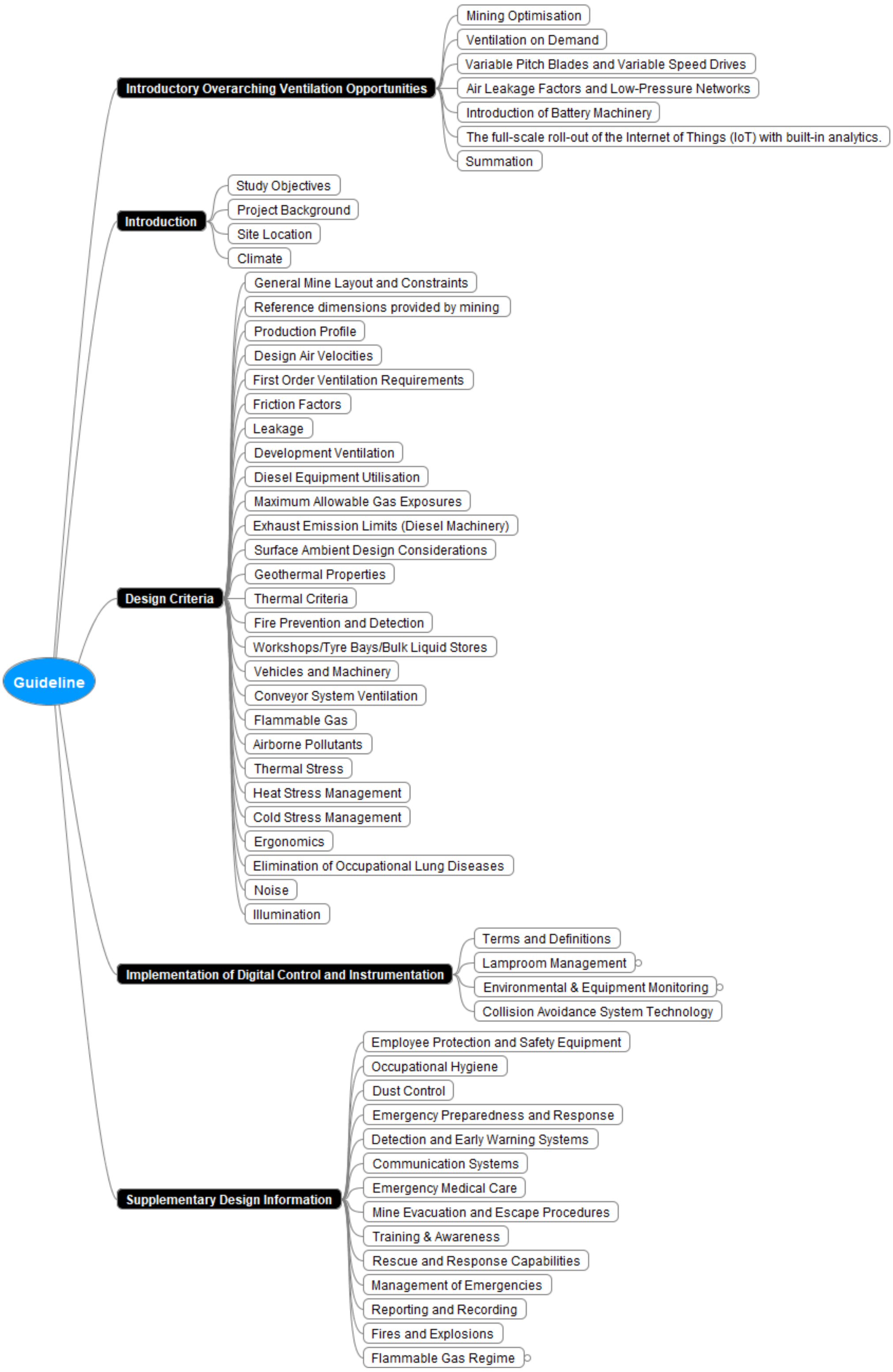


Figure 34: Guideline Layout

6.1.13 Terminology & Definitions

%	:	Percentage
<	:	Smaller than
>	:	Larger than
≥	:	Larger than or equal to
°C	:	Degrees Celsius
AUF	:	Air Utilisation Factor
BP	:	Barometric Pressure
Capex	:	Capital Expenditure
CO	:	Carbon Monoxide
CO_2	:	Carbon Dioxide
COP	:	Code of Practice
dB	:	Decibel
dB(A)	:	A-weighted decibels
$dBL_{Aeq,8h}$	:	Eight-hour equivalent of dB(A)
DMRE	:	Department of Minerals and Energy
DPM	:	Diesel Particulate Matter
EC	:	Elemental Carbon?
EU	:	European Union
f/mL	:	Fibres per millilitre
GPS	:	Global Positioning System
hr.	:	Hour
HV	:	High Voltage
Hz	:	Hertz
IoT	:	Internet of Things
km	:	Kilometer
km/h	:	Kilometer per hour
ktpm	:	Kilotonne per month
kW	:	Kilowatt
LHD	:	Load Haul Dump Truck
m	:	Metre
m/s	:	Metre per second
$m^3/s/kW$	:	Cubic metre per second per kilowatt
$m^3/s/m^2$	:	Cubic metre per second per square metre
mg/m3	:	Milligram per cubic metre
MHSA	:	Mine Health and Safety Act
mm	:	Millimetre
mSv/annum	:	Millisievert per annum
NIHL	:	Noise-induced Hearing Loss
NO	:	Nitric Oxide
NO_2	:	Nitrogen Dioxide
NO_x	:	Nitrogen Oxides
Ns^2/m^4	:	Newton-second squared per metre to the power of 4
OEL	:	Occupational Exposure Limit
OEM	:	Original Equipment Manufacturer
OIS	:	Occupations Information System
Opex	:	Operational Expenditure
PNOC	:	Particulate not Otherwise Classified
ppm	:	Parts per million

Terminology & Definitions (continued)

RAW : Return Airway
RCD : Residual-Current Device
RF : Radio Frequency
ROI : Return on Investment
SABS : South African Bureau of Standards
SCADA : Supervisory control and data acquisition
SCSR : Self-contained Self-rescuer
SMS : Short Message Service
SO_2 : Sulphur Dioxide
STEL : Short-term Exposure Limit
STS : Standard Shift Threshold
TC : Total Carbon
TOU : Time of Use
TRK : Tropomyosin Receptor Kinase
TWA : Time-weighted Average
ug/m^3 : Microgram per cubic metre
UPS : Uninterrupted Power Supply
VOC : Volatile Organic Compound
VOD : Ventilation on Demand
VOIP : Voice over Internet Protocol
VPB : Variable Pitch Blades
VRT : Virgin Rock Temperature
VSD : Variable Speed Drive

Terminology & Definitions (continued)

Asset and Personnel Tracking: The ability to track equipment/machinery and all personnel in real-time.

Asset Management System: This is all hardware (active/passive tags) required to manage the access and asset movement daily. The information is updated through the lamp room management system.

Cap Lamp Charging Racks: BarNel manufactures its charging racks in various sizes and combinations as required by the client.

Cap Lamp Lux Test Tunnel: This device is used to determine the light intensity of cap lamps is still meeting the required standard.

Cap Lamp: The cap lamp can fit different devices into/inside the cap lamp. (I.e. noise temperature and gasses).

Distress Call: The ability for all personnel to send a distress notification in real-time to a centralized control room.

Early Warning/Messaging: The ability to send a mine-wide or safety or evacuation message.

Gas Instruments: BarNel has a fast range of fixed, portable, and multi-gas and warning devices, as the OEM the products can be tailor-made to suit the requirement of the client's needs.

Heat Stress Monitor: This is a small device that is clipped to the cap lamp cable to log and indicate heat stress conditions.

Lamp Room Management System: This is a management software tool that controls and manages all the employees regarding different criteria.

Lamp Room Management: This is the labour and equipment required to manage the lamp room daily (24/7).

Master Key Padlock: The master key padlock is important when performing quarterly pressure testing of SCSR to reduce time looking for spare keys if available.

Pedestrian Detection System (PDS): The ability to prevent pedestrian-to-vehicle accidents.

Re-entry Watch: This device indicates when the centralized blasting was activated and when it is safe to re-enter.

Vehicle Detection System (VDS): The ability to prevent vehicle-to-vehicle accidents.

Velocity Test Tunnel: This device is used as a reference to determine if the Kestrel/Sky mate is operating at the required parameters.

Ventilation on Demand (VOD): The ability to direct and control air in an underground mine, to the area that requires it, at the quantity needed for the local activities and ambient conditions at the time.

Voice Over Internet Protocol (VOIP): The ability to deliver voice communications and multimedia sessions over Internet Protocol networks (Internet).

6.2 Introduction

The following is a structured proforma guide that can be followed by any practicing ventilation engineer to derive a comprehensive ventilation design document, which covers most aspects that need to be addressed, to ensure due diligence and achieve an optimized design.

Give a brief introduction about the mine and mining house.

Example: XXX is the mineral right holder of the YYY prospects in the Free State Goldfields. The two prospects are being considered together as a single entity and have been named the ZZZ Project).

The ore body target mining area depths will vary between 1 500 m and 1 900m, and it is important to note that the ZZZ Project extends over numerous farms and/or prospecting titles.

6.2.1 Study Objectives

State the client's objectives of the study, and list specific standards or practices which form the basis of the study.

6.2.2 Project Background

Give a brief overview of the background to the project, inter alia, type of mine, ore body reef types, mining layout, and life of mine.

6.2.3 Site Location

Give a brief overview of the mine location. Closest towns, global positioning system (GPS) coordinates.

Example: The XXX project is located in the Southern Free State Gold Fields adjacent to the YYY mine in the Free State Province of South Africa, and approximately X km south of the town of Y. The closest major towns to X are Z, 24 km, and K 136 km. X is approximately 270 km by national road from Johannesburg. Include figures showing:

- Site Map
- Locality map

6.2.4 Climate

Give a brief overview of the climatic conditions.

Example: Of the 24 climatic regions in South Africa, the xxx project occurs within the “dry” Highveld grassland” region. The climate is typical of a continental plateau with a wide diurnal temperature range that reaches a maximum of 19^{0}C in the dry winter months. Temperatures vary from 0^{0}C to 21^{0}C during the winter months and 11^{0}C to 30^{0}C in the summer months. Prevailing winds are predominantly northerly and north-easterly, with wind speeds seldom exceeding 20 km/h.

An average of 76 days per year has recorded a maximum temperature greater than 30^{0}C, whilst 49 days per year record a minimum temperature of 0^{0}C or less. The highest temperature recorded was 39^{0}C and the lowest was -8^{0}C. The most rain recorded in 24 hours was 103mm, thunderstorms are less frequent, with an average of 39 lightning strikes per year. The weather variant temperature conditions associated with this climatic region require special cognizance when determining cooling requirements and specific safety precautions need to be developed due to lightning strikes and high methane content in workings. These aspects need to be considered in the design.

6.3 Design Criteria

The purpose of this section is to outline the key constraints and design parameters to be used for the (State study level) ventilation engineering design and simulation.

The following examples of constraints and design parameters are listed for use in the engineering design, simulations, and report. These parameters need to be reviewed and updated according to site-specific and legal requirements.

6.3.1 General Mine Layout and Constraints

To be updated pending Mining Engineers layout. Some key information would be inter alia:

The project has the following features and design assumptions:

- Main adits ramps will be developed at X gradient.
- Mining will be on a Y hour cycle.
- Blasting of production 'hang-ups' will be synchronised at the end of a shift on a fixed-time system (Electronic detonation be used)
- All workshops, belts, and crushers are ventilated to return.
- The design must cater for a one-hour re-entry interval with two shifts per 24hr day (The minimum as prescribed by the Department of Mineral Resources and Energy (DMRE) is 30min) Noting that the re-entry period is calculated by the air replacement period multiplied by 8.

6.3.2 Reference dimensions provided by mining [finished]

Provide main ventilation infrastructure such as:

- Main material decline [adits].
- Main belt decline [adits].
- Where reasonably practical, all belts should be ventilated to return.
- Chairlift decline [adits].
- Strike drive (on reef drive).
- Return airways.
- Upcast shafts.
- Downcast shafts.

For Access Development:

- Twin or single haulage from Shaft to reef for Intake and return air design to be determined in conjunction with the Mining Engineer and is layout driven.
- Return Airway (RAW) requirements and design are layout driven. Where possible vertical shafts should be considered unless footwall development is on the reef.

Capital & Operational Cost of infrastructure from Ventilation Design such as cooling power, refrigeration, electrical cost, fan efficiency to be an integral part of design and adjudication.

6.3.3 Production Profile

The annual total production rate will be X ktpm.

Provide production profile graph.

6.3.4 Typical Design Air Velocities

The design air velocities are shown in Table 10.

Table 10 Design Velocities

Description	Ideal design range
Downcast shafts – men, material, and rock [equipped]	10 – 12 m/s
Max. upcast shafts [unequipped]	22 m/s
Max. intake airways [personnel]	6 - 7m/s
Max. return airways [personnel and tramming]	6 - 7 m/
Max. dedicated return airways	12 - 14 m/s
Min. workshops	0.3 m/s

6.3.5 First-order Ventilation Requirements

The primary airflow requirements are shown in Table 11.

Table 11: Primary airflow requirement (Specific site data according to Mine design required here)

Area	Number	Air per area	Total Required

6.3.6 Friction Factors

Design friction factors used for modelling are listed in Table 12.

Table 12: Friction factors

Factor	Value
Blasted airways [intake/return]	0.010 Ns^2/m^4
Corten ventilation ducting [shaft sink]	0.0025 Ns^2/m^4
Ventilation flexible duct	0.003 Ns^2/m^4
Galvanised steel ventilation duct	0.005 Ns^2/m^4
Raise bore holes [unequipped]	0.004 Ns^2/m^4

6.3.7 Leakage

Leakage factors used for modelling are listed in Table 13.

Table 13: Leakage Factors

Factor	Value
Surface leakage	5%
Primary leakage [main intake to main return airways]	10%
Secondary leakage [doors, seals, etc.]	15%
In Stope Air Utilisation Factor (AUF) – Good controls	80%

6.3.8 Development Ventilation

Requirements for capital development and production phases are listed in Table 13.

Table 14: Development Ventilation

Factor	Value
Force quantity at face [minimum – diesel requirements will normally dictate]	0.25 $m^3/s/m^2$ face

Factor	Value
Exhaust quantity at face [minimum – diesel requirements will normally dictate]	0.30 $m^3/s/m^2$ face
Maximum force column distance from face [after the blast]	15m Conventional 20m Trackless
Maximum exhaust column distance from face [after the blast]	30 m
Leakage, steel duct	5% per 100 m
Leakage, plastic tube	10% per 100 m
Through ventilation between open-circuit fans	0.4 $m^3/s/m^2$ face
Re-entry	After a minimum of 8 air changes

6.3.9 Diesel Equipment Utilisation

The design factors for diesel equipment utilisation are shown in Table 15.

Table 15: Diesel Equipment Utilisation Factors

Factor	Value
Air requirement for dilution of Diesel Particulate Matter (DPM)	0.12 $m^3/s/kW$ rated at point-of-use
Heat added by load haul dump trucks (LHD)	1.8 kW/kW rated power
Heat added by haul trucks	0.7 kW/kW rated power
Diesel heat load – LHD [production crosscut]	60% load for 90% of the time
Diesel heat load – trucks	60% load for 90% of the time
Diesel heat load – utility vehicles	50% load for 55% of the time
Diesel Sulphur content	< 50 ppm

Notes:

1. Exhaust gas dilution accounts for DPM particulates. [Anglo American are planning to move this up to 0.15 $m^3/s/kW$ rated at point-of-use] see additional note on DPM
2. Engine specifications [European Union (EU)-Type 4 / Tier 4 or higher], diesel sulphur content [<50 ppm], after exhaust treatment [Catalytic Converter]. Diesel particulate filters will be investigated, and these specifications need to be reviewed closer to the implementation phase.
3. Heat added by haul trucks allows for vehicles operating on a 'Level' gradient based on historical fuel consumption.

The diesel vehicle fleet provided by mining is listed in Table 16.

Table 16: Diesel Fleet (Specific site data according to Mine design required here)

Machine Type	Series	Rated kW	Quantity	Swing	Total	Total kW
Drilling						
Charging						
Loading						
Trucking						
Bolting						
Cable bolting						

6.3.10 Maximum Allowable Gas Exposure

Schedule 22.9(A) of the Mine Health and Safety Act (MHSA) lists the occupational exposure limits (OEL) for airborne pollutants and include gases and vapours. Short-term exposure limits (STEL) are provided for toxic gases and should always be adhered to for the protection of the employee.

There are two principal situations in an underground mine where the immediate danger to persons can be caused:

- Deficiency of oxygen in the general atmosphere (normal level 21%). The usual causes are displacement by other gases or a fire.

- Presence of high levels of carbon monoxide (CO). The usual causes are fire or inadequate air to dilute the diesel exhaust gases.
- High levels of methane in the ore released during mining activities can result in explosions.

Other harmful gases can occur in mines, generally, if there is insufficient air to dilute and remove them, examples are:

- Oxides of nitrogen from diesel engines.
- Blasting fumes.
- Welding fumes (welding/cutting of cadmium plated metal is particularly dangerous.
- Fumes from chemicals used on the mine (check product data sheets).

6.3.11 Exhaust Emissions Limits (Diesel Machinery)

Currently, in South Africa, there are no occupational exposure limits in place for DPM. An OEL of 3 mg/m3 (respirable) for exposure for platinum mine dust is prescribed in Section 22.9(2) a. of the MHSA. Table 16 provides some guidance on exposure limit values that are currently used internationally for DPM, and Table 18 provides information on typical exhaust emission levels but depends on the condition of the engine.

Table 17: Exposure Levels Ambient Monitoring

Regulator/ Agency	Date Submitted	Exposure Guideline/Limit	Substance Measured
MSHA, USA	2001	0.4 – 0.16 mg/m^3	Total Carbon (TC)
Anglo Platinum (South Africa)	2010	0.30 mg/m^3	Elemental Carbon (EC)
	2011	0.25 mg/m^3	Elemental Carbon (EC)
	2013	0.15 mg/m^3	Elemental Carbon (EC)
	2019	160ug/m^3	Total Carbon (TC)
Western Australia	2020	100 $\mu g/m^3$	Elemental Carbon EC

Table 18: Typical Exhaust Emissions Limits

Gas	Typical Exhaust Emissions Limits
CO	1 200ppm
NO_x	750ppm
CO_2	5 000ppm

6.3.12 Surface Ambient Design Conditions

The surface ambient design conditions are shown in Table 19.

Table 19: Surface Ambient Design Conditions (Specific site data according to Mine design required here)

Factor	Value
Design wet bulb	
Maximum wet bulb	
Surface density	
Barometric Pressure (BP)	

6.3.13 Geothermal Properties

Reference virgin rock temperature (VRT) values are given in Table 19.

Table 20: Virgin Rock Temperatures (Specific site data according to Mine design required here)

Level	VRT [°C]

6.3.14 Thermal Criteria

The thermal criteria are provided in Table 21.

Table 21: Thermal Criteria

Criteria	Value
Maximum design wet-bulb temperature	29°C
Maximum design dry-bulb temperature	37°C

Schedule 22.9 (2) (b) lists the occupational exposure limits for physical agents, included thermal stress. The mine should have a code of practice (COP) that was developed to comply with the requirements of the MHSA "Guideline for mandatory code of practice for occupational health programme (occupational hygiene and medical surveillance) on thermal stress". The ventilation design and operation should comply with the requirements as set out in such a COP.

The mine operates in a warm climate with heat-generating diesel-powered vehicles. Thus, the possibility exists of heatstroke conditions (wet bulb temperature over 32.5°C) occurring if the ventilation is not up to standard or some other abnormal circumstance occurs. Instruments to measure wet and dry bulb temperature, air velocity, and air humidity must be made available. As part of the Mine Standards, any place where the wet-bulb temperature is ≥32.5°C, persons should be withdrawn.

6.3.15 Fire Prevention and Detection

There are two guidelines issued by the DMRE that must be complied with:

- "Guideline for the compilation of a mandatory code of practice for the prevention of flammable gas and coal dust explosions in collieries"; and
- "Guideline for the compilation of a mandatory code of practice for the prevention of flammable gas explosions in mines other than coal mines".

Schedule 5 of the MHSA has requirements related to fire and explosions. "The employer, at any mine where the risk assessment indicates a risk of the presence of flammable gas, must ensure- that all flammable gas measuring instruments and flammable gas warning devices used at the mine for the detection of methane or hydrogen or a mixture of both, comply with the South African National Standard Specification SANS 151 5-1: 2006, Edition 2.1 "Gas measuring equipment primarily for use in mines: Part 1: Battery operated portable, flammable gas measuring instruments and warning devices".

Compliance with best practice, and any legal requirements:

- Dedicated water supply.

- Service level agreement with Original Equipment Manufacturers (OEM) taking responsibility for their system and or equipment (liability).
- Quarterly calibrations, checks, and verification on supervisory control and data acquisition (SCADA) (fail to safe blocking use of equipment if not done).
- Control room procedures inadequate, control room operators not adhering to procedures and response (eliminating human error, refresher training), ergonomics of Control Room – supply of fresh air, strict fatigue management compliance, furniture.

6.3.16 Workshops/tyre bays/bulk liquid and oil stores

Workshops, bulk fuel, and oil storage tanks are ventilated directly to return. Where this is not practical, a permanent means of isolating the ventilation supply to the storage area will be provided. An automatic foam/sprinkler system will be installed in these areas.

- Bund and separation walls between commodities.
- Exceeding flammable liquids and component quantities in the workshops.
- Additional fire-fighting equipment – fire extinguishers, hose reels.
- Compliance with workshop procedures and fire prevention measures.
- South African Bureau of Standards (SABS) compliant accessories – flashback arrestor register and checks, fuel refilling hoses.
- Tyre compounds and Fire Lab tests.

6.3.17 Vehicles and Machinery

All vehicles and machines will be equipped with an automated approved onboard fire suppression system.

- Automatic operator pre-use checks inter-locking preventing unauthorized use of equipment (using the equipment after suppression system has been activated, the system not pressurized).
- Service level agreement from OEM to take liability in case of a fire incident.

6.3.18 Conveyor System Ventilation

The conveyor system is not considered as the main intake airway and, as a result of fire risk, will be ventilated directly to return. Following a risk assessment where this is reasonable not practical additional precautions/mitigation practices as alluded to below should be introduced.

- Automated fire doors/barriers (uninterrupted power supply (UPS)/battery backup) interlocked with belt fire detection system isolating conveyor belt installation.
- Automated door installations opening to the RAW.

6.3.19 Flammable Gas

A code of practice (COP) must be provided in compliance with best practice, and any legal requirements.

6.3.20 Airborne Pollutants

Schedule 22.9(A) of the Mine Health and Safety Act (MHSA) lists the occupational exposure limits (OEL) for airborne pollutants and include gases and vapours. All exposures to airborne pollutants to be within the schedule OELs. Some OELs are specified in Table 214.

Table 22: Summary of Airborne Pollutants OEL

Pollutant	OEL
Silica dust, crystalline	0.1 mg/m^3 Time Weighted Average [TWA]
Fibres	2 f/mL Time Weighted Average [TWA]
PNOC	inhalable 10 mg/m^3 and respirable 3 mg/m^3
Carbon Monoxide [CO]	30 ppm [TWA] and 100 ppm [OEL-Stel]
Carbon Dioxide [CO_2]	5 000 ppm [TWA] and 30 000 ppm [OEL-Stel]
Nitric oxide [NO]	25 ppm [TWA] and 35 ppm [OEL-Stel]
Nitrogen dioxide [NO_2]	3 ppm [TWA] and 5 ppm [OEL-Stel]
Sulphur dioxide [SO_2]	2 ppm [TWA] and 5 ppm [OEL-Stel]
Diesel Particulate Matter – Total carbon	160 µg/m^3
Diesel Particulate Matter – Elemental carbon	123 µg/m^3
Flammable gas	< 1.0%
Radiation	< 20 mSv/annum [personal exposure]

Note:
It is recommended that a Code of Practice [COP] is prepared according to the MHSA "Guideline for the compilation of a mandatory code of practice for an occupational health programme (occupational hygiene and medical surveillance) on personal exposure to airborne pollutants". The COP requires that a system of occupational hygiene measurements on personal exposure to airborne pollutants when the following hazard limits prevail:

- Particulates ≥ 10% of the OEL
- Gases ≥ 50% of the OEL

The hierarchy of controls will be initiated once exposure action limits [50% of OEL] are detected, i.e. elimination, engineering controls, administrative controls, and/or personal protective equipment.

6.3.21 Thermal Stress

Thermal stress management is a multifaceted approach to promote worker health and safety by minimizing human thermal stress and the incidence of heat or cold disorders. The mine should have a code of practice (COP) that was developed to comply with the requirements of the "Guideline for mandatory code of practice for occupational health programme (occupational hygiene and medical surveillance) on thermal stress". The ventilation design and operation must comply with the COP on thermal stress.

6.3.21.1 Heat Stress Management

A COP for an occupational health programme on personal exposure to thermal stress must be prepared, in compliance with this guideline, and implemented in terms of Regulation 9.2(2), which requires that a system of occupational hygiene measurements on personal exposure to thermal stress must be prepared and implemented when the results of the risk assessment conducted has identified that the following limits prevail: - Heat >25, 0˚C wet bulb and/or >32, 0˚C dry bulb and/or 32, 0˚C radiant temperature (monitoring level) – Cold.

Heat may be classified into two areas

- Heat Stress - This is the burden or load of heat that must be dissipated if the body is to remain in thermal equilibrium.
- Heat Strain - is the normal physiological or abnormal pathological change resulting from heat stress. The physiological condition referred to as heat strain is characterised by

increases in deep body temperature, heart rate, blood flow to the skin, and water and salt loss due to sweating.

Most adverse effects arise from a failure of the body's cooling mechanisms or as a result of overloading of the system. Normally, several physical and physiological mechanisms assure the transfer of excess body heat to the environment. Even when the body is at rest, heat is generated by normal metabolism. With exercise, the heat produced by muscle activity rises rapidly. This generated heat is moved to the skin by the blood to transfer body heat to the environment. Heat may then be lost through convection, evaporation of sweat, radiation, and conduction.

To maintain the appropriate body temperature three issues are essential:

- The metabolic heat produced must be transferred to the skin via the circulation for dissipation.
- The sweat glands must be able to produce the necessary amount of sweat.
- The sweat must be able to evaporate. Failure in any of these mechanisms for heat transfer may cause the body core temperature to rise, leading to heat strain and subsequent heat illness.

Additionally, for the successful maintenance of the thermoregulatory system, adequate fluids must be consumed to prevent dehydration.

When the air temperature is above skin temperature (around 36°C), evaporation of sweat is the main mechanism for the body to lose heat.

Six factors are influencing a person’s capacity for heat exchange with the environment:

- Air temperature (dry bulb). Above 36°C the body can gain heat from the environment.
- Absolute humidity (wet bulb temperature). When the absolute humidity is high, evaporation of sweat is reduced, thereby reducing the body's opportunity to lose its heat.
- Radiant heat from objects such as the sun, furnaces, and other hot surroundings. The direction of heat transfer depends on the absolute temperature difference between the body and the surrounding surfaces. It is not affected by air temperature or humidity.
- Air movement. This can influence both convection and evaporation and can have a marked effect on heat exchange at the exposed skin surfaces (face, arms, and legs). Convective heating or cooling does depends on the air temperature. Air movement assists with the evaporation of sweat from the skin and hence cooling capacity.
- Muscular activity. This is the most significant as it imposes a variable heat load. Work rates may increase heat production up to ten times the resting level and can cause a rapid increase in body heat if this cannot be lost to the surroundings.
- Clothing. This can have a major effect on the amount of heat transfer from the body. Clothing may limit convective exchange and may interfere with the body's capacity to lose heat through the evaporation of sweat.

6.3.21.2 Cold Stress Management

Table 23 provides the maximum time of exposure.

Table 23: Maximum Time of Exposure

Temperature Range			Exposure Time
0ºC	to	-18ºC	No restriction
-19ºC	to	-34ºC	Fifty minutes per hour
-35ºC	to	-57ºC	Two periods of 30 minutes each, after at 4-hour interval
Below		-57ºC	Fifty minutes during any period of 8 hours

6.3.22 Ergonomics

The Handbook on Mine Occupational Hygiene Measurements of the Mine Health and Safety Council (MHSC) contains a chapter on ergonomics that can be used for guidance.

Several concerns must be highlighted in terms of ergonomic hazards with regards to workstation design interface, these include:

- Body positions and movement.
- Handling loads.

It is recommended that an ergonomic survey be conducted as part of the risk assessment process. Also, manufacturers of machinery demonstrate their duty of care by furnishing reports on their machinery in this regard.

The mine must have a COP that was developed to comply with the requirements of the "Guideline for the compilation of a mandatory code of practice for risk-based fatigue management at mines. This guideline takes into consideration how the environmental conditions in the workplace contribute to worker fatigue.

6.3.23 Elimination of occupational lung diseases

At the 2014 MHSC Occupational Health and Safety (OHS) Summit, several milestones were agreed upon between all stakeholders.

By December 2024 95% of all exposure measurement results must be below the following limits for the respective respirable dust:

- 0.05 mg/m3 for silica dust
- 1.5 mg/m3 for platinum dust
- 1.5 mg/m3 for coal dust

No new cases should occur amongst previously unexposed individuals.

6.3.24 Noise

2014 agreed OHS Summit milestones of the elimination of noise-induced hearing loss (NIHL) are:

1. By December 2024, the noise emitted by the equipment should not exceed 107 dB(A).
2. By December 2016, no employee standard threshold limit will exceed 25 dB from the baseline.

Furthermore, the mine must have a COP that was developed to comply with the "Guideline for the compilation of a mandatory code of practice for an occupational health programme (occupational hygiene and medical surveillance) for noise".

6.3.24.1 Silencing of Equipment

By December 2024, the total operational or process noise emitted by any equipment must not exceed a milestone sound pressure level of 107 dB (A).

6.3.24.2 The Individual

By December 2016, no employee's Standard Threshold Shift (STS) will exceed 25 dB from the baseline when averaged at 2000, 3000, 4000 Hz in one or both ears.
Actions required to reduce noise exposure include:

- A policy of purchasing "quiet" machinery will be implemented.
- All hand-held machines will be muffled.
- All fans will be silenced.
- Issuing of hearing protection.
- No equipment will emit more noise than 107 dB (A).

All exposures to noise are to be within the OELs as specified below:

- Noise Exposure 85 $dBL_{Aeq,8h}$
- Peak Sound Level 105 dB[A]

A COP on personal exposures to airborne pollutants must be prepared, in compliance with DMR Guideline 16/3/2/4-A1, and implemented in terms of the Mine Health and Safety Act Regulations.

6.3.25 Illumination

Underground mine lighting is critical for the safety of miners and for the ability of miners to perform their tasks. Measuring luminance to determine proper illumination within an underground mine is faced with many challenges. Luminance measurements are affected by the photometer accuracy, measurement method, and condition of the measurement surface.

Good illumination levels and the use of energy-efficient lighting require the appropriate design and management to ensure the efficacy of the system deployed. The following tabulation (Table 23) gives indicative requirements.

Table 24: Illumination Levels

Description	Illumination Level
Material decline	20lux
Chairlift decline	50lux
Conveyor decline	50lux
Level stations	160lux
Substations	100lux
Workshops	160lux
Battery bays	100lux
Refuge bays	20lux
Haulages and travelling ways	20lux
Tips	120lux
Conveyor loading points	120lux

6.4 Implementation of Digital Control & Instrumentation

The following is a short rendition of current proven control and instrumentation technologies, about Lamp rooms, Collision Avoidance Systems (CAS), Safety and Communication Systems, Environmental and Equipment monitoring. It has been specifically included in the design criteria to increase awareness of the various systems available, and to foster a better understanding of these technologies to improve safety, productivity, and operating expenditure. In terms of the available digital technologies, the following systems should be investigated as to their appropriateness and cost where necessary.

6.4.1 Lamproom Management

6.4.1.1 Available Equipment

- Intelligent Gas Detection instrumentation and systems.
- Intelligent Miners Caplamps and Chargers.
- Multi-Gas Instruments (Wireless).
- Auto Test point for Gas, Lux, Velocity, Active & Passive tags.

6.4.1.2 Available Lamproom Management System

- Access control, reports, status, tracking, management reports.
- Asset management equipment radio frequency (RF) readers, active and passive tags.
- Self-Contained Self Rescuers (SCSR).
- Gas Instruments & warning devices.
- Heat stress monitor.

6.4.1.3 Lamproom Services

- Full maintenance on all equipment.
- Pressure testing of SCSR.
- Cap lamp Lux Test Tunnel.
- Velocity Test tunnel (Kestrel/Skymate/Wave).
- Re - entry watch (Real time/ Blasting/Re-entry.

6.4.2 Environmental & Equipment Monitoring

Different sensors for different applications are used, and the panels/ sensors are designed and manufactured to meet in-situ requirements. Depending on the requirement the product is customized to alarm, detect, log, and activate control measures. All the information is live (Real-Time) on SCADA/ Occupations Information System (OIS)/Cloud/Wireless/ Internet of things (IoT).

6.4.2.1 Available Equipment Monitoring

- Main fans –Typical monitoring sensors include -Vibration/pressure/speed voltage and current & voltmeter, etc.
- Refrigeration plant –sensors (Temperature, flow, pressure, current & voltmeter) are installed at strategic places to monitor the efficiency.
- BAC -sensors (Temperature, flow, pressure, current & voltmeter) are installed at strategic places to monitor the efficiency.
- Compressor house –sensors (Temperature, flow, pressure, current & voltmeter) are installed at strategic places to monitor the efficiency.

- Conveyor Belts (Fire Detection & Suppression) –Fixed gas & smoke detectors, bearing sensors, temperature scanners, linear wire, the belt speed status, and weight can be monitored in real-time, starting and stopping of belts from the control room when required.
- Main power and water status –Monitoring consumption per area and section.
- Substation status –monitoring of power usage, temperature, and smoke.
- Battery bay charging status –monitoring power packs/vehicles, temperature, voltage, current in-out status, smoke, battery capacity, etc.
- Production achievement status (Tons moved) -Weightometers.
- Conveyor belt status (Activity) –Motion sensor / current sensor, bearing temperatures, etc.
- Compressed air usage/status –Monitoring pressure and flow sensors.

6.4.2.2 Available Environmental and Personnel Monitoring and Communication Systems

- Air volume control –monitoring velocity and pressures to regulate volume flow by opening or closing flaps/ doors, etc.
- Development of end ventilation recirculating –monitoring pressure, velocity, and temperature.
- Shaft clearance –environmental controls –gas, temperature, velocity.
- Refuge bay status –measuring pressure/ differential pressure/ flow and gas/ smoke I.e.,
  - Compressed air
  - Water
  - Communication
  - Pressurizing
  - Equipment
- Active and Passive Personnel Asset Tracking and Tagging Systems.
- Real-Time Video Monitoring and Control Systems.
- Early Warning & Distress Signaling.
- VOIP Communication.

6.4.2.3 Environmental Condition Monitoring

- Gasses
- Volatile Organic Compound
- Noise
- Vibration
- Temperature
- BP
- Velocity
- Heat stress
- DPM
- Dust
- Lab Monitoring
- Weather station
- Lightning detection
- Dam level
- Water quality
- Air quality

6.4.2.4 Fully Automated Systems

- Dust suppression & extraction.
- Fire detection/suppression.
- Ventilation on demand, control of ventilation systems in real-time.
- Ventilation and Fire doors.
- Vehicle Lux verification system.
- Environmental controls i.e. activation of extractions systems.
- Waiting to place real-time information monitor.
- Fever screening with face recognition.
- Water treatment.
- Re-entry notification.
- Fatigue management –Time & attendance interface, shift durations.

6.5 Supplementary Design Information

The following interventions and safety precautions are included for reference and are not part of this scope of work. These interventions need to be reviewed during the build stage to make them site-specific.

It is however important to be aware at an early stage, of any risks so that appropriate measures can be instituted to effectively control, reduce, or eradicate them. These interventions could include the following:

6.5.1 Employee Protection and Safety Equipment

It is incumbent on the employer to ensure, as far as reasonably practicable, that the underground workings are designed, constructed, and equipped to provide for a safe and healthy working environment. It is, therefore, important that all of the significant occupational health and safety hazards be identified timeously and incorporated into the risk management system.

This section of the report discusses the high-profile risk issues that are expected to prevail in underground mines and is included as a reference.

6.5.2 Occupational Hygiene

Best practice ventilation principles have been incorporated into the design for safety and health. Hygiene issues related to the ventilation design are discussed in the following sections.

6.5.3 Dust Control

There must be compliance with the minimum requirements for the mine COP that was developed to comply with the “Guideline for the compilation of a mandatory code of practice for an occupational health programme (occupational hygiene and medical surveillance) on personal exposure to airborne pollutants”.

The following minimum measures will be applied to limit or prevent dust generation:

- Wet drilling is to be conducted at all times.
- Watering down of broken rock before loading operations start.
- Atomised sprays at tipping points. Additional best practice measures are:
    - Automated high-pressure water system (10 to 18Bar).
    - Dosing of water with a chemical to breakdown water particles and create dust attraction.

- Fixed ambient air dust measurement. Sensors for continuous monitoring.
- Daily checks on water nozzles for blockage (installing and maintenance program for strainers).
- Monthly maintenance – all systems, sensors, solenoids, coverage, etc.

6.5.4 Emergency Preparedness and Response

Appropriate measures must be instituted to effectively control, reduce, or eradicate any risks. These interventions could be inclusive of the following:

6.5.4.1 Detection and Early Warning Systems

To ensure that emergencies are detected as early as practicably possible and persons are warned timeously of such emergency, the emergency plan will address the following issues:

- Types and position of fixed detectors/early warning systems [localised alarms, stench gas, etc.] for the early detection and warning of all identified possible emergencies e.g., fires, flooding/mud rushes, seismicity, gases, chemical/toxic/biological releases, lightning, power failures, snow inundation, etc.
- Types and quantity, including back-up units, of personalised detectors/early warning systems e.g. flammable gas measuring instruments, flammable gas warning devices, Carbon Monoxide detectors, pagers, radios, etc.
- Detailed procedures for personal issues of detectors/early warning.
- Procedures to ensure that actual settings of alarm levels remain effective.
- Frequencies of maintenance, calibration, and testing procedures.

6.5.4.2 Communication Systems

An effective communication system to deal with an emergency, including arrangements for a back-up system will be in place. There will be arrangements for communications from the mine to outside parties and the effectiveness of the communication systems will be tested regularly.

6.5.4.3 Emergency Medical Care

Appropriate emergency medical care and facilities will be readily available to deal with any emergency. The provision of emergency medical care, including the locality of facilities, provision of suitably trained medical persons, response times, capabilities to treat and evacuate multiple injured persons, must be ensured.

6.5.4.4 Mine Evacuation and Escape Procedures

To ensure the safe evacuation and escape of affected persons to a place of safety in the event of an emergency, the mine will cover the following:

- Procedures for the escape and/or rescue of persons from e.g. single and multiple entry working places, surface working places, confined spaces, elevated places, etc.
- Provision of places of safety, including the locality, quantity, distance about working places, and the provision of life-sustaining facilities, such as food, potable water, breathable air, etc. body-worn self-contained self-rescuers will be issued.
- The mine must also have a second means of exit from the workings and eventually to the surface should a portion of the main decline suffer a collapse preventing persons from exiting. (Monthly checks of the route by Mine, Ventilation, and Rock Engineering officials needs to be done and documented.)

6.5.4.5 Training and Awareness

To ensure that all potentially affected persons are educated, trained, and made aware of how to deal with emergencies, the mines training centre will address the following issues:

- The procedures and appropriate actions to be taken in the event of an emergency, including simulated exercises.
- The correct procedures and applications on the use of emergency equipment.
- The actions required relating to the location and description of shutdown controls/lockout devices.
- Instructions in the use of belt-worn self-contained self-rescuers.
- The locality of copies of the emergency procedures and instructions.
- Ex-leave and novices to be inducted by their supervisor from the 1st shift until found competent with emergency procedures (signed off induction form).

6.5.4.6 Rescue and Response Capabilities

To ensure that emergencies are reacted to timeously with adequate rescue and response capabilities the mine will have the rescue and response capabilities in place:

- Access to sufficient rescue personnel.
- Arrangement for and access to specialised rescue equipment.
- Arrangements with a mines rescue service provider.
- Additional instrumentation and equipment are available to maintain rescue brigades, e.g. a means to detect carbon monoxide, carbon dioxide, flammable gas and oxygen, ancillary rescue equipment, etc.

6.5.4.7 Management of Emergencies

The following management controls will be implemented to ensure that emergencies can be managed and dealt with effectively:

- Emergency manuals, contacts of neighbouring mines, contacts of emergency services, internal and external telephone directory.
- Emergency control centre/s including, equipment required, plans, communication, etc.
- The duties and responsibilities of persons required during an emergency.
- Procedures to deal with adverse environmental conditions, which could be encountered during an emergency, e.g. flooding, gases, heat, etc.

6.5.4.8 Reporting and Recording

To ensure that the emergency preparedness and response measures and procedures remain effective, there will be a procedure for the inspection, testing, and maintenance of all equipment and facilities that may be used in an emergency at appropriate intervals, as well as the duties of persons designated for this purpose.

6.5.4.9 Fires and Explosions

There are two guidelines issued by the Department of Mineral Resources (DMR) that must be complied with:

- "Guideline for the compilation of a mandatory code of practice for the prevention of flammable gas and coal dust explosions in collieries"; and

- "Guideline for the compilation of a mandatory code of practice for the prevention of flammable gas explosions in mines other than coal mines".

The mine should conduct a risk assessment to determine the risk of fire, explosion, and/or a toxic release, which may endanger the safety and health of those so affected.

Fires involving rubber tyred vehicles present a considerable risk to any underground mine. If the fire is not quickly suppressed and spreads to the tyres, then it can only be extinguished with water. Dry powder is unable to extinguish a rubber tyre fire as it does not remove sufficient heat to prevent re-ignition of the gases emanating from the hot rubber. If the fire is not quickly extinguished with water, then it is almost inevitable that the vehicle will be destroyed. Dense black smoke with high levels of CO from burning rubber tyres will quickly circulate through the mine and for this reason, body-worn SCSR and availability of Refuge Bays are mandatory.

All rubber tyred vehicles should be equipped with automated onboard fire suppression and a fire extinguisher to control any fire quickly. Vehicle maintenance plays a vital role in ensuring no leaks of diesel fuel and no accumulations of oil or grease are present.

All diesel re-fuelling should be carried out by a mine standard and trucks should only be re-fuelled on the surface unless this is unavoidable. Also, fire suppression systems are required to be installed within all underground workshops, which service diesel vehicles, tyre bays, and re-fuelling stations.

An integrated escape and rescue strategy, specific to the operation under consideration, is required for each section of the workings and for all other places in which persons may travel. This will ensure that all measures, to the extent that it is reasonably practicable, have been put in place to assist in the safe passage of employees in times of emergency.

As a minimum, the following life support devices and systems will be considered:

- At all working places underground, the employees so affected should have adequate warning of a deteriorating environmental condition.
- All underground employees in areas considered high-risk areas as determined through a risk assessment must be issued with body-worn self-contained self-rescuers.
- Body-worn self-contained self-rescuer supplied to an employee must be allocated for the sole use of that employee for the duration of the deployment of that specific self-rescuer.

During the primary development of the production sections, it is recommended that several refuge bays be installed at strategic locations within the development complex. From then on refuge bays are established on every level and thereafter in tunnels every 500 m to ensure personnel travel no further than 500 m from the furthest face/development heading.

The mine should be equipped with a set of electronic carbon monoxide and smoke detector heads, and in any other areas where there is a high risk of fire. A comprehensive system covering all intakes and main returns should be installed. The information is to be relayed electronically to a specific control room.

6.5.4.10 Flammable Gas Regime

6.5.4.10.1 Identification of flammable gas sources, occurrences, and composition

Flammable gas may be present in strata of all mines and can be very inconsistent and often of short duration. As there are no defined patterns, a high level of awareness and caution must be maintained by all employees, at all times. It is therefore important that employees are aware of where flammable gas can enter the workings:

- At faults, fissures, and dykes.
- From worked out and or abandoned workings through seals.
- At diamond drilling cover holes.
- During pilot-hole and normal shot-hole drilling.
- At fractures in strata caused by blasting and seismic events.
- With water intersections.
- With changes in barometric pressure and changes in season.
- Any workings underground where it is least expected.

The composition of gases is important as lower and upper explosive limits will vary; samples should therefore be analysed.

6.5.4.10.2 Control of Gas Emissions

Control of gas emissions will include:

- Routine tests and report emissions immediately so that necessary remedial steps can be taken.
- All working places must be adequately ventilated.
- Drilling of pilot holes and cover holes.
- Cementation/plugging of cover/geological boreholes.
- Gas emissions and high-volume water intersections to be plotted on a plan and this plan must be taken to planning meetings especially development planning to predict possible intersections. Ideally, this plan should depict geological formations such as dykes, fissures, and faults.
- Hydrogen sensors to be installed in battery bays and High Voltage (HV) substations with tripping battery sets.

6.5.4.10.3 Detection of Flammable Gas

Detection of flammable gas will include the provision of flammable gas measuring instruments/warning devices issued to appropriate personnel, includes maintenance, calibration, and training.

- Gas emissions and high-volume water intersections to be plotted on a plan and this plan must be taken to planning meetings especially development planning to predict possible intersections. Ideally, this plan should depict geological formations such as dykes, fissures, and faults.
- Hydrogen sensors to be installed in battery bays and HV substations with tripping battery sets.
- Flagging of sensors with alarm mode if calibration is not done as per COP.

6.5.4.10.4 Ignition Sources

Prevent ignition of flammable gas by ensuring proper control of:

- Contraband
- Open flame
- Electrical equipment
- Re-establishing electrical power after a power failure
- Frictional ignitions
- Static electricity.

7 CONCLUSIONS FROM MILESTONE

There is no doubt that a step-change in ventilation optimisation in mining operations is realistic, which will greatly assist the mining engineer in developing an unconstrained mining extraction plan.

The available technologies need to become a focal area of optimisation where both the mining and ventilation engineer combine their respective skills set and challenge the current “self-inflicted” production limitations by “thinking out the box” and developing novel yet feasible mining plans which allow “sweating the asset” from tonnage build-up through to an optimised mining cycle to final tail management.

8 WAY FORWARD

Get approval for the draft of a guideline for Best Practice applications of mechanised ventilation strategy.

9 RECOMMENDATIONS

It is incumbent on the mining and ventilation engineer, to integrate the planning of new mechanised operations to ensure fit for purpose efficient designs.

New ventilation systems that will allow uninterrupted operations, via a short (30-minute re-entry interval) need to be developed in conjunction with the mining engineers.

This will allow for concentrated mining, where the assets are used continuously in a focused operational approach with improved supervision. The aim is to improve efficiency thus reducing the capital required and improving the Return on Investment (ROI).

The ventilation engineer must be part of the entire planning process, giving input into effective, and where possible on reef mine designs, equipment selection, and mining cycle.

The ventilation engineer must also take cognizance of existing infrastructure making use of it where reasonably practical taking due care to resistances and potential leakages.

Every effort needs to be taken through the entire design process to reduce the overall pressure drop by introducing an intelligent fit for purpose air supply which leads to a reduction of the total required airflow and pressure requirement within a mine. By reducing the total airflow and pressure, energy can be saved in disproportionately high amounts due to the cubic relationship between volume flow and fan power as shown with the following formulas:

$P = \Delta p \cdot V'$ and $\Delta p = R \cdot V'2$ result in $P = R \cdot V'3$

Robust ongoing management of the designed ventilation system is further required to ensure optimised air distribution with minimal leakages. This will further require a critical review of current acceptable leakage parameters, coupled with an effective fit for purpose sealing and air distribution methodologies. (Stanton 2020).

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