REAL-TIME MONITORING OF ENVIRONMENTAL CONDITIONS IN DEEP METALLIFEROUS MINES: VOD OPERATIONAL READINESS

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Date: 04 January 2022

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ABSTRACT

The purpose of this report is to outline the results of an empirical study conducted at South Deep on locating underground environmental sensors. The environmental monitoring sensors were installed at South Deep, as an enabler for various modernisation techniques, namely; real-time monitoring for workplace re-entry time optimisation and ultimately automation of underground operations.

The literature shows that VOD systems have great benefits including energy savings, health and safety improvements and productivity improvements. The knowledge gap in the implementation of such systems has led to many hard rock mines missing out on these benefits. The industry has continued to rely on outdated means of monitoring the underground environment. This is due to the lack of SA manufactured real-time sensors and knowledge of how select and position these sensors. This means that even attempting to modernise SA hard rock mines is limited by the knowledge ceiling.

The project followed a quantitative methodology, as the objectives are quantifiable and any credible results need to be compared to the base case. A base case was established by gathering quantitative data from the mine which include environmental surveys and energy audits. This data was used to form models for simulations required for planning

The real-time monitoring installation project at South Deep Mine was critical in establishing the operational readiness of the mine for VOD systems. With a POC undertaken at a single production corridor, the learning costs of the project were kept at a minimum. The system is an enabler for various modernisation projects such as VOD and automation.

The sensors were selected based on criteria focused on system compatibility with the communication network. The requirements of the system, accuracy & reliability, durability & robustness and the size of the instruments were also critical parameters. The health and safety of the personnel will depend on these systems, hence the validation of errors and accuracies is required before commissioning is required.

After selection, locating these sensors is another critical step for real-time monitoring projects. With global monitoring used at South Deep, critical monitoring points had to be established while ensuring the tunnel uses, dimensions and plans are considered before choosing the exact location.

After testing, the mine reduced workplace re-entry times by 35 min, a 29% reduction, by implementing remote early-entry examination. This translates to an increase of 8.6% in effective shift time. Theoretically, this should translate to a production gain of the same amount, which equates to an additional ZAR 600 million in revenue. Theoretical energy savings based on a scheduled control of the auxiliary system can save the mine up to ZAR 28 million per year, a 41% reduction in energy costs

Through the real-time monitoring system, the mine will also improve the health and safety standards at the mine. By practising remote early-entry examinations through the real-time monitoring of the system, the mine will reduce the risk rating of the activity from level nine (9) to level three (3).

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LIST OF ABBREVIATIONS AND UNITS

Ammonia	(NH_3)
Bulk-air coolers	(BACs)
Carbon dioxide	(CO_2)
Carbon monoxide	(CO)
Consumer Price Index	(CPI)
Degrees Celsius	(ºC)
Diesel particulate matter	(DPM)
Dry-bulb	(DB)
Effective shift time	(t)
Effective ventilation time	(v)
Long hole stoping	(LHS)
Megawatts	(MW)
Meters	(m)
Meters cube per second	(m^3/s)
Meters per second	(m/s)
Meters squared	(m/s^2)
Methane	(CH_4)
National Energy Regulator of South Africa	(NERSA)
Nitrous oxides	(NO_x)
Non-effective ventilation time	(nv)
Occupational exposure limits	(OEL)
Parts per million	(ppm)
Percentage	(%)
Proof-of-concept	(POC)
Short-term exposure limits	(STEL)
South African	(SA)
South African Rand	(ZAR)
Sulphide dioxide	(SO_2)
Ventersdorp Contact Reef	(VCR)
Ventilation-on-demand	(VOD)
Wet-bulb	(WB)
Workplace re-entry time	(w)

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CHAPTER 1

INTRODUCTION

1.1. BACKGROUND

Since the establishment of Eskom, South Africa's utility provider in the 1920s, the electricity supply industry has been monopolised by a single state-owned and vertically integrated entity (Deloitte, 2017). For much of the past five decades, the nominal price of electricity has always been on the rise from year to year. These annual price changes have always been kept below the inflation rate. From 2008, the National Energy Regulator of South Africa (NERSA) approved several sharp increases in the annual tariffs. This has resulted in annual electricity tariff increases above inflation Figure 1.1 shows the average Eskom tariff increases compared to the annual Consumer Price Index (CPI) or inflation.

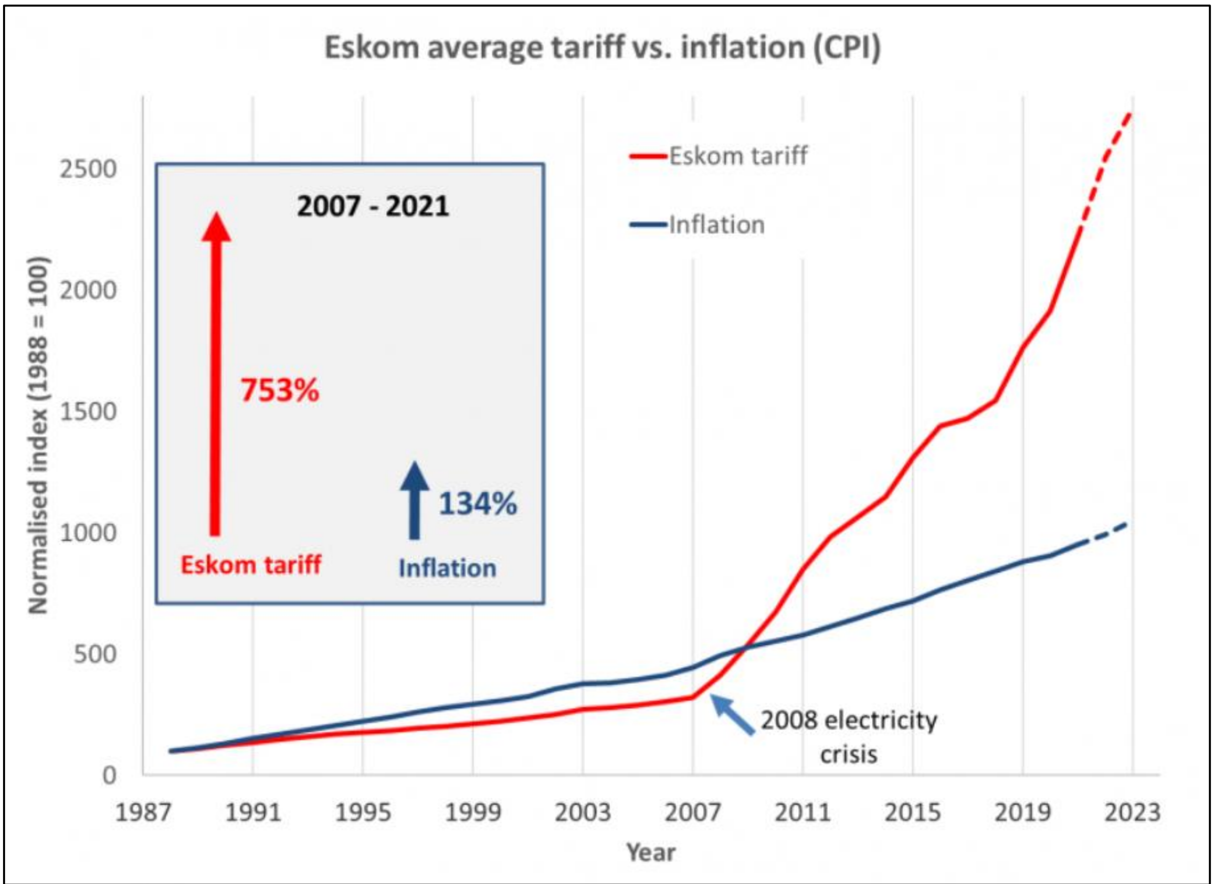


Figure 0.1: Eskom average tariff vs inflation (CPI) (Moolman, 2021)

The graph shows that there is a clear and sharp inflection point with tariffs increasing by 753% from 2007 until 2021, whilst inflation increased by only 134%.

The rising cost of electricity, along with the struggling Eskom is casting a dark shadow over the industry. Mines have become less profitable due to excessive energy costs and disrupted electricity supply. Deep level underground mines such as South Deep are agitating to supplement Eskom power with renewable power supply i.e. solar energy. The South Deep solar project has a capital expenditure of over ZAR 600 million, hence the mine has taken a radical approach of reducing energy wastage. This will be done by implementing a ventilation-on-demand (VOD) system in the mine.

VOD solutions can assist mines by supplying qualitative and quantitative airflow to parts of the mine where personnel and/or machinery is working or travelling. In doing so, energy savings can be realized whilst the health & safety of workers remains a priority.

Underground hard rock mines are homes to many noxious and flammable gases including carbon monoxide (CO), nitrous oxides (NO_x) and methane (CH_4). These gases are produced and/or released during drilling and blasting, decay of timber material, oxidation processes, and by machines such as diesel equipment. These gases present a hazard for explosions and can have a serious effect on air quality. The underground atmosphere is limited and confined and if gases and fumes are not controlled, extracted or diluted to acceptable thresholds, they can harm or kill miners inhaling them.

A real-time monitoring proof-of-concept (POC) project at South Deep, a deep hard rock mine, was designed to reduce noxious gas-related health and safety risks. By providing real-time monitoring of environmental conditions in the production zones, the mine can have better control of the environment to which they expose their employees. This project was undertaken as an enabler for VOD systems in South African metalliferous mines.

The monitoring system at South Deep is based on the VOD system at Kidd Creek (Hardcastle, et al., 2008), where real-time monitoring of environmental conditions led to shorter post-blast re-entry times.

1.2. PROBLEM STATEMENT

Eskom's deteriorating financial position puts the South African mining industry's sustainability and profitability at risk. Companies that operate in a competitive environment with little pricing power such as mines are vulnerable to electricity price changes. Figure 1.2 shows the South African mining industry profit sensitivity to real electricity tariff increases

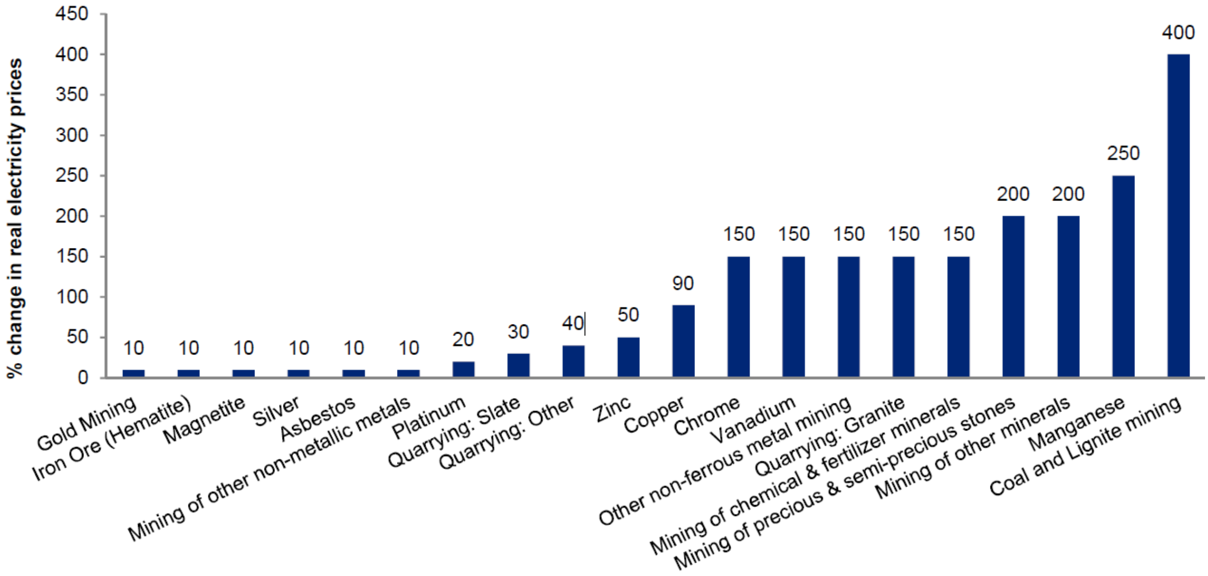


Figure 0.2: Mining Sector profit sensitivity (Deloitte, 2017)

In the mining industry, gold mining is the most vulnerable to electricity increases at level 10 profitability. This means that real tariff increases above 10% will erode the mine's profitability. While coal mining with a profitability level of 400, can absorb electricity price increases up to 400%. With Eskom agitating for further 15% increases in nominal electricity tariffs, South African gold mines such as South Deep are looking into energy reduction strategies to survive. Mochubele (2014) recommended that South Deep adopt VOD strategies and automation to sustain the mine by lowering electricity costs.

VOD systems are widely used in the mining industry for continuous monitoring of underground production zones and control of airflow based on the condition (quality-based), demand (event-based), or shift schedule (time-based). Adoption of these systems is still lagging in South African deep metalliferous mines. This is mainly due to the limited academic research on the practical implementation of these systems; such as how to select or locate the sensors in these mines.

This report outlines the learnings from an environmental sensor installation project which serves as a VOD operational readiness project at South Deep. The sensors were installed to provide real-time monitoring of production zones on a proof-of-concept (POC) stage. The POC helps capture and analyse all the benefits and challenges of implementing real-time monitoring systems while keeping the learning curve gradient and capital costs low. The project was used to determine the requirements for VOD systems in SA mines and the criteria for selecting the systems.

1.3. SOUTH DEEP MINING BACKGROUND

South Deep Gold Mine is located in Westonaria, 45km west of Johannesburg in the Gauteng province of SA as shown in Figure 1.3. Three different mining methods are used at South Deep to extract the massive orebody predominantly consisting of the Ventersdorp Contact Reef (VCR) at depths greater than 2500m. The main stoping levels consists of de-stress sections where 5 m cuts are taken in a room and pillar layout through the strike. Long hole stoping (LHS) is used for bulk extraction between the cuts, while a modified drift and bench method is used where the orebody is greater than 5 m but less than 10 m. Long hole stopes are then backfilled to ensure regional stability.

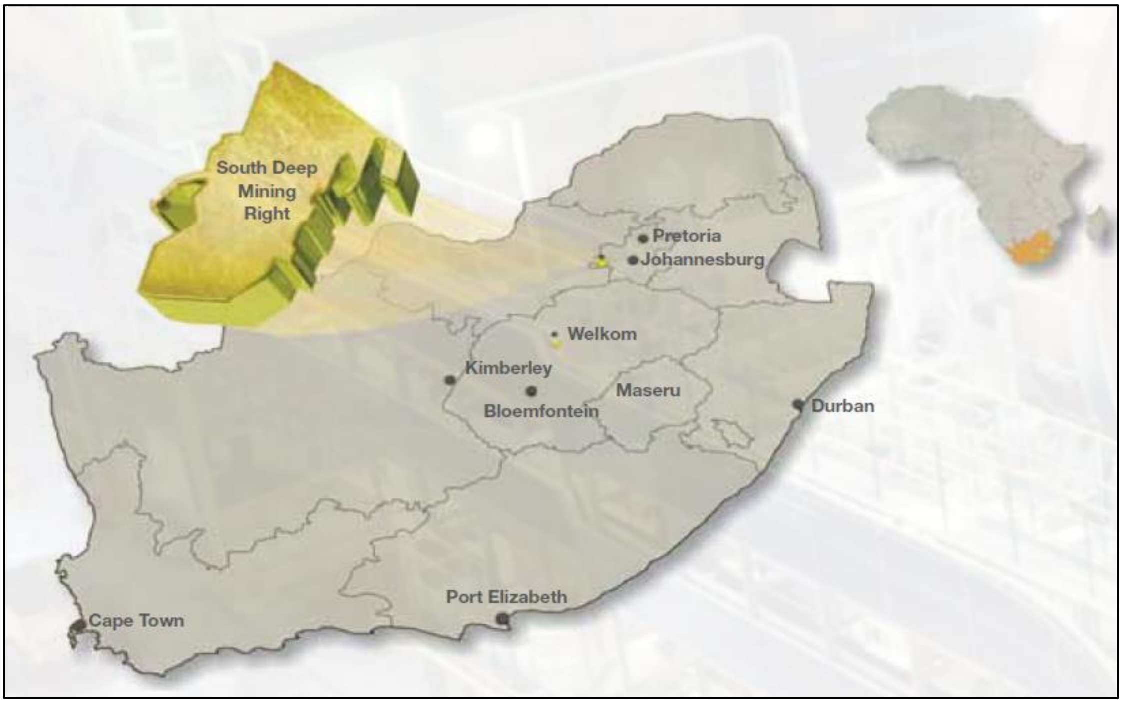


Figure 0.3: South Deep Location (Gold Fields, 2017)

The ventilation requirements at South Deep are based on the diesel equipment exhaust requirements. A dilution factor of 0.06 m^3/s/kW with the highest-rated machine used in the section being a 6 ton LHD with a 243 kW power rating. This translates to 14.6 m^3/s of airflow per heading. De-stress mining accounts for most operating faces, and thus presents the greater footprint of the three methods. Optimisation tests are done on the de-stress sections at the mine, as they present greater opportunities for savings which will affect the entire mine. Figure 1.4 is an overview of the ventilation layout at South Deep

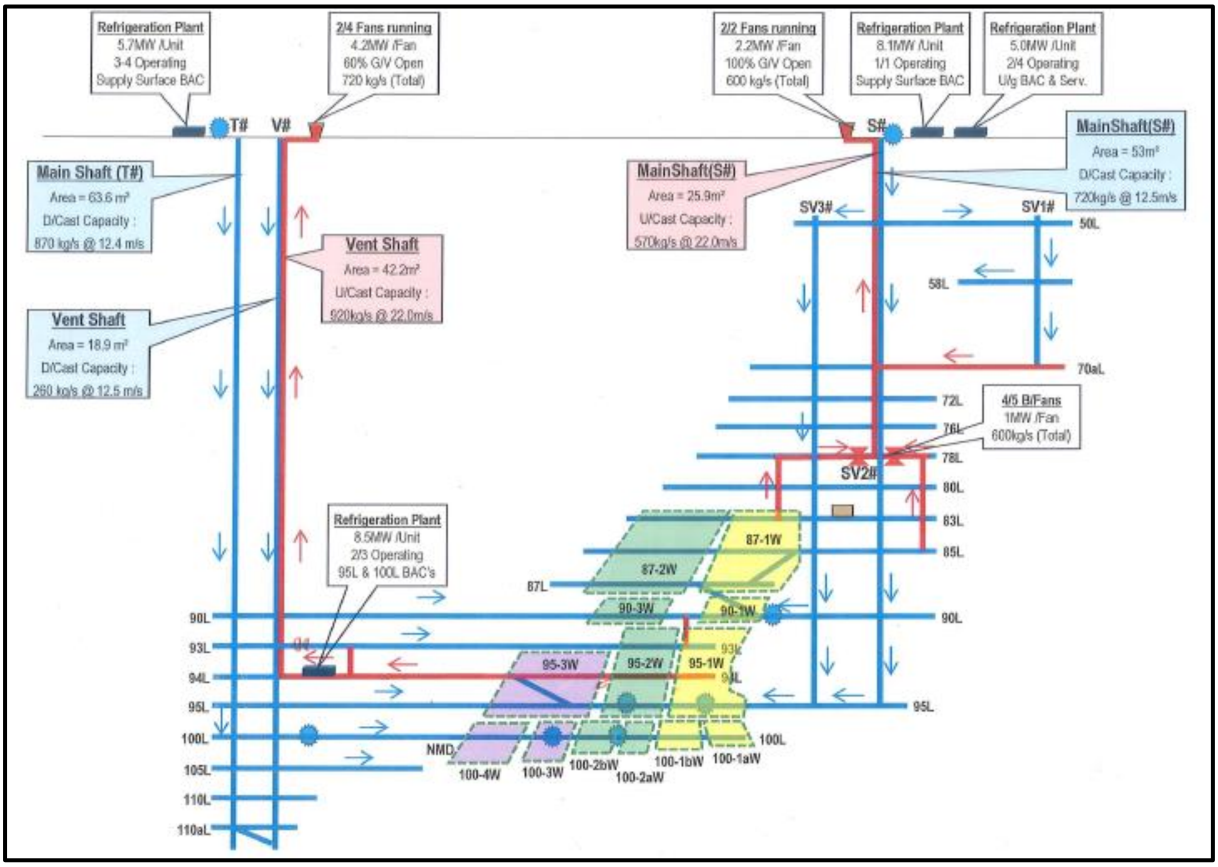


Figure 0.4: South Deep Basic Ventilation Flow Diagram

Four main fans are used to draw 1200 m^3/s of airflow into the mine through the Twin Shaft and South Shaft complexes. Four booster fans on level 78 are used to assist the main fans to overcome all the increased resistance experienced over time as the mine expanded. Auxiliary ventilation is required at South Deep to draw air from the main intake airways at each level into the production corridors. The project at South Deep focuses on optimising the auxiliary system within the production corridors.

1.4. OBJECTIVES

South Deep mine has decided to take the first step of moving from theory to implementation on digital transformation, by installing underground environmental real-time sensors. The aims of installing the underground sensors were three-fold:

a) to be able to monitor the underground environment remotely in real-time to reduce the re-entry period;
b) to act as an enabler for other optimisations such as access control of workers and mobile equipment remotely; and
c) to be able to make sound decisions based on real-time information for production, energy-saving and health and safety based on the environmental conditions.

The main objective of the project is to investigate the operational readiness of South Deep for VOD strategies. In the long term, these strategies will form the basis of an integrated energy management plan for the mine. The short-term objective is to reduce the electricity costs of ventilation through the control of airflow in the mine based on the demand of machines and personnel. Added objectives include maintaining the health and safety of employees through real-time monitoring and increasing effective face time through remote re-entry examinations.

1.5. SCOPE AND DELINEATION

The research work is confined within massive gold orebodies such as that of Gold Fields South Deep, where the POC project is based. Cost savings achieved through VOD require extensive real-time monitoring of workplaces for contaminants. In gold mines, the main air contaminants include heat, respirable dust, radiation noxious fumes, diesel particulate matter (DPM) and blasting fumes (Butterworth, 1999). Contaminants liberated during blasting include carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), radon, ammonia (NH_3), sulphide dioxide (SO_2), methane (CH_4) and other hydrocarbons. This project focuses on the three most dangerous gases released into underground mines namely carbon monoxide (CO) and nitrous dioxide (NO_2) (Stewart, 2014), as they pose an immediate risk to human life; and methane (CH_4) which is an explosive gas that can be found in rock fissures and cracks (du Toit, 2017). VOD monitoring will be limited to these three gases, with air velocity, humidity and pressure being added parameters.

South Deep follows a series arrangement of working faces. The return air from one development end is used to ventilate the following development ends sequentially until all the development ends are ventilated. Series arrangement of sensors is implemented to achieve global monitoring of the production zones.

1.6. REPORT STRUCTURE AND USE OF CHAPTERS

The report follows the following structure:

1. Chapter 1 is the introduction of the report and outlines the problem background, the problem statement, South Deep's mining background and the report scope and delineation.
2. Chapter 2 is the literature review focusing on environmental monitoring and control background, health and safety implications of environmental monitoring; VOD requirements for operational readiness; and real-time monitoring implementation.
3. Chapter 3 outlines the methodology used in the report including the sensor location and selection criteria. The validation methods include VUMA 3-D modelling and risk assessments.
4. Chapter 4 provides the results and analysis obtained and made from the model and risk assessment:
5. Chapter 5 contains the report conclusions and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

South Deep mine was the first to apply and get approval for a ministerial deviation to generate 40 megawatts (MW) of solar power at ZAR 660 million. As part of the operational readiness for the solar project, South Deep has embarked on a journey of reducing energy inefficiencies and wastage. This review of literature focuses on real-time monitoring as an enabler for VOD systems. Environmental monitoring techniques used in South African (SA) hard rock mines are also reviewed.

2.1. ENVIRONMENTAL MONITORING AND CONTROL BACKGROUND

According to Abu-Mahfouz et al. (2014), real-time sensors capable of accurate and reliable monitoring in the high dust and humidity environment of hard rock mines exists in the global mining industry. Nonetheless, hard rock mines in South Africa still rely mostly on routine surveys by personnel with hand-held sensors for environmental monitoring. This is due to the lack of readily available academic knowledge into the use of these sensors in South African hard rock mines. The report by Abu-Mahfouz et al. (2014) outlines the implementation of real-time monitoring in shallower coal mines where awareness of flammable gas incidents is prioritised. The lack of implementation of real-time monitoring in hard rock mines where awareness of flammable gas accidents is limited is concerning. In recent years, there has been an increase in flammable gas accidents and over exposures in these mines (Abu-Mahfouz, et al., 2014). There is a need for an integrated study of real-time monitoring implementation in hard rock mines.

Post-blast re-entry time standards are put in place in underground mines to ensure blast fume clearance before personnel re-enter workings. Estimation of these times is based on empirical methods such as the eight-air changes guideline and throwback methods (Stewart, 2014). Such methods lead to overestimation of re-entry times which have safety and productivity implications. Longer re-entries mean safer working conditions but reduced face-time for production. In theory, real-time monitoring removes the need for manual re-entry examinations and the need to estimate re-entry times. This can potentially increase the mine’s production time. Practically, this has never been practised in SA mines and existing guidelines and laws are based on the conventional means of stope monitoring. The knowledge gap between theory and practical implementation is a barrier for all South African underground mines other than coal mines.

Kocsis et al (2003) recommended that mines move away from the conventional ventilation system design and use a phasing-in approach based on the mine production requirements. Mochubele (2014) argues that with hard rock mines in South Africa expanding laterally and vertically, the electricity costs to provide brute-force ventilation throughout the operation of the mine is unsustainable. As early as 2012, Karsten and Mackay (2012) recommended that hard rock mines should look into VOD systems to remain sustainable and competitive. These academic reports lack practical implementation knowledge of VOD systems, as they only highlight generalised benefits of the system without a South African case study to back the findings. This shows that there is a huge gap in the South African mining industry for VOD based research works.

2.2. HEALTH AND SAFETY IMPLICATIONS

The Mine Health and Safety Act (MHSA) of 1996 (No. 29) was the first stand-alone health and safety legislation for mines in South Africa. Under the MHSA, the employer has the duty to protect and promote health and safety in the workplace (Mohapi & Zarske, 2018). This means mines have to actively take steps to reduce health and safety risks.

The MHSA has regulations that govern health and safety standards in South African mines. Under the regulations, occupational exposure limits (OEL) are outlined, which represent the minimum health and safety standards that mines should achieve. The OELs are written as maximum airborne concentrations of toxic substances to which employees can be exposed over a period of time without harmful and irreversible consequences.

Table 2.1 outlines the OELs of the three noxious gases identified for this project as most problematic, requiring real-time monitoring.

Table 0.1: Explosive gas exposure limits

Gas	OEL	STEL
NO_2	3 ppm	5 pm
CO	30 ppm	400 ppm
CH_4	1.4%	-

Short-term exposure limits (STEL) refer to acceptable exposures over a short period, usually 15 minutes, as long as the time-weighted average is not exceeded. Thermal stress OELs are set at 32.5 ^{o}C wet-bulb (WB) and 37.0 ^{o}C dry-bulb (DB).

2.2.1. Early-entry Examinations

Ventilation air is circulated in underground mines to dilute and/or exhaust pollutant concentrations to safe levels for men and machinery. Routine monitoring of working conditions is prescribed by the MHSA regulations, with re-entry periods imposed where blasting is used for ore extraction. The main purpose of the re-entry interval is to protect the health and safety of personnel. This is done by ensuring that dangerous fumes are exhausted out of the working areas before personnel can enter post blasting. Poor ventilation or premature entrance into working areas can expose personnel to poisonous gases.

There is a need for early-entry examinations in underground mines after the re-entry period, to ensure the environmental conditions are within acceptable limits before re-entry into working areas. In SA hard rock mines, these are manually conducted by a handful of personnel with hand-held devices. This increases the risk of over-exposures of the observers to noxious gases and toxic fumes. With real-time monitoring, examinations are done remotely by checking the real-time gas readings in the system. This reduces the risk of exposure and hence improve the health and safety of the mine.

2.2.2. Real-time Monitoring

As early as 2003, Kocsis et al recognised the potential of VOD systems for energy savings, with Johnson in 2012 and Mochubele (2014) all reaffirming the same notion. The system’s ability to provide real-time monitoring is highlighted as instrumental in maintaining the health and safety of employees. Real-time monitoring doesn’t just maintain health and safety but improves it considerably.

The system reduces the need for physical environmental surveys which put observers in hazardous areas to conduct surveys. The risk of exposure is reduced while the monitoring capacity of underground environmental conditions is increased. The monitoring is in real-time, hence changes in environmental conditions can be dealt with timeously by evacuating personnel from the affected areas in time. The health and safety of the personnel in the production zones is always managed through the monitoring of pollutants. This improves the health and safety of underground mines. This goes a step further than the reports by Kocsis et al (2003) and Johnson (2012) which paint VOD systems as to only ‘maintain’ health and safety.

2.2.3. Heat Stress Management

South Africa is host to the world’s deepest mines reaching depths between 3km and 4km. At these depths, unventilated stopes can reach temperatures as high as 60 ^{o}C. Employees working in such mines are highly susceptible to heat stress conditions. Effects of heat stress are divided into three categories, i.e. physiological effects; psychological effects and productivity effects. Physiological heat stress disorders occur when there is more heat than the body can dissipate. These occur in various forms including heat rash, heat cramps, dehydration, heat exhaustion and more severely, heatstroke.

Figure 2.1 indicates the relationship between the wet-bulb (WB) temperatures and air velocity which should not be exceeded to avoid conditions conducive to heatstroke.

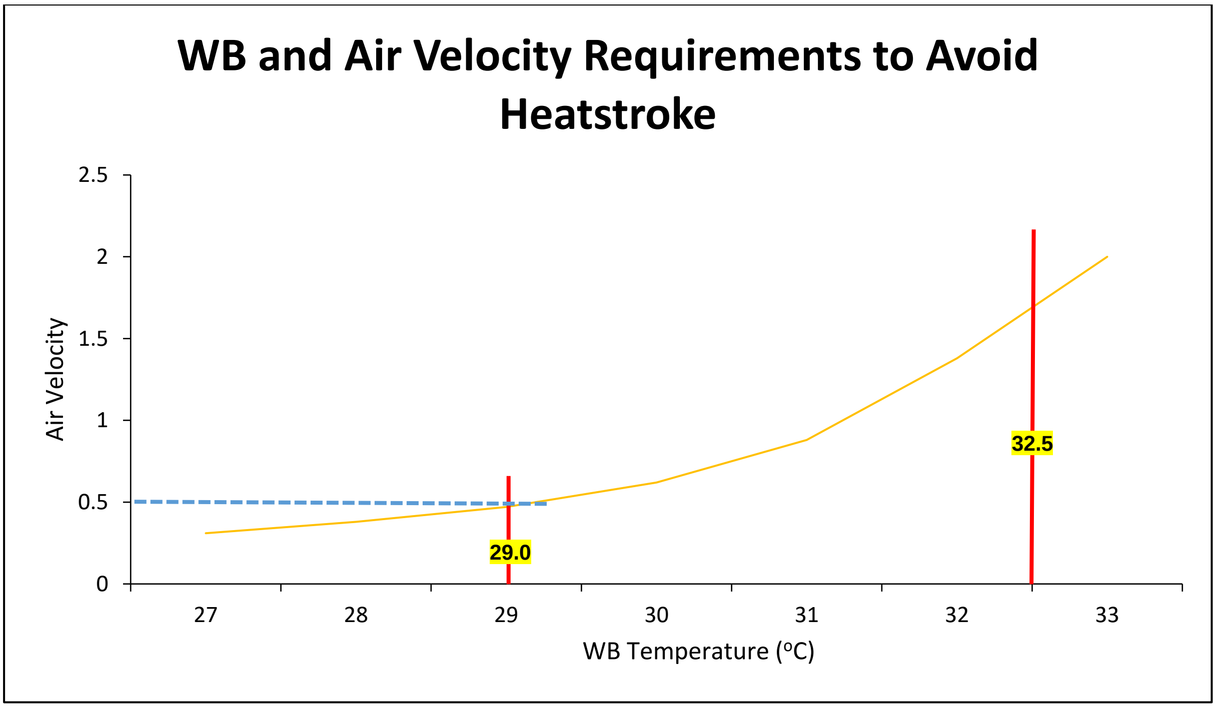


Figure 0.1: WB and Air Velocity Requirements to avoid heatstroke (du Toit, 2017)

Effects of heat stress can start developing at WB temperatures of 29 ºC, where air velocities are less than 0.5 m/s as can be seen in Figure 2.1. It is recommended for underground mines to have thermal standards below this temperature. At South Deep, the thermal standard is set at 28.5 ºC. It is of great importance to monitor temperature changes at deep mines such as South Deep, as heat exhaustion and temperature control are the overriding parameters for the ventilation requirements.

The work performance of underground employees depends entirely on the WB temperatures of the ventilating air and its velocity (du Toit, 2017). The WB is controlled through mechanical cooling and refrigeration, where the chilled air should be delivered as close as possible to the working place. Underground bulk-air coolers (BACs) are used at South Deep to deliver cooling as close as possible to the working places. Air velocities are a direct result of good and effective ventilation control and can be increased through mechanical ventilation. Table 2.2 illustrates how WB and air velocity affect worker performance.

Table 0.2: WB and air velocity effects on work performance (du Toit, 2017)

WET-BULB TEMP ^{O}C	AIR VELOCITY m/s	% WORK PERFORMANCE
27.0	0.5	100
30.0	0.5	96
30.0	2.0	98
32.0	0.5	83
32.0	2.0	93
32.0	4.0	95
32.5	0.5	80
32.5	2.0	90
33.0	0.5	72
33.0	4.0	90
34.0	0.5	65
34.0	4.0	80

From Table 2.2, it can be seen that worker performance decreases as the WB temperature increases. Increasing the air velocity counters the effects of increased WB temperatures on worker performances as cooling is delivered quicker to employees. Dynamic control of ventilation systems can result in improved work performance indices as ventilation outputs can be set to match high work performance requirements.

The real-time monitoring and control of ventilation parameters such as gases and airflow can be used to improve health and safety. This is done through quality-based VOD systems. This is where automatic control points are set based on the mine's environmental quality standards. Quality-based VOD systems regulate airflows based on the need to bring a working place to within acceptable mining standards.

2.3. VENTILATION-ON-DEMAND OPERATIONAL REQUIREMENTS

Ventilation-on-demand (VOD) is defined as the process of adjusting mine airflow to supply qualitative and quantitative airflow in the required area, in real-time to maintain environmental standards (Mochubele, 2014). The definition, although broad enough to encapsulate the main idea of VOD, does not outline the requirements of the system such as the system components and operational readiness.

VOD system components include various sensors for gases, airflow and location of personnel and machines. The positions of personnel and machines, along with airflow and gas sensor readings are communicated to a control system. Events are scheduled and setpoints are created for desired airflow quantities and velocities, temperatures, percentage gases in the general atmosphere.

A central communication network is critical for VOD systems as it links all the different devices to a central server. This allows for data from real-time sensors to be viewed on computer gadgets in real-time and allow for real-time control of the control devices to respond to any environmental changes in real-time. Implementation of this system should be phased in stages to reduce the learning curve costs as it has its challenges.

2.3.1. VOD Challenges

Despite the obvious benefits of VOD technology, adoption is very limited in the South African mining industry. The main reason is the lack of appropriate cost-effective, comprehensive, and reliable implementation knowledge and SA based solutions.

There is a belief that VOD technologies and their associated risks are too high and that the capital investment required is also high. Increased maintenance of autonomous devices is too costly and require reliable strategies, which are not currently featured in the mining industry in South Africa.

To add to these, the software requirements for VOD systems are demanding and challenging. Most mines planning to install a VOD system have pre-existing ventilation systems. These need to be retrofitted with new technology requiring initial capital costs (Howden, 2018). To ensure that the system operates smoothly, personnel need to be trained in the use and maintenance of the new system and equipment. The hardware equipment i.e. sensors, control relay instruments, network nodes and cables require regular maintenance, calibration and repair (Jahir & Mohamed, 2011). However, these drawbacks are relatively minor in comparison to the benefits. VOD is the better choice in comparison to existing ventilation systems.

2.4. REAL-TIME ENVIRONMENTAL MONITORING

According to Brink et al (2010), much of the measurements that drive decision making in a typical South African hard rock mine are acquired relatively infrequently through monthly and sometimes quarterly (3-months) surveys. The report argues that health and safety can be greatly improved if real-time monitoring systems can inform decision making. The report focuses more on sensing personnel bodily conditions and reactions to the underground environment. The actual environment monitoring is overlooked which provides a better framework to control the underground environment.

Traditionally, underground mine environmental monitoring sensors were used for reactive approaches. Turner (1982) describes an analogue monitoring system used for the early detection of fires in gold mines. This system of monitoring is still widely used in hard rock mines in SA. The system relies mostly upon the human perception of the alarms from the sensors and administrative controls such as evacuation standards to react to the alarms. Real-time access to such environmental data allows for corrective controls to be implemented timeously as a prevention, rather than a reactive method.

In South Africa, a handful of locally manufactured and produced sensors exist as most companies have positioned themselves as middle-man suppliers of the monitoring instruments. Information that is readily available from these companies pertains to the marketing of said instruments, not on the practical use and installation of the equipment. Information on the sensor accuracy, resolution and sensitivity is difficult if at all possible to attain from the middle-men. Testing of these instruments on-site before installation serves a very critical part in sensor installation projects. The reliability and accuracy of the sensor readings are crucial in maintaining the health and safety of the employees.

2.4.1. Wireless vs wired sensors

In modern underground mines, there is a migration away from cable-based monitoring systems towards wireless systems (Mine Design Technologies, 2020). Theoretically, the adoption of wireless communication systems in underground mines should allow for interfacing with a very wide range of data gathering instruments including wired and wireless environmental sensors. Practically, not all communication network solutions are compatible with monitoring devices. At South Deep, various suppliers were tried and tested before a suitable supplier with compatible devices was found.

Recently, there has been a sudden global shift towards modernisation. This is brought about by several things including developments in internet-of-things (IoT) technologies and the COVID-19 pandemic which has forced the entire world to go online due to movement restrictions. Due to this shift, sensor and underground communication leading manufacturers are partnering to develop a host of new technologies such as wired sensors capable of interfacing with wireless communication systems (CONSPEC, 2020). These sensors combine the multi-functionality and robustness of wired sensors with the flexibility and scalability of wireless sensors. There remains the need to test and validate the functionality of these sensors in South African hard rock mines.

The decision to use wired or wireless sensors should be based on the communication system used at the mine, as modern communication networks have a wide scope of compatibility with various instruments. Both the wireless sensors and wired sensors can be used for real-time monitoring with relative ease. Ultimately, both sensors need to be interfaced with the communication network and powered up either via batteries for wireless sensors or connected to nearby electrical sources for wired sensors to provide real-time monitoring. In South Africa, criteria of how to select sensors do not exist for hard-rock mines. The POC at South Deep allows for SA based research to determine the guidelines of selecting sensors for hard rock mines.

2.4.2. Sensor location

Using wireless gas sensors, (Stewart, 2014) investigated the dissipation rate of blasting fumes (CO & NO_2) in the estimation of post-blast re-entry periods. The investigation determined that variations in the readings were caused predominantly by the location of the sensor and air velocity. The investigation does not attempt to quantify and validate the effect of the sensor location on the variations.

The specific density of the gas being monitored is crucial when locating gas sensors. Monitoring instruments of gases with high specific densities should be located near the footwall, where heavier gases are most likely encountered. While those with lower specific densities are located closer to the hangingwalls where lighter gases are most likely to be encountered.

Sensors monitoring airflow properties such as temperature and the volumetric flow rate should also be located carefully as well. Temperature readings should be taken on the centre of the tunnel, mounting the sensor to the hanging wall with bolts or cable ties. Air flowing near the sidewalls tends to be less of a representing sample than that flowing within the tunnel. This is due to dead spots and eddies that form near the sidewall when the airflow hits kinks or bends on the tunnel. Figure 2.2 illustrates the formation of dead spots and eddies which result in lower or higher velocities than the actual airflow. Locating these sensors on the centre of the hanging wall increases the chance of reliable readings.

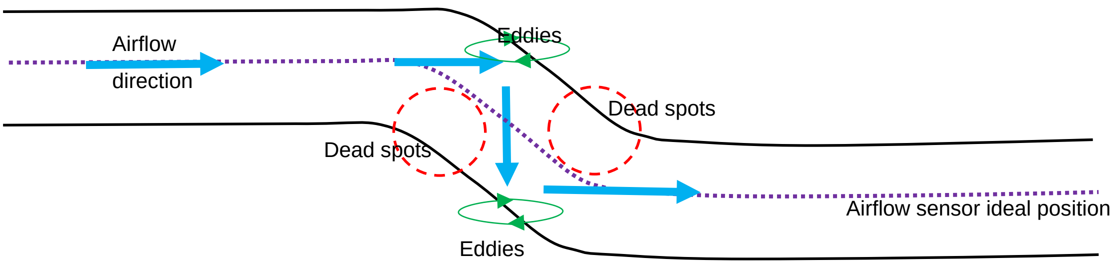


Figure 0.2: Formation of dead spots and eddies (de Walt, 2021)

A clear criterion on how to locate environmental sensors in hard rock mines does not exist for SA mines. As part of the VOD operational readiness at South Deep, sensor location is investigated to create sensor location guidelines for hard rock mines in SA.

2.4.3. Re-entry examinations

South Deep mine prioritises the monitoring of three contaminants, i.e. Carbon Monoxide (CO), Methane (CH_4) and Nitrogen Dioxide (NO_2), and airflow properties which include dry-bulb temperature, velocity, pressure and humidity. CO and NO_2 gases are released during blasting and are extremely dangerous as over-exposures may cause severe poisoning and can lead to death (Bascompta, et al., 2016). CH_4 pockets are encountered during cover drilling and prospect drilling, which poses a risk due to its explosive and flammable nature.

The implementation of real-time monitoring at Glencore's Kid Creek mine reported by (Keen & Allen, 2008) and (Hardcastle, et al., 2008) showed that real-time monitoring can be leveraged to optimise post-blast re-entry procedures to save on workplace re-entry time. South African hard rock mines are legally required to observe re-entry periods after blasting. The reports from the Canadian mine fail to quantity how these times impact the entire post-blast re-entry examinations even with real-time monitoring.

At South Deep, post-blast re-entry times are estimated based on the Department of Mineral Resources and Energy (DMRE) guideline of allowing eight air changes after blasting to dilute and exhaust blasting fumes. These post-blast re-entry times are validated empirically, through re-entry examination surveys. This is done with the supervision of a ventilation officer, where the miner and a health and safety representative manually assess the environmental conditions after blasting using electronic gas detecting instruments (GDI). Readings are taken 30 minutes after the blast and at every 15-minute interval until environmental conditions are within the mine standards shown in Table 2.3.

Table 0.3: South Deep Mine Standards

Contaminant	Mine Standard
Methane	1%
Carbon Monoxide	25 ppm
Nitrogen Oxide	3 ppm
Temperature	28.5 ^{O}C wet bulb (WB) / 37.0 ^{O}C dry bulb (DB)

With real-time monitoring, early-entry examinations can be done remotely. This can save the mine over 30 minutes in workplace re-entry times. The real-time monitoring system must be tested and validated to ensure that inherent errors of the sensors are taken into account. This will ensure a true representation of the underground environment and appropriate action can be taken when required.

2.5. CHAPTER SUMMARY

The literature shows that VOD systems have great benefits including energy savings, health and safety improvements and productivity improvements. The knowledge gap in the implementation of such systems has led to many hard rock mines missing out on these benefits. The non-existence of SA manufactured real-time sensors has meant that the industry has continued to rely on outdated means of monitoring the underground environment. Knowledge of how to select and locate these sensors means that even an attempt to modernise is limited by the knowledge ceiling.

CHAPTER 3

METHODOLOGY

The VOD POC project at South deep servers and operational readiness investigation for deep hard rock mines in South Africa. The project seeks to adopt a phased approach to VOD implementation by focusing on level 1 control over the auxiliary ventilation system in a single production corridor. The system objectives are to provide real-time monitoring of CO, CH_4, NO_2, and temperature and air velocity in the production zones and to provide looped control over the section exhaust fans in a single corridor.

Quantitative research data is used when the researcher attempts to quantify a problem (Albertson & Hillemann, 2021). This is data that can either be counted or compared on a numerical scale. Qualitative data on the other hand describes qualities or characteristics and is collected using interviews and observation (Albertson & Hillemann, 2021). The objectives of the project are finite and quantifiable hence quantitative research methods are used.

A base case study is required to establish a comparison standard for the system. The instruments to be used need to be carefully selected as all mistakes are costly. Operational data from the instruments are collected and compared to that of trusted instruments currently used at the mine. The comparison serves as validation of the system operation. Simulation models are used for the planning of the system in terms of locating sensors. The simulations are validated by the collected data.

3.1. ENVIRONMENTAL MONITORING

Quantitative data of the energy requirements of the ventilation system at the mine are required. This data will be used to establish a base case scenario. Quantitative data of the environmental conditions, the ventilation system’s effectiveness and the shift configuration of the production zones are also required for the base case. Data formats for these, include ventilation surveys in a Microsoft (MS) word format; energy audits in MS excel formats; time studies in an MS Word format; and environmental sensor readings in an MS Excel format. Photographs were also taken during the data collection which is presented in image file formats (JPEG and PNG).

3.2. INSTRUMENENT SELECTION

The type of communication network used can limit the options for the type of real-time sensors as compatibility is critical in selecting sensors. The author puts forward the following consideration for selecting real-time environmental sensors for underground mines:

i) **System compatibility** – the team must endeavour to interface the sensors with existing underground communication systems, rather than a complete overhaul of existing infrastructure.

ii) **System requirements** – the expected outcomes and objectives of the system need to be carefully considered as multi-functional sensors are widely available.

iii) **Accuracy and reliability** – the sensors are of utmost importance as lives depend on these results. Any inaccuracies should be accounted for in the overall control parameters of the system. Testing and validation of the sensors against known parameters or monitors are crucial before commissioning.

iv) **Durability and robustness** – underground mining environments are very harsh and require equipment that cannot be damaged easily. Sensors should be able to handle exposure to large amounts of dust, moisture and vibrations which persist in deep metalliferous mines.

v) **The size and shape** – underground mines have finite tunnel sizes that are based on the size of the machines and other services. The size and shape of the sensors are critical when retrofitting them in a tunnel.

3.3. SENSOR LOCATION

There currently is no criteria to follow when locating sensors. At South Deep, the following factors were considered when locating the sensors i.e. critical monitoring points; tunnel dimensions; tunnel uses; and production plans.

3.3.1. Critical monitoring points

Critical monitoring points are defined as locations handling the bulk of the return airflow from the development ends in the case of global monitoring. Such areas are characterised by higher mass flow rates, preferably with air streams from multiple ends converging into them. In local monitoring, critical points should be located on the return air of the development end.

For forcing columns, critical monitoring points should be ahead of the discharge column away from the face as shown in Figure 3.1. For example, if the column discharge is 15m from the face, the sensor should be located at least 25m from the face or where practically possible. Apart from ensuring the safety of the sensors, this ensures the airflow being monitored is from the face. Furthermore, it ensures the airflow from the face mixes well with any leaks in the column to provide reliable and accurate readings of the face conditions.

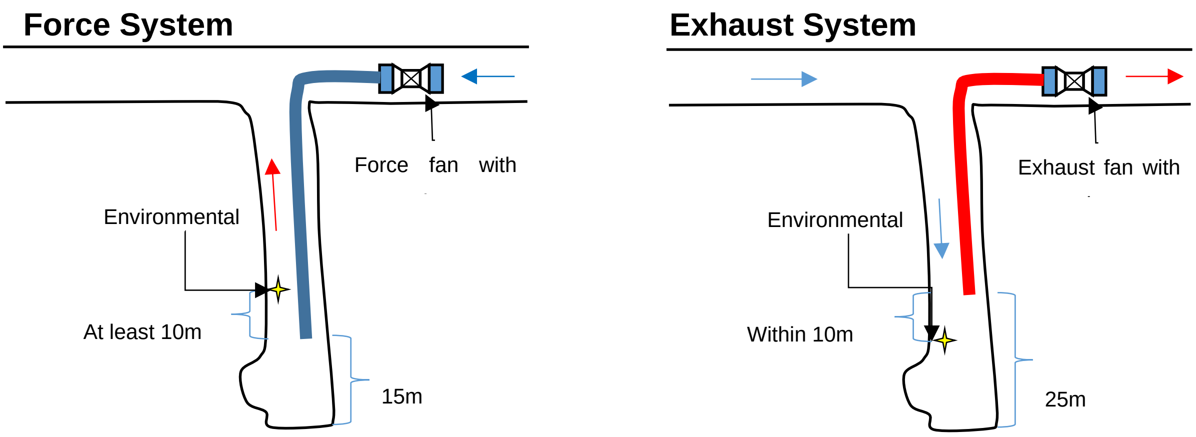


Figure 0.1: Critical Monitoring Points (Local Monitoring) _ Exhaust vs Force Systems

In exhausting ventilation systems; locating the sensors in front of the column intake theoretically gives the best readings, as the area shows the most mass flow from the VUMA3D modelling. A hybrid combination of these two basic dead-end ventilation techniques such as force-exhaust requires further investigation for sensor placement.

3.3.2. Tunnel dimensions

When all critical locations are identified, collaboration with the planning, production and engineering (electrical and instrumentation) departments is critical to choose the exact location to place monitoring stations. This is to avoid unnecessary damage to the instruments through uncoordinated planning as was the case at South Deep. Poor communication and planning between the departments led to a monitoring station being damaged by fly-rock from the blasting of a secondary escape route. Sections within the tunnel with uniform cross-sectional areas and shapes are more suitable for environmental monitoring stations. Area changes in a tunnel affect the airflow in many ways, resultant local turbulent flows can reduce the accuracies of various air property monitoring sensors such as air velocity sensors.

3.3.3. Tunnel uses

Tunnels heavily relied upon for travelling, loading and hauling proved to be more of a challenge for sensor location as machines easily damage mounted sensors during their operation. Avoiding main access routes for sensor locations is recommended. If it is impossible to avoid, the use of smaller sensors that are easily concealable is recommended and should be accompanied by signs marking their location. Such sensors may offer fewer capabilities though, as more sophisticated sensors have bigger hardware for their multi-purpose functionality.

3.3.4. Production plans

To avoid moving the sensors frequently, future production plans must be considered to locate the sensors with the future in mind. Locating them too close to future working areas increases the risk of damage from a blast or being knocked by equipment. Locating them too far from future production levels will lead to inadequate monitoring once sections become active. This will require additional sensors or moving the existing sensors to cover the footprint of the section.

3.4. DATA COLLECTION

Data is grouped into four main types based on the collection method i.e. observational data; experimental data; simulation data; and derived data (Albertson & Hillemann, 2021). All four data types are used in this study.

3.4.1. Observational Data

Observational data is captured through the observation of an activity or behaviour. Measuring instruments were used during ventilation surveys to observe the airflow velocities, temperatures, carbon monoxide (CO) and methane (CH_4) levels. To reduce any discrepancies in the data, the same person conducted the surveys for the entire observation time of two weeks. This type of observational data can be affected by the methods of measuring used and the skill of the observer.

The whirling hygrometer was used for measuring the dry-bulb and wet-bulb temperatures; the electronic gas-detection instrument (GDI) was used to monitor the CO and CH_4 levels; a barometer (BP) is used to measure the Barometric pressure and a vane manometer was used to measure the airflow velocity.

During the energy audits, the observer uses a digital multi-meter to measure the input power into the fan motors at the fan starter boxes. Limited skill is required for this process, hence the accuracy of the data doesn't rest on the skill of the observer. These measurements were taken by an electrician daily for two weeks. At the mine, only appointed electricians have access to the fan starter boxes.

Time studies were conducted for the day shift only, for two weeks. The purpose of the time studies was to determine the effective ventilation times (v); the workplace re-entry times (w); and non-effective ventilation times (nv); and the effective shift time (t).

3.4.2. Experimental Data

Experimental data is collected through active intervention by the researcher to produce and measure change or to create a difference when a variable is altered (Albertson & Hillemann, 2021). To test the accuracy and reliability of the purchased instruments. A test site at the mine's 'Mock-up mine' was established. This testing site allowed for comparing the accuracy of the sensors against trusted measuring instruments at the mine such as the GDI, whirling hygrometer and vane manometer. The site also allowed for comparing of the sensor accuracies at different positions within a tunnel i.e. footwall, hanging wall and sidewall.

3.4.3. Simulation Data

Simulation data is generated by imitating the operation of a real-world process or system over time, using computer test models (Albertson & Hillemann, 2021). The observational experimental data collected were used as data points for the models that were created for the simulation process. These data points include environmental conditions, airflow qualities, sensor accuracies, and sensor positions. The simulation results were used as an additional planning strategy for locating sensors.

3.5. VALIDATION

Checking to prove the validity or accuracy of a system is very critical when testing a new system. The project undertaken at South Deep gold mine aims to test the impact of real-time monitoring on the mine's early-entry procedures and health and safety standards. Validation and evaluation of the system are required in three stages i.e. computer models and simulation; mock-up testing; system evaluation.

Computer models of the section where installations took place were created through the VUMA3D software package and simulated. These simulations were validated against legal *'ventilation survey reports'* to adjust the model to fit the real conditions in the section. The models are used to identify *critical monitoring points*, more details are contained under results and discussions.

The mock-up testing was conducted over two weeks to collect enough information to track trends for the reliability of the readings. The system was then installed and commissioned in the underground POC site. The sensor readings seen on surface gadgets were compared with monthly environmental surveys to validate the system.

Table 3.1 shows the risk assessment matric used to quantify the health and safety risks at the mine.

Table 0.1: Risk matrix (Dominguez, et al., 2019)

		CONSEQUENCE CLASSES			
		C1 (1) Insignificant Consequence	**C2 (2) Significant Consequence**	**C3 (3) Serious Accident**	**C4 (4) Major Accident**
LIKELYHOOD CLASSES	**F4 (4) Frequent**	R4	R8	R12	R16
	F3 (3) Probable	R3	R6	R9	R12
	F2 (2) Improbable	R2	R4	R6	R8
	F1 (1) Very Improbable	R1	R2	R3	R4

The scope of the risk assessment needs to be outlined before the actual assessment i.e. improving health and safety during re-entry procedures. The following steps are followed to quantify the health and safety risks at the mine (Yahnke, 2021):

i) Hazard identification – listing potential hazards relating to the scope of the assessment

ii) Likelihood determination – determine the probability (%) of the hazard occurring and group it into the following brackets:
  - Very Improbable (below 10%)
  - Improbable (10% - 35%)
  - Probable (35% - 65%)
  - Frequent (65% - 100%)

iii) Consequence determination – determine the potential loss, and based on the severity of the consequence group them into the following brackets:
  - Insignificant – negligible i.e. no personal harm
  - Significant – minor damage i.e. recoverable injuries
  - Serious – a great deal of damage i.e. severe injuries
  - Major – catastrophic consequences i.e. death

iv) Risk rating determination – assign each hazard with a corresponding risk rating based on the likelihood and consequence. The risk ratings are divided into the following brackets:
  - Low – represented in **green**
  - Medium – represented in **yellow**
  - High – represented in **orange**
  - Extreme – represented in **red**

v) Create Risk Assessment Matrix – simplifies the risks for easier pinpointing of major and minor threats to health and safety.

3.6. CHAPTER SUMMARY

The project follows a quantitative form of methodology, as the objectives are quantifiable and any credible results need to be compared to the base case. A base case was established by gathering quantitative data from the mine which include environmental surveys and energy audits. This data was used to form models for simulations required for planning purposes. Experimental data was used for validation of the errors and accuracies.

CHAPTER 4

RESULTS AND ANALYSIS

The installation of real-time environmental monitoring sensors at South Deep is part of a bigger modernisation strategy. The immediate objective is to achieve real-time monitoring of the underground working places for re-entry optimisation. The results of the project focus on the selection of the sensors; the locating of the sensors; the system validation and evaluation. The communication network used at the mine forms the backbone of real-time monitoring as the medium of data transmissions. The expansion of this network is also outlined.

4.1. BASE-CASE SCENARIO

Before the roll-out of VOD systems to the entire mining footprint, a proof-of-concept (POC) plan is underway, where a single production corridor will be used as the test site, i.e. Corridor 3.

The proposed POC solution will be based on the following objectives:

- Provide real-time monitoring of CO; NO_2; CH_4; humidity; barometric pressure; temperature and air velocity.
- Provide remote control over the auxiliary fans in the section

4.1.1. POC location

The mining methods used at South Deep take place in individual corridors with dedicated intake and return airways. This makes the control of airflow in individual corridors easier to achieve. This makes it easier to test new systems in a single corridor, where all airflows can be tracked and controlled from intake to the return airways.

The 100 level, 4-West cross-cut corridor shown in the colour purple in Figure 1.4 of Chapter 1 was chosen as ideal for this POC. This corridor is also referred to as Corridor 3. The Corridor is in the New Mine Development (NMD) section, where mining is still relatively close to the ramps (within 240m). This corridor also boasts dedicated intake and return airways that are not connected to any older corridors. This ensures that any changes made to the ventilation system do not affect any other areas further downstream. With relatively a few sections opened (cuts 3 and 4), supervision of the system is relatively easy as all the sections had a single mine overseer.

4.1.2. Shift configuration

Table 4.1 summarises time studies done at South Deep gold mine Corridor 3 in October 2020. The purpose of the time studies was to determine the effective ventilation times (v); the workplace re-entry times (w); and non-effective ventilation times (nv); and the effective shift time (t).

Table 0.1: Shift Time Studies at South Deep

CATEGORIES			DAY SHIFT (05H40 – 18H00)	TIME
START OF SHIFT PROCEDURE	nv		Clocking in	05H40 – 06H00
	EFFECTIVE VENTILATION TIMES (v)	WORKPLACE RE-ENTRY TIME (w)	**CENTRALISED BLASTING**	**06H00**
			Travelling time (Surface to waiting place)	06H00 – 07H00
			Waiting-place procedure (incl. early-entry exam)	07H00 – 07H50
			Travelling to the workplace	07H50 – 08H00
		EFFECTIVE SHIFT TIME (t)	Machine pre-checks & Risk Assessments	08H00 – 08H15
EFFECTIVE PRODUCTION TIME			PRODUCTION ACTIVITIES (Ventilation infrastructure maintenance, loading, supporting, marking, water control, drilling, shotcreting, housekeeping etc.)	**START: 08H15** **STOP: 15H00**
END OF SHIFT PROCEDURE			Woking place clearance; waiting-place procedures;	15H00 – 15H45
	NON-EFFECTIVE VENTILATION TIMES (nv)		Travel to shaft & wait for the cage	15H45 – 17H30
			Shaft travelling to the surface (Shaft Clearance)	17H30 – 17H45
			CENTRALISED BLASTING	**18H00**

The shift configuration used at South deep is that of two 12-hour shifts, with centralised blasting taking place at 06:00 and 18:00. Workers only start descending to the working areas after the blasting. The travelling times from the surface to the waiting places, the waiting place procedures and travelling times to the workplace make up the workplace re-entry time. This is the total time from blasting until the time when employees re-enter the working places for production. During this time, auxiliary ventilation is required to dilute and exhaust blasting fumes.

At the end of the shift, personnel retreat to waiting places that are usually situated at the ramps, which are in the main through ventilation. After workplace clearance procedures, when all personnel have been cleared by the section supervisor to have left the production zones, continued ventilation in the production zones is wasteful. Table 4.2 summarise workplace re-entry; effective ventilation and non-effective ventilation times at South Deep.

Table 0.2: Workplace re-entry; effective ventilation and non-effective ventilation

CATEGORY	DURATION
WORKPLACE RE-ENTRY TIME (w)	2 hours
EFFECTIVE VENTILATION TIMES (v)	6 hours 45 minutes
NON-EFFECTIVE VENTILATION TIMES (nv)	3 hours 15 minutes

From Table 4.2, it can be seen that for a single 12-hour shift, 3 hours and 15 minutes is non-effective. The continued ventilation during this time is an unnecessary expansion of energy to ventilate areas that do need ventilation. There is a potential to reduce the energy consumption of the auxiliary ventilation system by 27%.

4.1.3. Airflow requirements

The ventilation requirements of the section at South Deep are based on the diesel equipment exhaust requirements of 0.06 $m^3/s/kW$. This translates to 14.6 m^3/s of airflow per heading as the highest-rated machine used in the section is a 6 ton LHD with a 243 kW power rating. Figure 4.1 shows the ventilation layout for Corridor 3.

The section has a dedicated intake hole that brings fresh air, and a return airway that is connected directly to the mines return airway. Four 75 kW fans are used to force airflow from the section intake to the respective districts. Each district is equipped with a single 45 kW fan that redirects from the district primary fan to the heading being worked on the day.

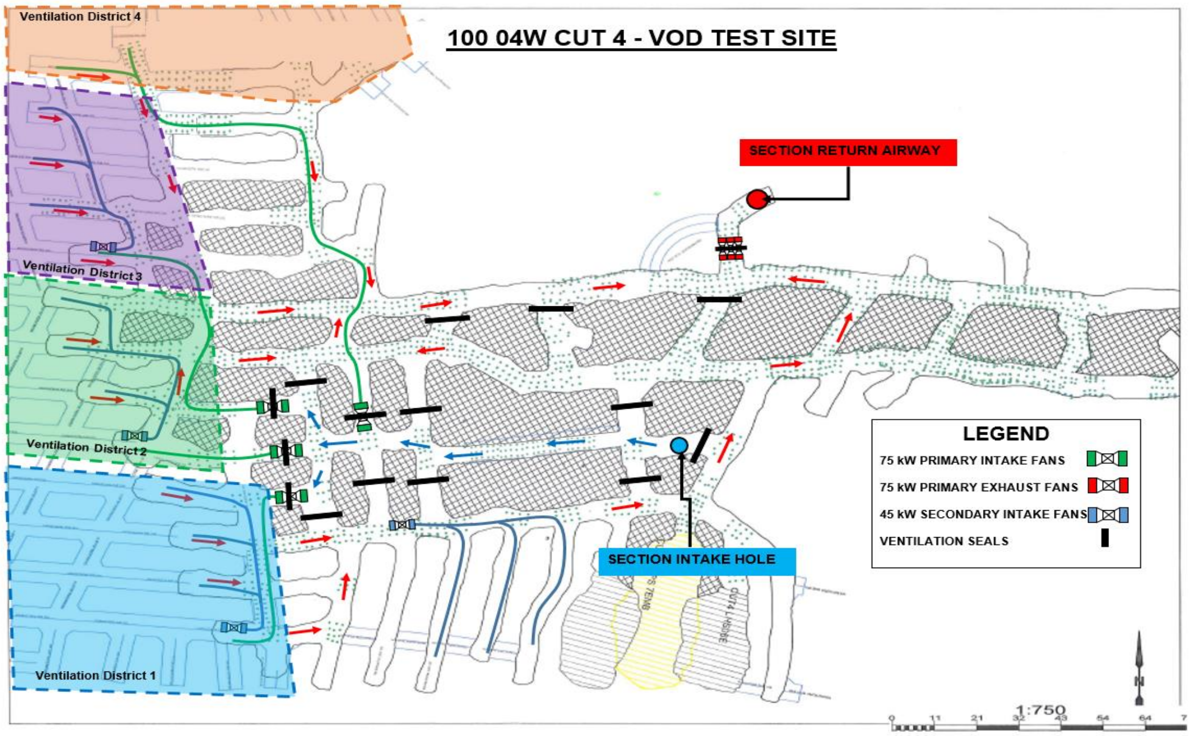


Figure 0.1: Ventilation layout of Corridor 3

The section return airway is equipped with three 110 kW fans which exhaust airflow from the section. A single 45 kW is used to ventilate the exploration drilling sites and long-hole stopes on the South in the section. All fans used are single-stage fans.

4.1.4. Energy audit

The mine uses power-intensive fans to drive auxiliary airflow. Table 4.3 summarises the energy requirements of the fans used in the section.

Table 0.3: Energy audit

Fan Type	QTY	Fan Input Power (kW)	Total Power (kW)
22 kW	18	32,4	583,2
30 kW	9	42,9	386,1
45 kW	56	51,7	2895,2
55 kW	7	61,8	432,6
75 kW	38	83,3	3165,4
110 kW	5	119,6	598
TOTAL	133		8060,5

The fan power input in kilowatts (kW) was measured by an electrician at the mine's fan starter boxes with a calibrated multi-meter. The total power (kW) is determined by multiplying the fan input power by the quantity of fans i.e. 5 x 51.7 kW = 258.5 kW.

With 133 auxiliary fans in use at South Deep at any given point, the total power input of the auxiliary ventilation system stands at 8.1 MW.

4.2. REAL-TIME MONITORING INSTALLATION

South Deep seeks to install underground mining environmental sensors capable of monitoring environmental changes in real-time. The project forms part of the operational readiness for VOD at the mine. The project spans all departments of the mine as all decisions made affect the entire value chain.

4.2.1. Project ownership

At South Deep, four main departments were identified as critical for the project success, namely: Environmental Engineering (ventilation); Mining & Production; Engineering (Instrumentation & Electrical); and the Planning department. A RACI chart was used to ensure all departments buy-in into the project before it begins.

Table 4.4 shows a RACI chart outlining all the different departments that should be Responsible (R), Accountable (A), Consulted (C) and Informed (I) about the project at a mine.

Table 0.4: RACI Chart_ Sensor Location Consideration Factors

Factor / Department	Ventilation Department	Production Department	Engineering (Instrumentation & Electrical) Department	Planning Department
Communication Network	A	I	R	C
Sensor Selection	A & R	I	C	I
Sensor Location	A	R	I	C
Installation & commissioning	A	C	R	I

The project at South Deep was divided into four stages i.e. communication network expansion; sensor selection; sensor location; and sensor installation and commissioning. As can be seen in Table 4.4, the ventilation department is accountable for the entire project, as it is a project meant to expand the environmental monitoring capacity of the mine. The department must select the sensors required for the project with close consultation with the Engineering department.

The engineering department is the custodian of modernisation projects at the mine, as they control all communication networks and all instrument installations. Their involvement is critical for consultation and information on the practical installation and interfacing of all the systems. They are responsible for the network expansion and installation of the sensors.

The production and planning departments work hand-in-hand to ensure production in the mine. Consulting and informing the departments of any changes in the mine is critical to ensure the safety of the devices and to get a buy-in from the employees who will rely on these devices for their safety.

Failure to follow the developed RACI chart for the project led to various communication breakdowns that led to many delays that could have been easily avoided at South Deep. It is important for those accountable for the duties to continually follow up with those responsible to ensure all deadlines are met timeously. All stakeholders must buy in on the project from the start.

4.2.2. Communication network expansion

South Deep migrated to a wireless MineHop communication network that incorporates both the mobile data terminal-remote telemetry units (MDT-RTU) and vibrating wire-RTUs (VW-RTU) for areas without power, fibre or Ethernet such as production zones. This network is established by installing a surface server that is connected to the mines Ethernet network. Ethernet gateways are established underground at the last Ethernet access points before production zones such as in waiting places, workshops or tipping boxes. The network is extended underground through the wireless battery-powered network nodes that connect wirelessly to each other for a range of up to 100 metres shown in Figure 4.2. The nodes act as signal repeaters to enable the signal from the sensors to hop back to the gateway which connects to the central server through the Ethernet network.

Figure 0.2: Newtrax Minehops Network Node

Figure 4.3 shows the network expansion layout for the POC test site at South Deep. Installing the nodes is a simple plug and play, as the nodes automatically connect to the network when turned on. As the node is moved away, the LED on the node will change from solid green to blinking green, to blinking red and solid red as the signal strength drops from good to bad. Nodes should be located before the blinking starts, to ensure a steady and reliable connection between nodes. Securing the nodes with cable ties on the hanging wall proved to be sufficient at South Deep to hold nodes in place with ease. This also makes it easy to remove and maintain the node in the case of connection failure and planned battery changes.

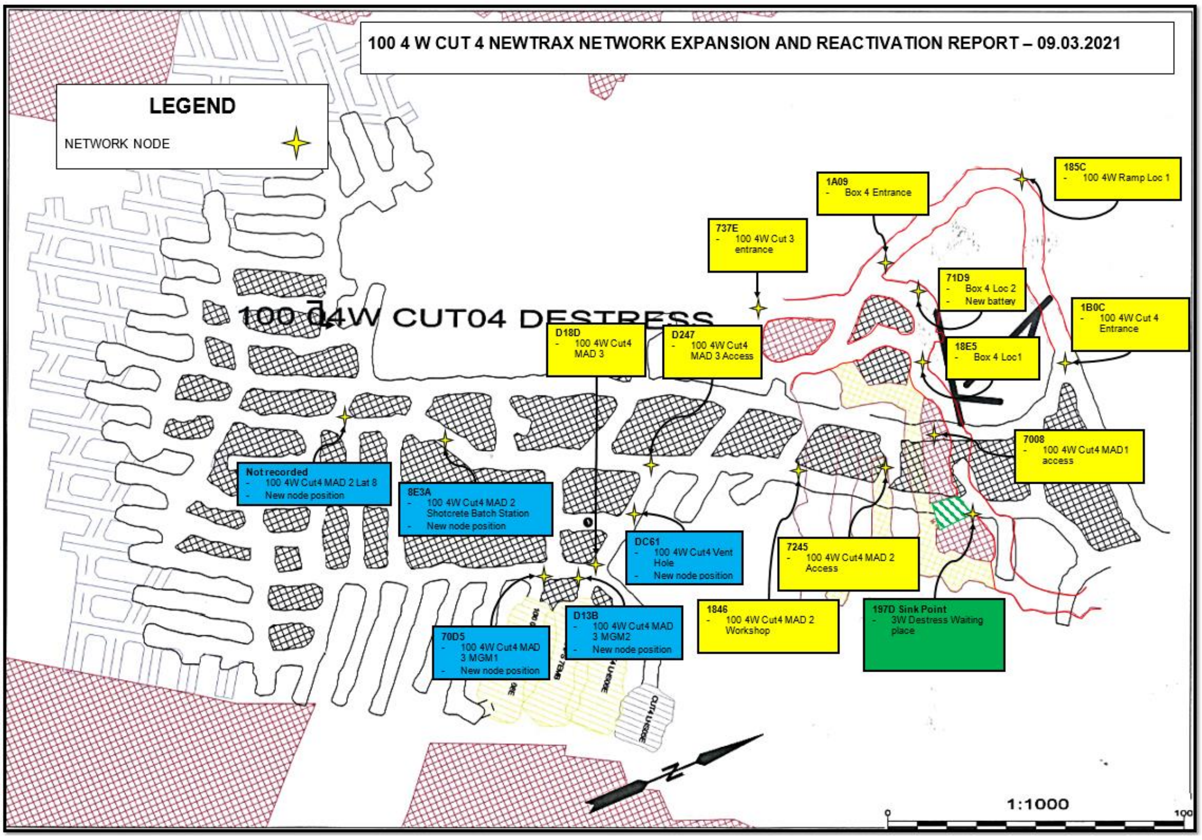


Figure 0.3: Network Node Expansion Layout

The geology and mining geography at South Deep affects the transmission of data from one node to the other which affects the location of these nodes. Even though the manufacturer specifications had determined the communication ranges to be at least 100m, the complex nature of underground tunnels at South Deep prevents the line-of-sight technology to reach 100 metres without bends, kinks or declines. It was found that as a general rule, a network node should be placed every 60 metres, or at each corner when there is a sharp turn as the mostly-silica geology of the exposed tunnels scatters the signal in many directions without penetration.

4.2.3. Sensor selection

The type of network used can limit the options for the type of real-time sensors as compatibility is critical in selecting sensors. The criteria put forward by the author for sensor selection is as follows:

i) System compatibility
ii) System requirements
iii) The accuracy and reliability

iv) Durability and robustness

v) The size and shape

The prevailing environmental conditions where the sensors will be installed should be considered. There are general fears around high concentrations of dust and humidity and sensor reliability. Dust is known to clog up the sensors which require a sample of air passing through them to make any reading. Humidity is known to cause corrosion of exposed metal parts of sensors. These generally reduce the accuracy of the sensors while increasing wear and tear. These concerns are not backed by literature and require further investigations.

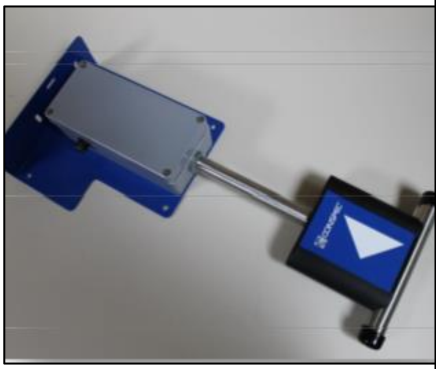
The wireless network at South Deep is a major determinant in the choice of supplier for the hardware as system compatibility is a top priority. It was recommended to use a single supplier for all components, especially on a POC level. This greatly reduces the learning curve associated with the project. There is one group of technicians to deal with, who are well versed in how the system works.

Hard wired sensors with capabilities of being interfaced on the wireless Minehops communication network were seen as ideal for the robust mining environment at South Deep. These sensors are multi-functional, robust, and reliable and have lower maintenance needs as they do not use batteries

The hardware was selected based on a proven track record and compatibility. The chosen supplier has provided monitoring systems for many mines in Canada with tried, tested and approved real-time monitoring systems such as Glencore's Nickel Rim South and Kidd Operations. Three main hardware instruments were identified as instrumental to real-time environmental monitoring, namely the multi-channel gas monitors (MGM); wireless CO monitors and air velocity sensors shown in Table 4.5.

It is important to ensure that the measuring range of the sensor is low enough to pick up even the smallest traces of CO. This is to prevent accidental exposures, and detect any CO inflows as early as possible before it poses a threat to the health and safety of personnel. The upper limit should also be high enough to get a proper dissipation trend of CO after blasting. This information has been used at mines such as Glencore's Kidd Creek operation to deduce the extent of damage to ventilation ducts before physical examinations (Newtrax Technologies Inc., 2016). This led to the mine reducing post-blast re-entry periods and ventilation ducts reconstruction times by 1-2 hours

Table 0.5: Real-time monitoring sensors (CONSPEC, 2020)

		
The **MGM** is an economical choice for toxic, combustible and oxygen gas monitoring. It utilises user-friendly plug and play (PnP) sensor technology. This significantly reduces installation time and costs as users can hot-swap factory calibrated and configured sensors. The MGM has been designed for use in hazardous locations such as underground mines. It supports various industry-standard interface protocols.	The **Air Velocity Monitor** (AVM) is a robust air velocity measurement instrument that uses differential pressure technology. The monitor is built to withstand the harsh conditions of underground mining, with user-friendly mounting options. The wide variety of interfacing options for the AVM provides a truly integrated solution, which works with almost all different applications and underground communication backbones.	The **Smarthead Wireless** CO transmitter is a robust underground ground CO sensor built to withstand very harsh conditions prevalent in underground mine workings. The sensor uses Wi-Fi transmission to the interface onto the Minehops network through the wireless Minehops nodes. The sensor is calibrated to sense in the range of 0ppm and 500ppm.

4.2.4. Sensor location

The proof-of-concept at South Deep yielded a few expensive learning curves which included: two multi-gas sensors getting damaged by fly rock; having to re-calibrate sensors; changing sensor location due to changed ventilation layouts, and uninstalling the sensors for maintenance and firmware updates. All these happened within just eight (8) months of installing the equipment. From these lessons, the author puts forward the following factors to consider when locating sensors:

i) Critical monitoring points
ii) Tunnel dimensions
iii) Tunnel uses
iv) Production plans

Critical monitoring points results

VUMA3D-Network simulation package was used to produce a simulated model of the corridor to see the mass flow patterns more clearly. Global monitoring is practised over the POC as a means of lowering the project capital costs while getting adequate monitoring in the section.

Ventilation theory and basic knowledge of the airflow in the section were critical for the model creation. According to Mochubele (2014), VUMA and all computer simulation software packages do not replace a good knowledge of basic ventilation theory and practice. Figure 4.4 is the resultant layout from the VUMA3D simulation.

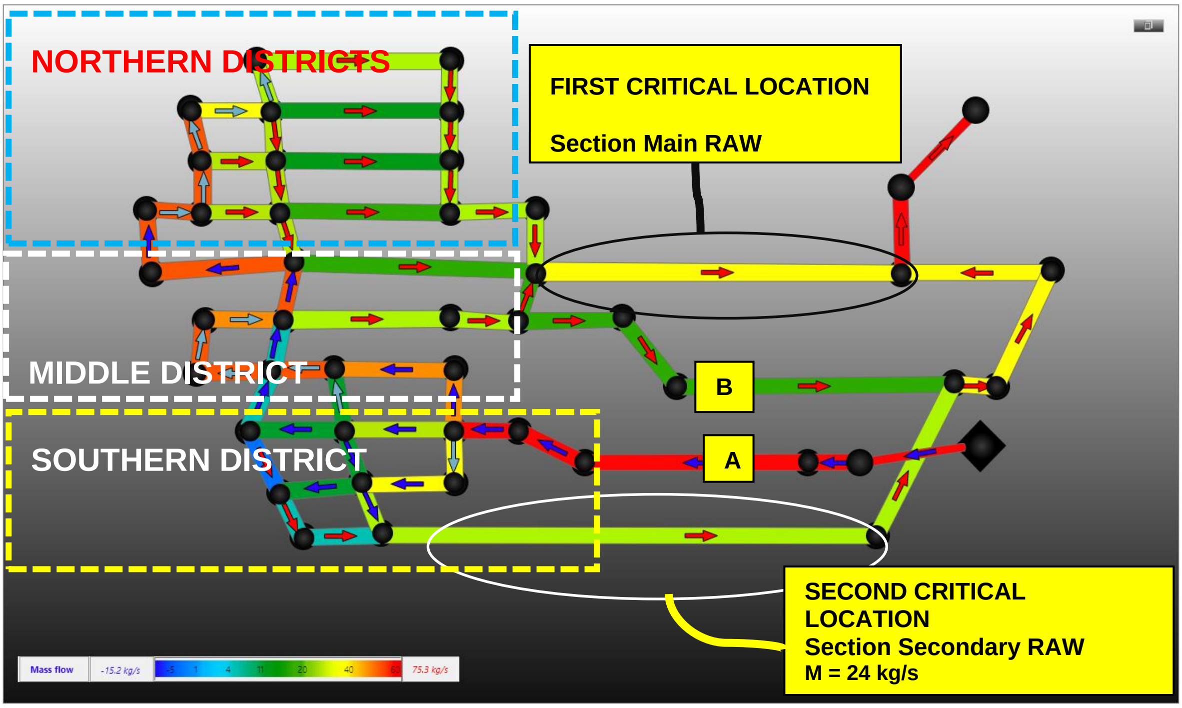


Figure 0.4: VUMA3D Simulated Model _ Mass Flow Rate (density = 1.2 kg/m^3)

The first critical location identified is the corridor's main return airway which handles 55% of the return air in the section with flowrates of 34 m^3/s. Monitoring this section removes the need for individual sensors on the northern sections as all airflows return in this section. The second critical location is the secondary return airway, where contaminated air from the Southern distress districts and long-hole stopes is returned.

Point A in Figure 4.4 is the section main intake from the intake ventilation hole while point B is on the main access route into the section, which handles just over 10% of the return air at 8 m^3/s. These four points were identified as the most critical for monitoring purposes as all the air in the mine passes at least one of these points as it circulates from the section intake to the section return ventilation holing.

As much as they monitor all the air flowing in and out of the mine, monitoring these locations gives little information about the exact conditions in each development end. Re-circulation within the ventilation districts should be kept at a minimum. Recirculation could lead to contaminants building up as they won't be exhausted out but rather recirculated in the same region. This should be avoided by having regular ventilation surveys.

Tunnel dimensions, uses and plans

When all critical locations are identified, collaboration with the planning, production, electrical and instrumentation departments is critical to choose the exact location to place monitoring stations shown in Figure 4.5.

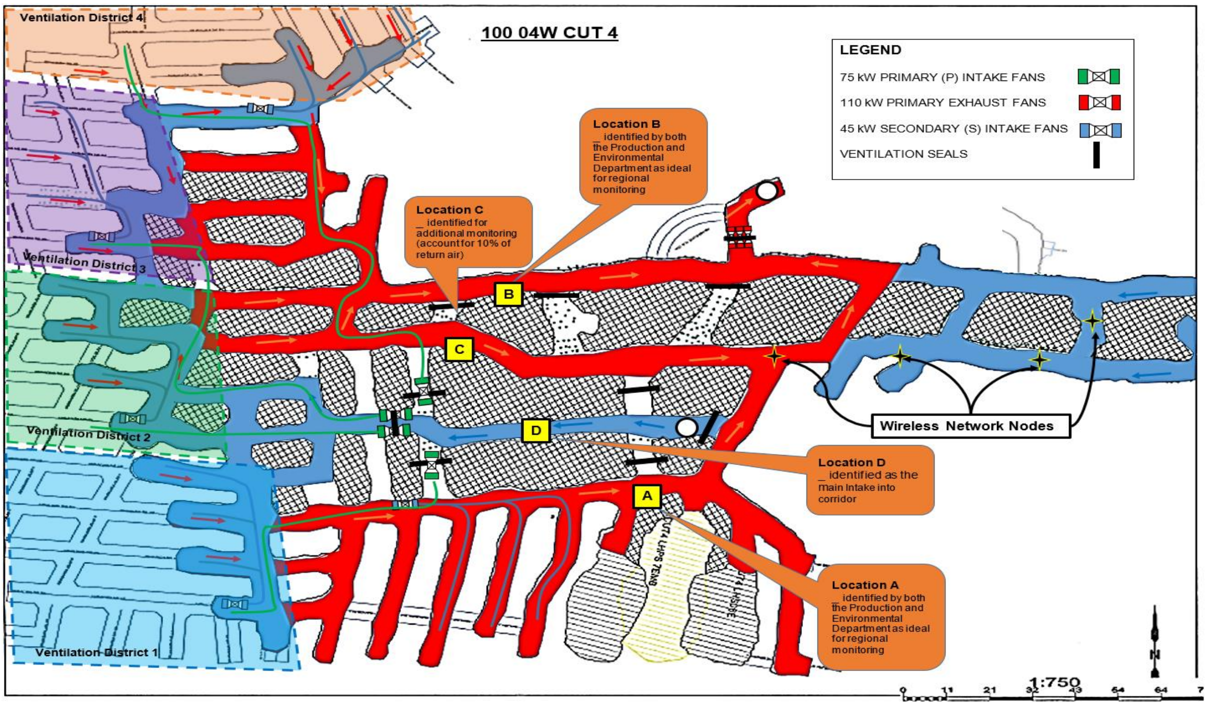


Figure 0.5: Monitoring Station Locations

Location A monitors the section secondary RAW, located after the long-hole pillar. This location serves both the long-hole and Southern Destress sections at a point where blasting the Long-holes will not affect the sensors. Location B is on the Main RAW catering for the Northern and Middle Destress sections. Location C is on the Main access to the section, with minimal air from the Middle Destress sections returning in this section. Location D is on the Main intake. The tunnel is characterised by a high presence of machines and personnel, as the diesel bay, section workshop, concrete bay and refuge chamber are located on it.

4.2.5. System Validation

System validation was required to check the accuracy, reliability and resolution of the real-time monitoring system. The following system components were set up in the surface training mock-up mine:-

- Multi-channel gas monitor (CO; NO_2; CH_4; humidity, temperature and pressure)
- Air velocity monitor
- Network gateway
- Wireless network node

A single development end with known levels of CO; NO_2; CH_4; humidity; temperature; pressure and air velocity were used at the mock-up mine to test the sensors. An electronic GDI that was tested every morning was used to validate the gas readings; while a recently calibrated whirling hygrometer, barometer and vane manometer was used to validate the airflow properties. The NO_2 readings were validated with Dragger and NO_2 tubes weekly for the duration of the test.

The MGM is used to monitor the following parameters at South Deep; CO, CH_4, NO_2, humidity, pressure and temperature. The instrument has six channels that can be used to install various sensors as per mine requirements and has a sensitivity of 13 Kbps. This 13 Kbps represents the smallest amount of difference in quantity that will change the instruments reading. The corresponding sensitivities for the different parameters are outlined in Table 4.6. This shows the changes in contaminant concentration changes detectable by the MGM.

Table 0.6: MGM sensitivity

PARAMETER	SENSITIVITY (13 Kbps)
CO	0.1ppm
CH_4	0.01 %
NO_2	0.01ppm
Temperature	0.2 ^{O}C

The sensors have a high sensitivity represented by the small range of differences the instrument can pick up for the different parameters. At a sensitivity of 0.2 ^{O}C, the temperature has the highest sensible range, which means temperature disparities above 0.2 ^{O}C are picked up. In comparison, the whirling hygrometer, used in underground mines for air velocity measurements has a resolution of 0.5 ^{O}C. The instrument has a much more reliable sensing sensitivity compared to this industry-trusted instrument. The GDI offers the same sensitivity for CO, but the NO_2 and CH_4 sensitivities are less than that of the MGM. Monitoring with the MGM offers a great deal of reliability for real-time monitoring as even the slightest changes in the environmental conditions can be picked up better than the instruments used for validation.

The accuracy of the MGM was investigated by mounting the MGM on different locations on the cross-section of the mock-up tunnel. Blast conditions cannot be replicated at the mock-up mine, natural ventilation is the main driver of airflow in and out of the mock-up. Validation of the readings concerning the position of the sensor from the face was not possible. Figure 4.6 illustrates the different position that was validated for sensor location indicated by X1 to X4.

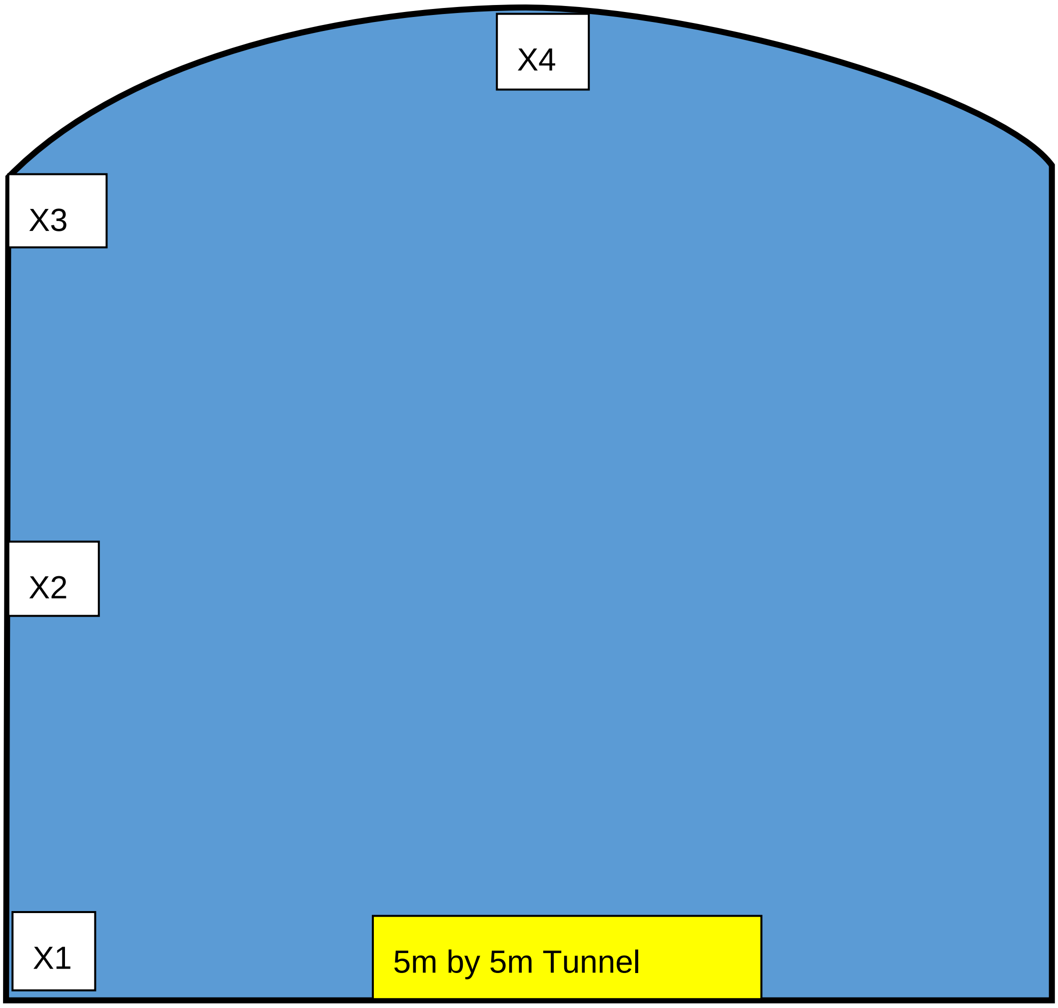


Figure 0.6: MGM Location Validation Layout

X1 is on the sidewall, close to the footwall, X2 is mid-way up the sidewall, X3 is on the top of the sidewall, and X4 is at the centre of the hangingwall. Each position was investigated over two days, with readings taken every two hours four times per day. Table 4.7 is a summary of the accuracy findings for the different parameters at different locations. The accuracies are shown as a percentage error deviation from the known and trusted GDI, barometer and whirling hygrometer readings.

Table 0.7: MGM %errors

	POSITION X1	POSITION X2	POSITION X3	POSITION X4
CO	3%	1%	4%	2%
CH_4	1%	1%	2%	1%
NO_2	-	-	-	-
Temperature	2%	1%	2%	1%
Pressure	3%	2%	7%	4%
Average	2.25%	1%	3.75%	2%

Table 4.7 shows that positions X2 and X4 are the most suitable for the positioning of an MGM for accurate readings. The GDI used for validation had no NO_2 sensor, hence the lack of readings for the NO_2. Position X2 has an average error of +/-1% and is the suitable location for the multi-gas sensors, with position X4 the close number two. Position X4 is on the hangingwall, where ventilation columns are installed in the production zones. These can easily block and seal out the sensors from the airflow, making the readings unreliable. All MGM installations at South Deep are positioned mid-way up on the sidewall as shown by position X2.

The air velocity monitors were also validated in the same manner as the MGM, and compared against a recently calibrated vane manometer, and Table 4.8 outlines the resultant accuracies.

Table 0.8: AVM %error

	POSITION X1	POSITION X2	POSITION X3	POSITION X4
Air Velocity	3%	3%	5%	2.5%

The air velocity monitor (AVM) is about 45cm long. When attached by its base, it can protrude 45cm into the tunnel from either the sidewall or footwall. This allows the instrument to take readings away from the wall, where velocities are lower and sometimes reversed or stagnant depending on the nature of the walls. Position X3 on the top corner of the tunnel is the position with the lowest accuracies as expected due to the lower velocities known to reside in these areas of rectangular tunnels. With an error of 2.5%, position X4 proves to be the most reliable position for reduced reading errors. Position X1 and X2 are on the sidewall, where the length of the AVM can be problematic where machines travel. Position X2 and X4 were chosen as ideal at South Deep depending on the tunnel use, X2 where tunnels are used for ventilation columns; and X4 where loading and hauling take place.

It is clear from the system validation that the instruments used at South Deep have built-in errors which can lead to over-exposures when ignored. The following alarms were developed with the errors accounted for to alert the system when conditions are approaching the mine standard. These alarms are meant to alert the surface control of critical conditions that require immediate action to control. Table 4.9 shows the alarm points for each parameter at South Deep.

Table 0.9: Sensor Alarms

Contaminant	Mine Standard	FAN ON ALARM	EVACTUACTION ALARM
Methane	1%	0.7%	0.9%
Carbon Monoxide	25 ppm	15ppm	24ppm
Nitrogen Oxide	2.5 ppm	1.5ppm	2.4ppm
Temperature	37.0 ^{O}C DB	33 ^{O}C DB	35 ^{O}C DB

The *evacuation alarm* point is set based on the mine standard and expected sensor error. For methane, the mine standard is 1%, the sensor has a 1% error. This translates to a sensor reading of 0.01%CH_4. 0.9% is then set as the alarm to accommodate these variations in readings. The correct action to be taken by the control room during this alarm is to call for an immediate evacuation of the area until the environmental conditions are within acceptable levels.

The *fan on* the alarm is meant as the first level of control when contaminants are encountered. The approach in setting alarms for the first level of control was selected to be between 50 and 70 per cent to ensure that the fans are triggered to dilute and eliminate the contaminants from the working areas before reaching the mine standard OELs. The other precaution that was adopted for the POC was to use twin-speed fans to ensure a minimum of 50% of the designed airflow when it is safe. This means even if there are no contaminants there will always be airflow and when contaminates reach level one, the fan will run at full capacity. This alarm is meant to alert the control room operator to either turn the fans ON (50%) if they were off or switch to full speed (100%) if they were on half-speed to reduce the contaminant by dilution and/or exhaustion.

4.3. SYSTEM BENEFITS

The re-entry time savings present real benefits for the South Deep system, while the potential to reduce energy costs is still theoretical.

4.3.1. Workplace re-entry time savings

The workplace re-entry period is the time taken from the moment of blasting to when employees re-enter working areas for production. At South Deep, the workplace re-entry time stands at 2-hours while the Post-blast re-entry stands at 1-hour. There is a potential to reduce workplace re-entry times by 1-hour.

The generally accepted re-entry time determination standard for deep underground mines is to allow 8 air changes in the haulages, return airways (RAW) and the active development ends. Equation 1 was used to determine the time it takes to make 8 air changes for the intakes, the RAW and the active ends. The calculated re-entry time is for Corridor 3 shown in Figure 4.1. The lengths were measured from the 75 W fan on MAD1 following the path of the air to the RAW, and each heading measured from the face to the breakaway. The area used for volume calculations is the standard de-stress dimensions of 5 m by 5 m.

Equation 1: Re-entry time equation

$$Re - entry\ time\ (t) = \frac{L \times B \times H}{Q \times 60} \times 8$$

$$t_{INTAKES} = \frac{9270.8}{45.5 \times 60} \times 8 = 27.2\ min$$

Table 4.10 summarises the re-entry times for all the sections in the corridor, with a combined re-entry time of 94 min. The largest of these re-entry times is that of the intakes, which is sensible as more volume of air travels in these haulages than any other haulage due to length. The intakes include MAD 2, MAD 3 and MAD 1. The RAWs include MAD1 until the exhaust fans and all the stope drives joining the stope access drives. The development ends were measured from the breakaway where through ventilation ends to the face.

The total re-entry time for this section is 94 min, but that would be assuming that all ends are active and blasted daily, which is not the case. A maximum of 3 ends is blasted per corridor. On any given day, the maximum re-entry time is 76.6 minutes, the minimum time is 41.4 minutes and many possible fluctuations possible in between.

Table 0.10: Re-entry time calculations

	LENGTH (m)	VOLUME (m^3)	QUANTITY (m^3/s)	RE-ENTRY (min)
INTAKES	337.1	9,270.8	45.5	27.2
ACC 02N	40.2	1,104.2	12	12.3
SAD 12E	41.7	1,145.8	12	12.7
SAD 13E	24.2	666.7	12	7.4
SAD 01S	22.7	625.0	12	6.9
MAD 02S	7.6	208.3	22	1.3
MAD 01S	9.8	270.8	22	1.6
SAD 03W	0.0	0.0	12	0.0
SAD 02W	37.9	1,041.7	12	11.6
RAW	193.2	5,312.5	54.7	12.9
TOTAL				93.9

The maximum possible re-entry time is calculated by adding the re-entries of the sections which always receive through ventilation, i.e. the intakes and the RAW. Air will need to pass through these sections regardless of which ends are blasted. If a maximum of three ends are mined per shift, then there's a possibility that all those three ends could be the ones with the highest re-entry times, i.e. ACC 02N, SAD 12E and SAD 02W. This gives a maximum possible re-entry of 76.6 min. The minimum re-entry time was calculated similarly, but instead of choosing the ends with the highest re-entry times, those with the lowest re-entry times were used. Setting a fixed re-entry time of 76.6 minutes can lose the mine 35.2 minutes depending on which ends are blasted. This accounts for a 45% reduction in re-entry time. The standard gas dissipation re-entry time at South Deep is 70 minutes, 6 minutes less than the calculated re-entry time. The disparities in the re-entry determination techniques make these methods unreliable. Gas dissipation is a function of gas production, air velocity, the efficiency of ventilation distribution and positional efficiency of exhaust and intake systems. Changes in any of these factors either through increased gas production, damaged ducts and/or damaged ventilation seals can result in higher re-entry times. Without real-time monitoring, re-entry times remain an estimation, requiring early-entry examinations to confirm conditions before work can commence.

At South Deep, early-entry exams are conducted by the miner, team leader and safety representative as part of the waiting place procedure. Table 4.11 shows that the waiting place procedure takes approximately 50 minutes from 07H00. 40 minutes of that time is for early-entry examinations (20 minutes for travelling to and from the working place and 20 minutes for actual examination). 10 minutes is used for the morning meeting and assigning of tasks. With VOD early-entry examinations, this time could be reduced greatly to just 15 minutes. 10 minutes is used for the assigning of duties and 5 minutes for the examination through monitoring screens at waiting places and communication with surface control.

Table 4.11 compares the total workplace re-entry times of conventional early-entry examinations and VOD examinations.

Table 0.11: Total time before shift work begins (Workplace re-entry time)

	FIXED TIMES (TRAVELLING TIMES)	WAITING PLACE PROCEDURE	TOTAL RE-ENTRY TIME
CONVENTIONAL	70 min	50min	120 min
VOD	70 min	15 min	85 min
TIME SAVINGS			**35 min**

The fixed times include all the travelling times from the surface to the waiting place and then to the working area, which stand at 70minutes for both cases. The waiting place time includes the early-entry examination time and morning meeting time. These make up the workplace re-entry time. VOD systems have the potential of saving the mine 35 minutes from re-entry procedures, which translates to a 30% reduction in workplace re-entry time. They also reduce the risk of exposure compared to the conventional examinations which require personnel to physically confirm gas levels before workplace re-entry can take place.

A 35-minute reduction in workplace re-entry time directly translates to an 8.6% increase in effective shift time.

4.3.2. Health and Safety Improvements

The mine has a re-entry standard of 70 minutes, with early-entry examinations conducted manually by the re-entry team. The re-entry team involves the shift supervisor (miner) and safety representatives. Hand-held gas detection instruments are used for this and the following hazards are identified for this process:

i) Short term overexposure to CO

ii) Short term overexposure to NO_2

Short term overexposure to CO

The acute effects of CO exposure include but are not limited to the following;

- Mental confusion
- Vomiting
- Loss of muscular coordination
- Loss of consciousness
- Death

High exposures, above 70ppm, leads to victims rapidly becoming mentally confused and can lose muscle control and consciousness without experiencing any mild symptoms (US Consumer Product Safety Commission, 2021), this effectively makes these exposures have major consequences for personnel.

With a re-entry time of 70 minutes in place at the mine, the probability of acute exposures of the re-entry team is quite high. Potential accumulations in muck piles and lingering accumulations caused by ineffective and damaged ventilation infrastructure poses a risk to the re-entry team. The likelihood for this event to occur is probable (35% - 65%)

Short term overexposure to NO_2

The acute health effects of short-term exposure to NO_2 may develop immediately after exposure and include but are not limited to the following (New Jersey Department of Health, 2000):

- Irritation to eyes and possible eye damage
- Irritation to nose and throat
- Lung irritation and pulmonary oedema
- Shortness of breath and possible death

NO_2 concentrations go as high as 50ppm during blast clearance which is 10 times the STEL of 5ppm. At these concentrations, the gas interferes with the ability of the blood to absorb and carry oxygen and can lead to instant death, which is a major consequence.

Without real-time monitoring, it is impossible to know exactly what concentration is before sending in the re-entry examination team. The likelihood for severe accidents remains probable (10%-35%)

1.1. Risk Assessment

The identified re-entry hazards have been categorised based on the likelihood and severity of the consequences. The risk assessment form shown in Table 4.12 summarises the risk rating of the identified hazards.

Table 0.12: Risk Assessment Form

Hazard Identification	Likelihood	Consequence	Risk rating
CO exposure	Probable (3)	Major (4)	R12
NO_2 exposure	Improbable (2)	Serious (3)	R6
Average	**Probable (3)**	**Serious (3)**	**R9**

Table 4.12 shows the CO exposure to be of extreme risk with a risk rating of 12 while NO_2 exposures have a risk rating of 6.

Table 4.13 tabulates these results in a risk assessment matrix for easier identification of the major and minor threats of the systems.

Table 0.13: Baseline Risk matrix – Re-entry examination

		CONSEQUENCE CLASSES			
		C1 (1) Insignificant Consequence	**C2 (2) Significant Consequence**	**C3 (3) Serious Accident**	**C4 (4) Major Accident**
LIKELIHOOD CLASSES	**F4 (4) Frequent**				
	F3 (3) Probable				CO exposure
	F2 (2) Improbable			NO_2 exposure	
	F1 (1) Very Improbable				

The CO exposures fall within the extreme risk bracket and should be prioritised when it comes to controls. The NO_2 exposures fall within the medium risk which require reasonable steps for prevention but is not a priority, while the propane accumulation falls within the low risks. The average risk rating for the re-entry procedure with regards to environmental exposures stands at R9, with a probable (3) likelihood of Serious (3) Consequences. This puts the early-entry examination at the high-risk activity when it comes to environmental exposures.

Real-time monitoring presented the mine with the opportunity to conduct remote early-entry examinations. Surface Control gives the production crew the green light to re-enter the working areas when the environmental conditions are within the mine standard. This information is readily available in real-time on the logic software. This reduces the likelihood of all the possible short-term exposures the re-entry examination team would be potentially exposed to, as shown in Table 4.14.

Table 0.14: VOD case Risk Assessment Form

Hazard Identification	Likelihood	Consequence	Risk rating
CO exposure	Very Improbable (1)	Major (4)	R4
NO_2 exposure	Very Improbable (1)	Serious (3)	R3
Average	**Very Improbable (1)**	**Serious (3)**	**R3**

The likelihood of exposure is reduced to Improbable (1) for all the potential hazards. This does not eliminate the risk as the sensors need to be strategically located to provide sufficient monitoring of the production zones. The calibration and maintenance of the sensors become a priority to ensure all readings have minimum deviations and errors. The consequences for the exposures do not change, as any accidental exposures through equipment error or human fault will lead to the same consequences. The real-time monitoring reduces the health and safety risks associated with overexposures during re-entry by 66%, from R9 to R3.

Table 4.15 shows the Real-time monitoring risk matrix for re-entry examination

Table 0.15: Real-time monitoring Risk matrix – Re-entry examination

		CONSEQUENCE CLASSES			
		C1 (1) Insignificant Consequence	**C2 (2) Significant Consequence**	**C3 (3) Serious Accident**	**C4 (4) Major Accident**
LIKELYHOOD CLASSES	**F4 (4) Frequent**				
	F3 (3) Probable				
	F2 (2) Improbable				
	F1 (1) Very Improbable			NO_2 exposure	CO exposure

Table 4.15 clearly shows the potential hazards that can occur during re-entry examination have all been reduced in terms of potential risk. The hazards are now in the medium-risk bracket compared to the baseline where they ranged from extreme to low. The overall risk now stands at medium risk. This shows that the removal of personnel from dangerous workings is far more beneficial for improving health and safety than managing the potential consequences.

4.3.3. Theoretical production gains

Theoretically, an increase of 8.6% in effective production time should lead to a direct increase in gold production gains of 8.6% at the mine. These gains in production are highly dependent on productivity. The number of employees; equipment availability and the planned mining schedule all affect productivity amongst other factors.

Figure 4.7 is a trend graph showing the labour productivity expressed as kilograms of gold produced per employee and the all-in sustaining cost (AISC) per employee from 2008 to 2019.

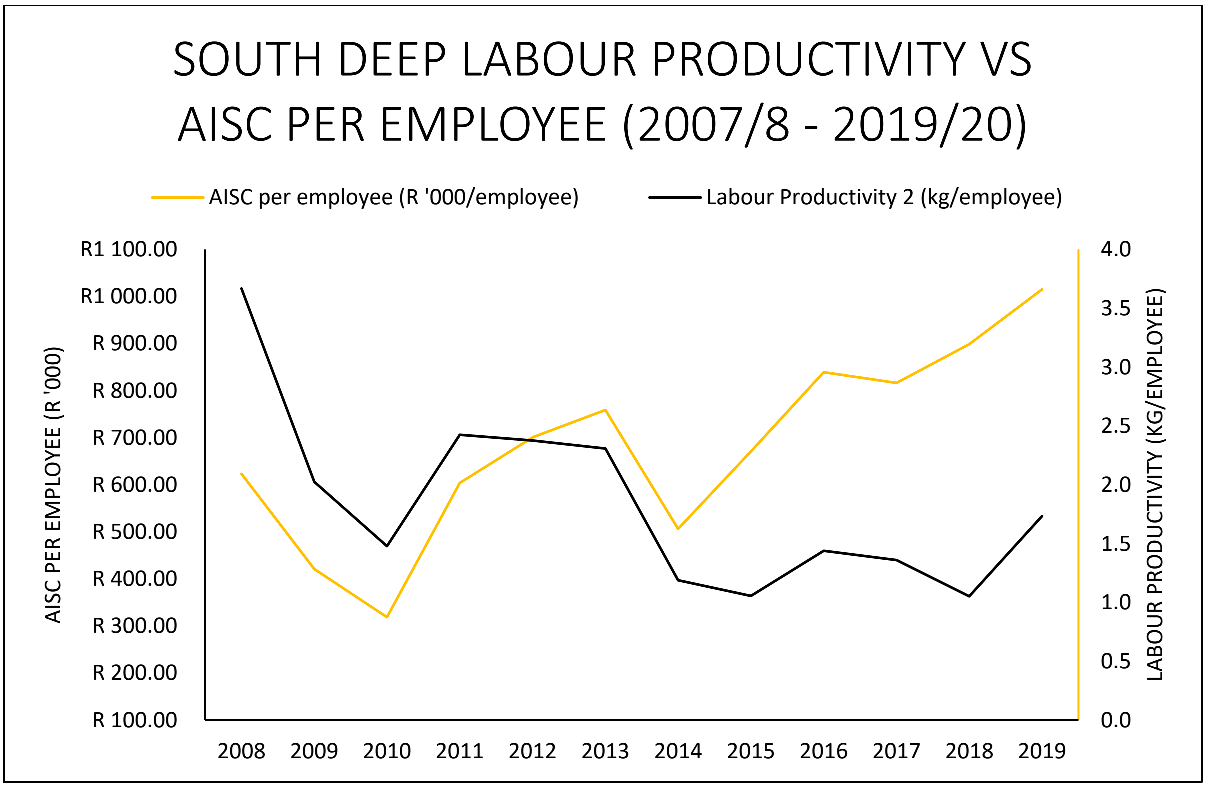


Figure 0.7: South Deep labour productivity vs AISC per employee (2007 - 2019) (Gold Fields, 2020)

Figure 4.7 shows that the trend at South Deep is that of declining labour productivity and increasing mining costs. The labour productivity dropped by more than 50% from 3.7 kg/employee in 2008 to 1.7 kg/employee in 2019. The AISC per employee on the other hand has increased by almost 40% from R 623,060.00 per employee in 2008 to R 1,015,040.00 per employee in 2019. From a business perspective, continuation in this trajectory will lead the company to further losses. To solve this issue, utilisation and availability of the labour force have to be drastically improved or the mine will forever fail to realise its labour potential.

Labour availability in South African gold mines is influenced by a plethora of factors including but not limited to absenteeism; annual leaves; and illnesses such as HIV, TB and more recently COVID-19. Labour utilisation on the other hand is the measure of the efficient use of available labour in the available working time. In a 12 hour shift, effective working time is greatly reduced by re-entry procedures, travelling times, waiting place procedures, idle time, heat stress and breakdowns.

Labour utilisation is calculated by dividing the labour utilisation time (effective production time) by the available shift time as shown by Equation 2. For instance, Mochubele (2014) showed that the effective shift time at South Deep is 6 hours and 5 minutes (365 min) from a 12 hour (720 min) available shift time at South Deep. The labour utilisation for South Deep in 2014 is calculated as follows:

Equation 2: Labour utilisation

$$Labour\ Utilisation\ (\%) = \frac{Effective\ shift\ time\ (minutes)}{Available\ shift\ time\ (minutes)} \times 100$$

$$Labour\ Utilisation\ (\%) = \frac{365\ minutes}{720\ minutes} \times 100 = 50.69\%$$

Table 4.1 shows the current effective shift time to be 6 hours 45 minutes, from the same 12 hours available shift time. The effective shift time has increased by 10% due to the optimisation of shift configurations and the introduction of centralised blasting. The current labour utilisation stands at 56.25 %, calculated from equation 3.

Gold production in 2014 at South Deep was 6,237 kg with a labour complement of 5,246 employees while in 2019 gold production was 6,907 kg produced by 3,984 employees. This shows that an increase in effective shift times directly affects gold production, as gold production also increased by 10% even though the number of employees (a function of labour availability) decreased by 24%.

A 35-minute reduction in workplace re-entry time directly translates to an 8.6% increase in effective shift time. This can potentially translate to an 8.6% increase in gold production, translating to an additional 596.9 kg of gold. At a gold price of ZAR 1,011,076.61 per kilogram (Goldrate24.com, 2020), this can potentially translate to additional revenue of over ZAR 600 million.

Energy savings from the auxiliary ventilation system presents a potential avenue for a reduction in energy costs for the mine.

4.3.4. Potential energy cost savings

South Deep uses 133 auxiliary fans at any given point with total power input at 8060.1 kW as shown in Table 4.16. This equates to 97.2 MWh power consumption per 12-hour shift.

Table 0.16: Auxiliary fans input power and half speed power

Fan Motor Rating	Qty	Unit Power input power (kW)	Total Power input (kW)
22 kW	18	32,4	583,2
30 kW	9	42,9	386,1
45 kW	56	51,7	2895,2
55 kW	7	61,8	432,6
75 kW	38	83,3	3165,4
110 kW	5	119,6	598
Total	133		8060,5

The use of auxiliary links connected to the single-stage fans provides remote control over the fans. Fans can be switched ON/OFF based on the shift schedule to reduce the energy usage of the auxiliary ventilation. The input power used by the fans is electrical power sold by Eskom. Table 4.17 shows the different prices for peak, standard and off-peak times

Table 0.17: Eskom Time-Of-Use (TOU) Tariffs (Eskom, 2020)

High demand season (Jun-Aug)			Low demand season (Sep-May)		
Peak	Standard	Off-peak	Peak	Standard	Off-peak
R 4,17	R 1,27	R 0,69	R 1,37	R 0,94	R 0,12

The time-of-use (TOU) tariff introduced by Eskom in 2008 has different prices depending on the time of day and season. The winter months (high demand season) i.e. June to August have higher tariffs than the low demand months from September to May. This translates to 92 high demand days and 273 low demand days.

Table 4.18 illustrates the different prices throughout the day for both the low demand and high demand seasons. The cost of ventilating the production zones is calculated for the base case scenario for both the low and high demand seasons using the different TOU tariffs. Using a simple ON/OFF scheduling of the auxiliary fans, the cost of ventilating using the VOD optimisation is shown. The differences in the annual cost of ventilating from the base case scenario and VOD optimisation scenario highlights the systems electricity cost savings.

Table 0.18: Electricity consumption: Base case vs VOD optimised

TIME OF USE TARIFF COSTING			BASE CASE SCENARIO			VOD CASE SCENARIO			
Time of day (hr)	Low	High	Base Power (kW)	Low	High	**Fan speed**	Power kW	Low	High
00:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	100%	8060,5	R 967,26	R 5 561,75
01:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	100%	8060,5	R 967,26	R 5 561,75
02:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	100%	8060,5	R 967,26	R 5 561,75
03:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	0%	0	R -	R -
04:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	0%	0	R -	R -
05:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	0%	0	R -	R -
06:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	100%	8060,5	R 967,26	R 5 561,75
07:00	R 0,94	R 4,17	8060,5	R 7 576,87	R 33 612,29	100%	8060,5	R 7 576,87	R 33 612,29
08:00	R 1,37	R 4,17	8060,5	R 11 042,89	R 33 612,29	100%	8060,5	R 11 042,89	R 33 612,29
09:00	R 1,37	R 4,17	8060,5	R 11 042,89	R 33 612,29	100%	8060,5	R 11 042,89	R 33 612,29
10:00	R 1,37	R 1,27	8060,5	R 11 042,89	R 10 236,84	100%	8060,5	R 11 042,89	R 10 236,84
11:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R 7 576,87	R 10 236,84
12:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R 7 576,87	R 10 236,84
13:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R 7 576,87	R 10 236,84
14:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R 7 576,87	R 10 236,84
15:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R 7 576,87	R 10 236,84
16:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	0%	0	R -	R -
17:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	0%	0	R -	R -
18:00	R 0,94	R 4,17	8060,5	R 7 576,87	R 33 612,29	0%	0	R -	R -
19:00	R 1,37	R 4,17	8060,5	R 11 042,89	R 33 612,29	100%	8060,5	R 11 042,89	R 33 612,29
20:00	R 1,37	R 1,27	8060,5	R 11 042,89	R 10 236,84	100%	8060,5	R 11 042,89	R 10 236,84
21:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R 7 576,87	R 10 236,84
22:00	R 0,94	R 0,69	8060,5	R 7 576,87	R 5 561,75	100%	8060,5	R 7 576,87	R 5 561,75
23:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	100%	8060,5	R 967,26	R 5 561,75
			Daily Consumption	**R 146 298,08**	**R 320 485,48**			**R 120 665,69**	**R 249 714,29**
LEGEND			**Annual Consumption**	**R 39 939 374,48**	**R 29 484 664,16**			**R 32 941 732,01**	**R 22 973 714,68**
peak			**Total**	**R**	**69 424 038,64**			**R**	**55 915 446,69**
standard			**Savings**	**R 13 508 591,95**					
Off-peak			**% savings**	**19%**					

The non-effective ventilation time is 27% of the shift time, theoretically, cutting off ventilation during this time reduces the energy usage by 27%. The cost of the energy on the other hand is dependent on the price of the electricity. With TOU costing used by Eskom for electrical energy, the peak tariff coincides with the times of peak ventilation supply. This translates to energy savings of ZAR 13.5 million, less than expected energy cost savings at only 19%. The times of non-effective ventilation coincides with off-peak tariffs at night, and standard tariffs during the day, which reduces the energy cost-saving potential of the mine.

The mine could achieve a lot more energy cost savings by changing the shift schedule such that the non-effective ventilation time coincides with the peak tariff costing. While the effective ventilation times coincide with off-peak and standard costing. If the mine could change the shift schedule from 06:00 – 18:00 to 09:00 – 21:00, the mine could achieve more energy cost savings.

Table 4.19 illustrates these potential savings of the proposed shift schedule of 09:00 – 21:00. With centralised blasting at 09:00 and 21:00, the effective ventilation time would coincide mostly with the standard tariff during the day and off-peak tariff at night. This would translate to energy cost savings of ZAR 28 million per year, at 41% energy cost reduction.

With the current shift schedule, the mine could potentially save ZAR 13 million, which is a 13% reduction. If the mine were to change the shift schedule to accommodate the different TOU tariffs imposed by Eskom, the mine could potentially save ZAR 28 million. This would reduce the energy cost of the auxiliary ventilation system by 41%.

Table 0.19: Scheduled VOD case vs Base case

TOU COSTING			BASE CASE SCENARIO			SCHEDULED VOD CASE			
Time of day (hr)	Low	High	Base Power (kW)	Low	High		Power kW	Low	High
00:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	100%	8060,5	R 967,26	R 5 561,75
01:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	100%	8060,5	R 967,26	R 5 561,75
02:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	100%	8060,5	R 967,26	R 5 561,75
03:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	100%	8060,5	R 967,26	R 5 561,75
04:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	100%	8060,5	R 967,26	R 5 561,75
05:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	100%	8060,5	R 967,26	R 5 561,75
06:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	0%	0	R -	R -
07:00	R 0,94	R 4,17	8060,5	R 7 576,87	R 33 612,29	0%	0	R -	R -
08:00	R 1,37	R 4,17	8060,5	R 11 042,89	R 33 612,29	0%	0	R -	R -
09:00	R 1,37	R 4,17	8060,5	R 11 042,89	R 33 612,29	100%	8060,5	R 11 042,89	R 33 612,29
10:00	R 1,37	R 1,27	8060,5	R 11 042,89	R 10 236,84	100%	8060,5	R 11 042,89	R 10 236,84
11:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R 7 576,87	R 10 236,84
12:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R 7 576,87	R 10 236,84
13:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R 7 576,87	R 10 236,84
14:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R 7 576,87	R 10 236,84
15:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R 7 576,87	R 10 236,84
16:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R 7 576,87	R 10 236,84
17:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	100%	8060,5	R -	R -
18:00	R 0,94	R 4,17	8060,5	R 7 576,87	R 33 612,29	100%	8060,5	R 7 576,87	R 33 612,29
19:00	R 1,37	R 4,17	8060,5	R 11 042,89	R 33 612,29	0%	0	R -	R -
20:00	R 1,37	R 1,27	8060,5	R 11 042,89	R 10 236,84	0%	0	R -	R -
21:00	R 0,94	R 1,27	8060,5	R 7 576,87	R 10 236,84	0%	0	R -	R -
22:00	R 0,94	R 0,69	8060,5	R 7 576,87	R 5 561,75	100%	8060,5	R 7 576,87	R 5 561,75
23:00	R 0,12	R 0,69	8060,5	R 967,26	R 5 561,75	100%	8060,5	R 967,26	R 5 561,75
			Daily consumption	**R 146 298,08**	**R 320 485,48**			**R 89 471,55**	**R 183 376,38**
LEGEND			**Annual Consumption**	**R 39 939 374,48**	**R 29 484 664,16**			**R 24 425 733,15**	**R 16 870 626,50**
peak			**Total**	**R 69 424 038,64**				**R 41 296 359,65**	
standard			**Savings**	**R 28 127 678,99**					
Off-peak			**% savings**	**41%**					

4.4. CHAPTER SUMMARY

Selecting the sensors was based on criteria that mostly focuses on compatibility with the communication network. The requirements of the system, accuracy & reliability, durability & robustness and the size of the instruments are also critical. The health and safety of the personnel is heavily reliant on these systems, hence the validation of errors and accuracies is required before commissioning is required.

After selection, locating these sensors is another critical step for real-time monitoring projects. With global monitoring used at South Deep, critical monitoring points have to be established while ensuring the tunnel uses, dimensions and plans are considered before choosing the exact location.

After commissioning, the mine reduced workplace re-entry times by 35 min, a 29% reduction, by implementing remote early-entry examination. This translates to an increase of 8.6% in effective shift time. Theoretically, this should translate to a production gain of the same amount, which equates to an additional ZAR 600 million in revenue. Theoretical energy savings based on a scheduled control of the auxiliary system can save the mine up to ZAR 28 million per year, a 41% reduction in energy costs

Through the real-time monitoring system, the mine has also improved health and safety standards. By practising remote early-entry examinations through the real-time monitoring of the system, the mine has reduced the risk rating of the activity from level nine (9) to level three (3).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The real-time monitoring installation project at South Deep was critical in establishing the operational readiness of the mine for VOD systems. With a POC undertaken at a single production corridor, the learning costs of the project were kept at a minimum. The system is an enabler for various modernisation projects such as VOD and automation at the mine.

Project ownership is important to the success of the project, as lack thereof leads to various communication breakdowns and costly delays as was the case at South Deep. The lack of accountability and responsibility led to some of the sensors being damaged by blasts.

The communication network is critical to the functioning of real-time monitoring and all other modernisation projects. Ensuring the compatibility of the devices with the network used at the mine is critical. Network installations and expansions form part of the most capital intensive projects at mines even though these costs are not investigated in this project. Expanding the network was done so that the devices could be interconnected and connected to the main server to enable remote monitoring of production zones in real-time.

Underground environmental sensors are beneficial for real-time monitoring and modernisation of underground metalliferous mines as indicated by this report. The learnings from the South Deep sensor installation project helped develop a checklist to be followed when locating sensors even at the POC level. Critical monitoring points have to be determined for the section by the ventilation department. With collaboration with the production, planning and engineering departments the exact location can be selected by scrutinising the tunnel dimensions; tunnel uses; and future tunnel plans. This location checklist must be plotted on a RACI chart to communicate to all those involved who are Responsible; Accountable; informed and Consulted.

Project learnings also led to the development of the sensor selection criteria to be used for deep metalliferous mine monitoring. System compatibility is the most notable of the criteria, as interfacing of the different components is crucial in creating real-time monitoring networks.

With the use of strategically located environmental monitoring sensors, South Deep optimised their workplace re-entry procedures at the POC site by adopting remote early-entry examinations to reduce workplace re-entry times by 35 minutes. This translates to an 8.56% gain ineffective production time. Global monitoring was used at South Deep, resulting in lower capital costs for the POC. The major disadvantage of this system is the limited monitoring it provides, as critical points are located in the section's intake airway, primary return away, secondary return airway and main access route. The actual production faces remain unmonitored. Entry into these zones will still require manual early-entry examinations to be conducted. This negates the time savings gained, and thus it is highly recommended South Deep expends monitoring to the actual production faces by practising local monitoring.

The project was only implemented on a proof-of-concept level, with the environmental monitoring sensors. South Deep should look into installing fan controlling relays on the auxiliary fans to take advantage of the non-effective ventilation time of over 3 hours per shift. This could save the mine from ZAR 13 million up to ZAR 28 million per year on energy costs. To realise the ZAR 28 million annual savings, the shift schedule should be changed such that the non-effective ventilation time coincides with the peak tariff costing.

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