OPTIMISING VENTILATION AND COOLING SYSTEMS FOR AN OPERATING MINE USING NETWORK SIMULATION MODELS

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SYNOPSIS

Input costs and, specifically, escalating energy and electricity costs have become one of the biggest expenditure drivers of deep level mining. However, safety and health remains of paramount importance and cannot be compromised to accommodate electricity cost savings. In an attempt to reduce the operating costs of ventilating an existing deep gold mine in the Free State of South Africa, an optimisation study was conducted on the ventilation and refrigeration systems currently in use at the mine, while maintaining impeccable safety and health standards. This paper describes the methodology used and the outcome of the optimisation study.

Network simulation models that accurately reflected the current mining and ventilation conditions were developed. These models were used to examine various options for improving the overall ventilation and cooling strategy. The ground conditions at the mine in question are poor and there has been significant closure of many airways, with both intake and return airways being affected. Therefore, the mine relies on booster and auxiliary fans to provide air to the mine extremities. In addition, ventilation air is cooled in two Bulk Air Coolers (BACs) on the surface and again by two smaller BACs underground to achieve design thermal conditions.

The methodology used to develop the network models involved agreeing ventilation design criteria and the different optimisation scenarios. This was followed by simulating them, including different ventilation (fan/airway) and cooling (refrigeration/pumping) configurations, to obtain the most energy efficient system that would satisfy design workplace conditions. The scenarios considered in the optimisation study included:

- Removal of or replacement of booster fans, quantifying the capital and power cost implications.
- The optimum position for underground bulk air cooling.
- The optimum refrigeration and cooling strategy, including the possibility of new underground refrigeration plants (reduced pumping with no chilled water supplied from surface) or supplying hard ice from surface to an underground melting dam.

The result of this study proved that, with careful planning, changes to current ventilation and refrigeration systems on deep level mines could result in major electricity operating cost savings, while maintaining safe and healthy workplace conditions. At Beatrix Gold Mine, by changing the inlet guide vane (IGV) setting of the main surface fans, the mine has already made energy savings of 10 400 MWhours per annum, resulting in an energy cost saving of R 8 million per annum.. It is possible for the mine to save an additional 3 300 MWhours per annum and effect a further energy cost saving of R 4 million per annum by stopping an underground booster fan. The main consequence of these changes is that the underground air flow would reduce by nominally 35 m^3/s (total air flow is nominally 550 m^3/s.)

A further significant saving, amounting to about R 20 million per annum, would result from refrigeration system efficiency improvement and a reduction in pumping cooling circuit water back to refrigeration plants on the surface when an underground refrigeration plant is installed.

INTRODUCTION

Input costs of deep level mines and, specifically, escalating electricity costs have become globally among the biggest cost drivers in the industry, resulting in offsetting higher gold prices and reducing margins. In addition to underground workplace conditions being safety critical, it is imperative that the ventilation and cooling systems operate as closely as possible to their maximum efficiency in order to reduce capital and operating costs while maintaining a safe and healthy environment.

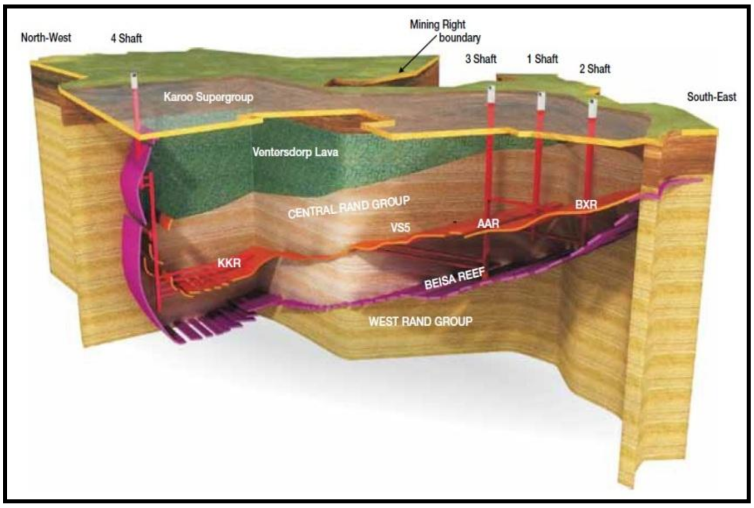
Gold Fields conducted an energy and carbon management study which showed that energy is now over 20% of their cost base [1]. From this study, an Integrated Energy and Carbon Management Strategy was developed to facilitate a holistic approach to managing energy and carbon. It covered generation sources, the main fuel and electricity consuming assets and it considered Gold Fields' mining methods and how they affect energy intensity. The Gold Fields' integrated Energy and Carbon Strategy has six pillars, namely:

Understand: measuring, monitoring and managing energy consumption and carbon emissions
Plan: factoring energy carbon into operational and life-of-mine plans
Operate: operating core assets more efficiently to achieve lower energy intensity
Replace: replacing carbon intensive sources of energy with renewable energy
Invest: spending now to reduce energy costs in the future
Enable: addressing underlying factors that will enable Gold Fields to reach its energy and carbon goals.

Within the context of this strategy, Beatrix Gold Mine carried out a review of current energy consumption with a view to reducing it. Ventilation and refrigeration systems were identified as large consumers and, in an attempt to reduce operating cost, an optimisation study was conducted on the current ventilation and refrigeration systems at Beatrix West Mine. This paper describes the methodology used and the outcome of the optimisation study [2].

Beatrix Gold Mine is a large, well-established gold mine located in the magisterial district of Matjhabeng near the towns of Welkom and Virginia in the Free State Province of South Africa. Beatrix Gold Mine consists of four operations including the West Section. The West Section is accessed from a sub-vertical shaft complex, with access to the ore body gained through horizontal tunnels (haulages) developed from the sub-vertical shaft. Reef is extracted from stoping panels where rock is blasted and scraped into ore passes then transported to the shaft station areas by locomotive-drawn hoppers. Mining at a depth of 2 100 metres underground had already presented some major ventilation and cooling challenges to the Beatrix Gold Mine's West Section. **Error! Reference source not found.** below is a schematic of the Beatrix Gold Mine complex.

Figure 1 - Schematic of Beatrix Gold Mine complex

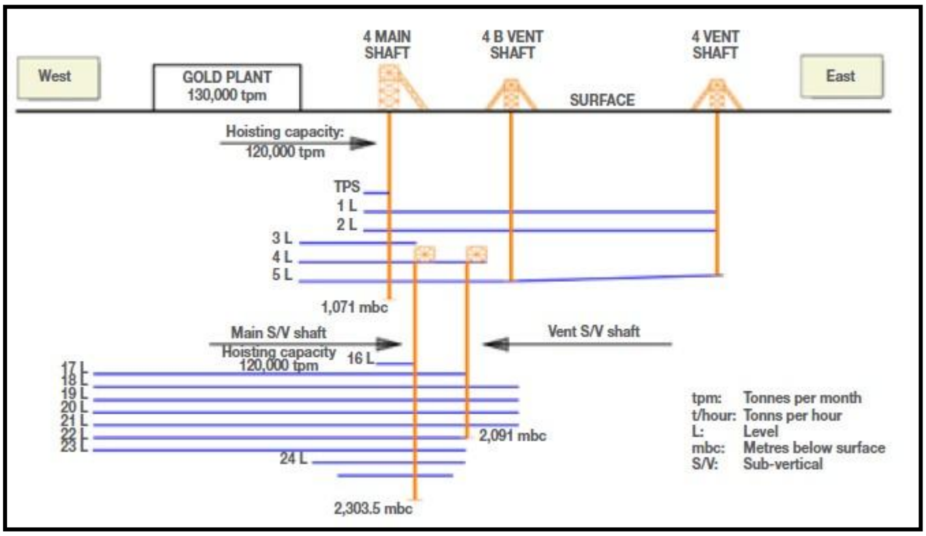


BACKGROUND

Downcast ventilation air is cooled in two BACs on the surface and again by two smaller BACs underground to achieve design thermal conditions (28.5 °C wet-bulb maximum). The mine relies mainly on booster and auxiliary fans to provide air to the mine extremities, due to the number of closed and restricted airways. Chilled water for the BACs is generated on the surface by four 9 750 MW(R) ammonia refrigeration machines. The chilled water is piped underground via two turbine stations (Level 5 and Level 16) and a dam on Level 18 to the lower workings. The hot water is pumped out of the mine from Levels 25 to 5 and then to the surface.

The mine is ventilated with 480 kg/s of air and relies on booster fans situated on the stations at Levels 17, 18, 19 and 21 to provide the design airflows to each level. Mining takes place in three blocks, with most of the production taking place between Level 19 and Level 21. Figure 2 shows the simplified section through the mine.

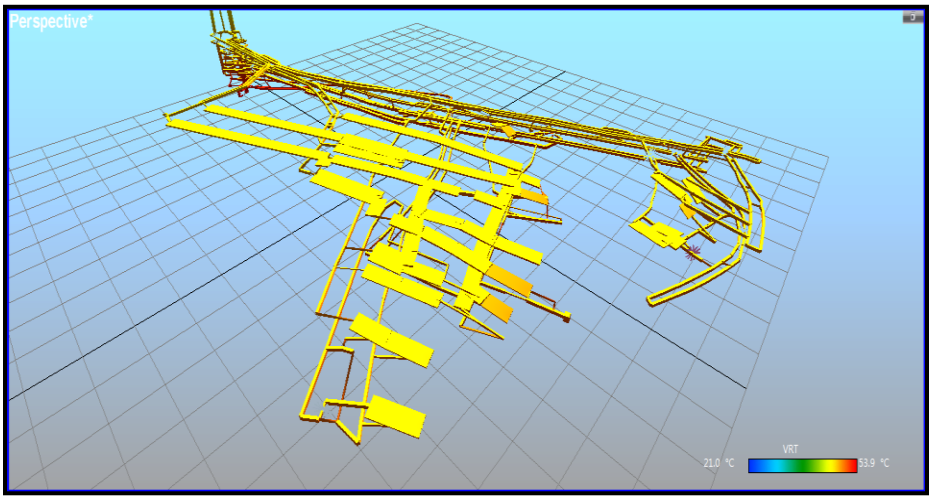
Figure 2 – Simplified section through the mine



METHODOLOGY

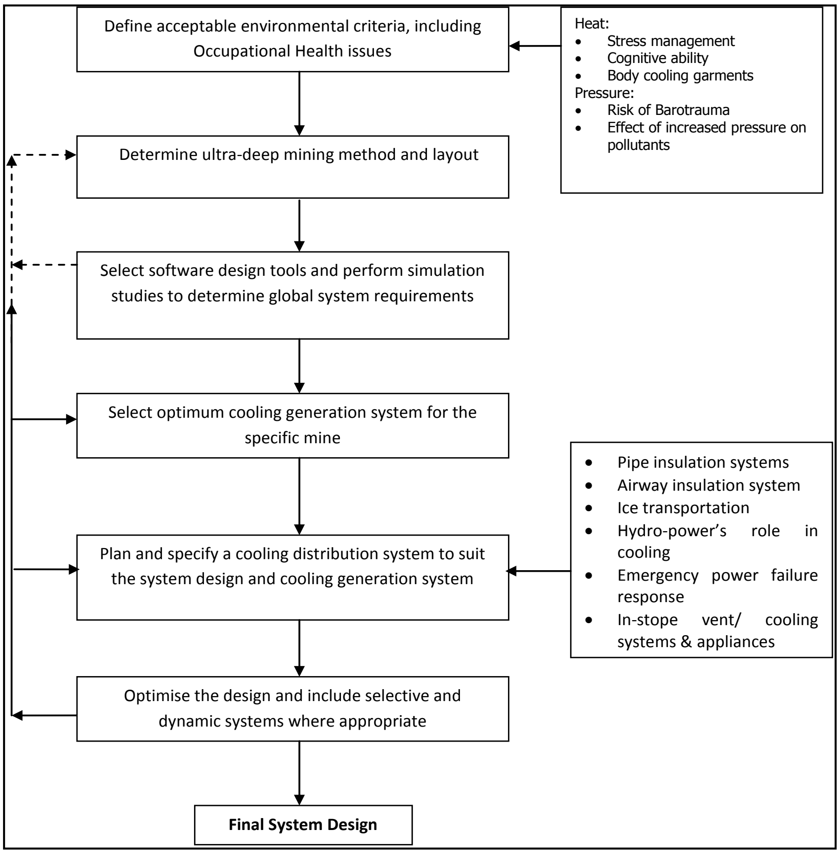
The methodology used included the development and simulation of network models, in VUMA3D-network, which accurately reflected the current mining scenario and ventilation conditions [Figure 3]. Part of the development of these models included the calibration and verification of the predictions, with measured environmental conditions, to ensure a high level of confidence. Then these models were used to examine various options for improving the overall ventilation and cooling strategy as well as for determining the effect of possible future changes. A number of scenarios, including different ventilation (fan/airway) and cooling (refrigeration/pumping) configurations, were examined to obtain the most energy efficient system that satisfied design and safe workplace conditions.

Figure 3 – Simulation network



World-leading research and development carried out by the South African Deep Mine and Future Mine Collaborative Research Programmes, developed best practice strategies for refrigeration and cooling systems for deep hard rock mines. The Deep Mine programme identified, analysed and developed technologies at system and component level to ensure cost effective deep mining operations in acceptable environmental conditions. 'Acceptable environmental conditions' means a working environment where underground mineworkers are able to work productively and safely with the minimum risk of developing heat, or other health disorders. Ventilation, refrigeration and cooling tactics as described in Deep Mine guidelines [3] (CSIR Mining Technology, 2002) and shown schematically below (Figure 4) were considered for the current study.

Figure 4 - Deep Mine design guideline

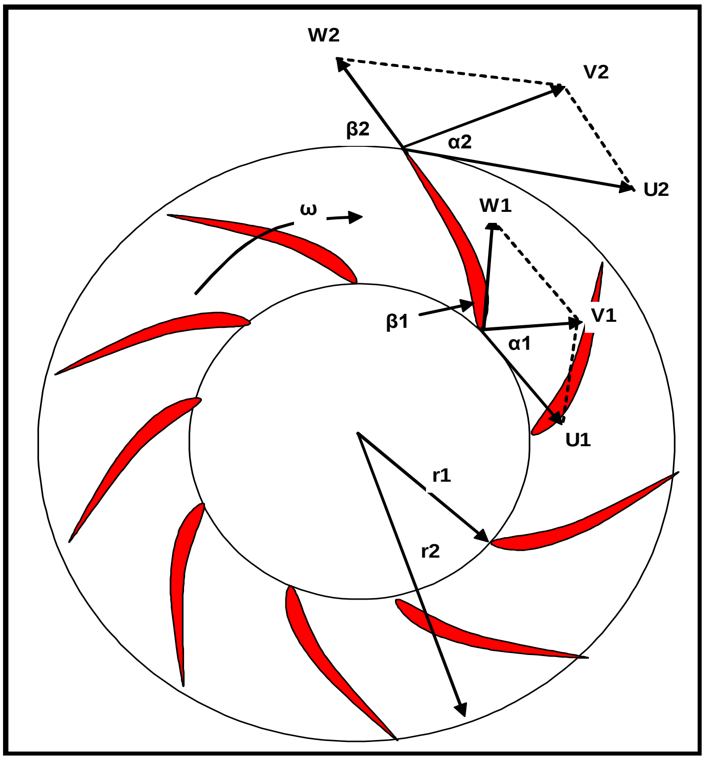


As can be seen from Figure 4, Occupational Health and Hygiene guidelines were developed for the effects of Barometric pressure changes, increased pressure and pollutants, and heat stress and cognitive ability, all providing 'do's and don'ts' for deep mining design. Component studies give guidance at equipment level such as insulation, energy recovery devices and cooling distribution and transportation.

The real benefit of Future Mine's research outcomes to this study is in guidance on optimising energy balances and efficiency improvements in mine ventilation and cooling systems [4] (Du Plessis, Marx & Biffi, 2005).

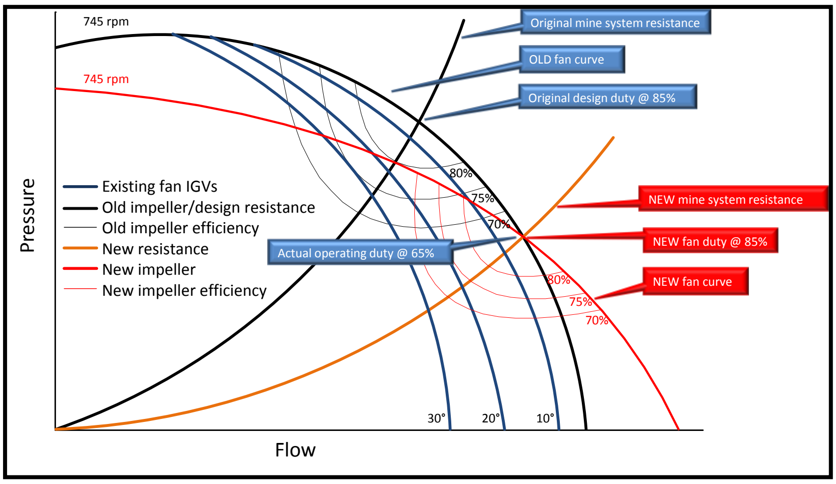
In the recent past, significant work has been done on energy optimisation of main fans in South Africa and, specifically, for some of the Gold Fields operations [5, 6, 7]. Following successful implementation at its other operations, this energy saving initiative was also considered at Beatrix Gold Mine and included the full implementation of IGV control at Beatrix West Mine. IGV control involves introducing specially designed adjustable vanes to the air stream entering the fan inlet, to generate a swirl of air in the direction of the impeller rotation. This reduces the performance capability of the fan which shows progressively reduced pressure/volume and power curves as the IGVs are closed to introduce more swirl. This, in turn, moves the operating point down the system resistance curve resulting in reduced power consumption. The schematic below (Figure 5) illustrates the reduction in load caused by an initial velocity vector V1 from the swirl, requiring less work to reach the ultimate velocity vector V2.

Figure 5 - IGV effect on velocity vectors



Another energy initiative being pursued is considering entire impellor replacements. This is required where main fans are operating far off their original design duty points as illustrated in the following Figure 6.

Figure 6 - Impellor replacement concept



In Figure 6, the difference in the original design duty point and the current mine duty point is shown. As the mine ages, operating points can change resulting in very inefficient operation of main fans. This can also be exacerbated by the deployment of booster fans underground moving the main fan operational point. Improved operational efficiency, resulting in reduced energy input, can be achieved through the implementation of drop in impellors.

OPTIMISATION STUDIES

The scenarios considered in this study included ventilation, refrigeration and cooling distribution for the underground sections of the mine and were as follows:

Ventilation and Booster Fans

- Utilisation of existing raise bore holes (RBHs) to improve ventilation distribution and reduce airway restriction and associated pressure loss through opening up of seals,
- Reduction of the number of booster fans utilised, and
- Provision of a practical and cost effective return airway system utilising existing combinations of booster fans and RBHs.

Refrigeration and Cooling distribution

- Conducting high-level trade-off studies between surface ice plant, energy recovery turbines, surface refrigeration, underground refrigeration plant and a combination of surface and underground plants.

For the optimisation of refrigeration, an energy model was developed to determine a projected baseline power usage (kW) for the shaft's refrigeration, turbines and pumping systems. The baseline model included the surface refrigeration plant, the energy recovery turbines on Level 5 and Level 16 as well as clear-water pumping systems on Levels 5, 21 and 25. Additional underground cooling of 2 000 kW was included in the baseline model to reflect future mine requirements. This is based on an additional 50 ℓ/s of cold water required for air cooling. The additional demand provides a projected baseline load on the current surface plants.

During the study it was necessary to agree to and use specific design criteria and assumptions. These are summarised below:

Design criteria and assumptions [8] (Du Plessis, *et al., 2010).*

- A minimum of 20 m³/s of airflow per stoping line and maximum face stope wet-bulb temperature of 27.5 °C.
- The current surface BACs were assumed to deliver to design at 20 MW(R).
- Chilled service water consumption of 3.5 ton (of water) per ton of rock for present and future mining.
- All fans were assumed to be standard and therefore operating on their fan curves as supplied by the manufacturer.
- Future planning and model simulations indicated that underground demand for cooling water will increase by 50 ℓ/s.
- Only one of the two installed turbines in each turbine station will operate (75 ℓ/s).
- Operational efficiency of energy recovery turbines was assumed to be 60% based on operational data.
- Coefficient of performance (COP) for surface and underground refrigeration plants was assumed to be 6 and 4 respectively.
- Return water temperature from underground was assumed to be 28.0 °C

STUDY RESULTS

At present, there are a number of RBHs (previously drilled) located between the various levels within the mine. Ventilation network simulations were carried out in which the various RBHs were "opened" and "closed" in a range of configurations to effect distribution of the air. The results indicated that there was limited benefit in changing the current RBH status and that less than 8% improvement in power consumption could be achieved when compared to the present operating conditions. Therefore, it was decided to test more complex scenarios of air distribution by changing the current fan operating conditions.

Surface and booster fan optimisation

In order to determine the effect of stopping underground booster fans, seven scenarios were considered with various IGV settings of the main surface fans. These are listed below:

1. Surface fans with 20% closed IGVs – All booster fans stopped
2. Surface fans with fully open IGVs – All booster fans stopped
3. Surface fans with 20% closed IGVs – All booster fans running
4. Surface fans with 20% closed IGVs – Level 21 booster fan stopped
5. Surface fans with 20% closed IGVs – Level 21 and Level 19 booster fans stopped
6. Surface fans with fully open IGVs – Level 21 booster fan stopped
7. Surface fans with fully open IGVs – Level 21 and Level 19 booster fans stopped

Table 1 indicates the effect of the above scenarios on return air volumes on Levels 17, 18, 19 and 21 in comparison to the base case:

Table 1 - Effect on air volume reduction for the seven scenarios

	Scenarios	**Return Air Volume (m^3/s)**				
		Level 17	**Level 18**	**Level 19**	**Level 21**	**Total**
	Base case	**108**	**160**	**190**	**125**	**583**
1	Surface fans 20% IGVs - All booster fans stopped	90	60	160	118	428
2	Surface fans open IGVs - All booster fans stopped	98	93	169	126	486
3	Surface fans 20% IGVs – All booster fans running	92	166	184	123	565
4	Surface fans 20% IGVs – L21 booster stopped	108	156	193	91	548
5	Surface fans 20% IGVs – L21+L19 booster stopped	116	173	125	90	501
6	Surface fans open IGVs – L21 booster stopped	109	163	195	94	561
7	Surface fans open IGVs – L21+L19 booster stopped	119	176	134	121	550

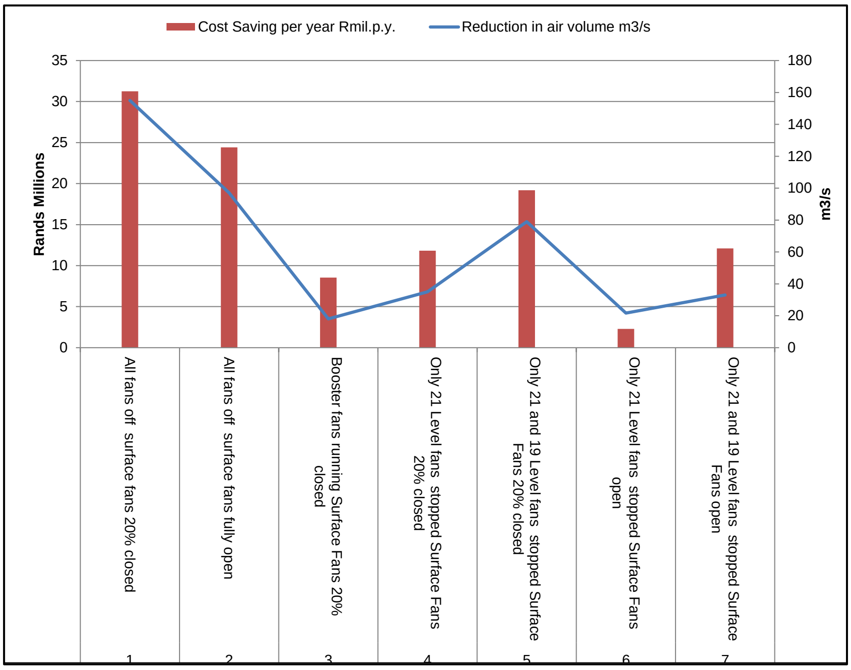
In **Error! Reference source not found.**, the results of the simulations, including the power saving and air volume reduction achieved for each scenario, are given. In order to assess the different options, they were ranked in terms of the lowest airflow reduction per megawatt of power saved. The scenarios with the least reduction in air volume per megawatt of power saved are 3, 4 and 7.

Table 2 - Reduction in Fan absorbed power and air volume

	Scenarios	Reduced Fan Input Power (kW)	Reduced Air Volume (m^3/s)	Reduced Air Volume per MW saved	Rank
1	Surface fans 20% IGVs - All booster fans stopped	3 784	155	41	6
2	Surface fans open IGVs - All booster fans stopped	3 004	97	32	4
3	Surface fans 20% IGVs – All booster fans running	1 191	18	15	1
4	**Surface fans 20% IGVs – L21 booster stopped**	1 564	35	22	3
5	Surface fans 20% IGVs – L21+L19 booster stopped	2 407	79	33	5
6	Surface fans open IGVs – L21 booster stopped	476	22	46	7
7	Surface fans open IGVs – L21+L19 booster stopped	1 597	33	20	2

The following figure (Figure 7) graphically demonstrates the effects of the reduction of air volume and cost saving for each of the modelled scenarios.

Figure 7 - Cost saving vs. air volume reduction



From Table 2 and Figure 7, it is clear that Scenario 3 (lowest air volume lost per MW saved) was the top-ranked scenario and the mine has implemented it recently. Scenarios 4 and 7 offer further power savings with a slight additional reduction in airflow. Of the latter, Scenario 4 is favoured by the authors as it meets practical implementation considerations. Although Scenarios 1, 2 and 5 would result in large reductions in power used, they are not recommended owing to safety considerations associated with the large reduction in airflow.

Potential Cost Savings

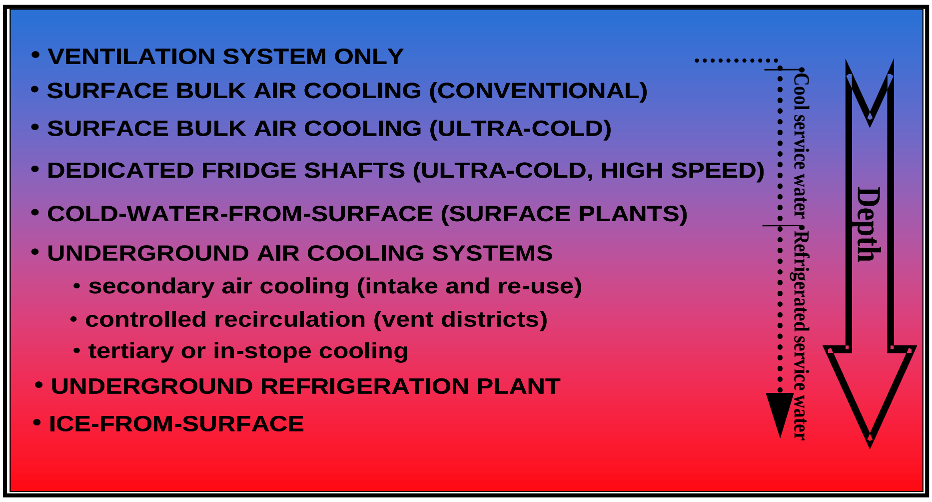
The potential cost savings were calculated for each set of circumstances. With surface fans already running at 20% closed IGVs (Scenario 3), the result is an energy cost saving of R 8 million per annum and an electricity saving of 10 400 MWhours per annum.. After presenting to and reviewing the various options with the mine personnel, Scenario 4 was recommended as the optimal scenario, saving an additional R 4 million per annum and effecting a further electricity saving of 3 300 MWhours per annum. In this scenario, the surface fans operate at 20% closed IGVs and, additionally, Level 21 booster fans are stopped. This saving is achieved without risk to ventilation flows within the mine workings and does not influence workplace conditions adversely.

The impact of stopping the Level 21 booster fan is shown in **Error! Reference source not found.** above. This scenario will require the mine to return 30 m^3/s of airflow to Level 21 which can be achieved through returning this air to Level 19 instead of Level 21 by utilising a return RBH. This will require additional development in the Northern area of the mine connecting these levels.

Refrigeration and Cooling Optimisation

A study by Dr S J Bluhm explained the hierarchy of cooling strategies that can be applied to deep, hard rock mines. This is shown in Figure 8 below and was considered in developing different refrigeration and cooling scenarios and, ultimately, in determining the best refrigeration and cooling strategy for Beatrix West Mine [9] (Bluhm, *et al., 2003)*. The hierarchy shows that shallow mines require ventilation only but, as mines increase in depth, more refrigeration and cooling are required whilst, at depth, ice systems are most economical.

Figure 8 - Hierarchy of cooling deep, hard rock mines



The following refrigeration and cooling options were modelled and simulated as part of the energy optimisation study:

Scenario 1 - Install underground refrigeration plants to provide all the underground cooling requirements

This option involves installing a new nominal 18 MW refrigeration plant on Level 17 to provide chilled service water as well as water for the air cooling installations, including spot and bulk air cooling installations. In this option, most of the chilled water is circulated between Level 25 and Level 17. The main advantage of this option is that the return water pumped from underground to surface will reduce by approximately 266 ℓ/s. The saving in pumping power more than compensates for the additional power used by the refrigeration machines and for the turbines becoming redundant.

Results of financial assessment

- Expected power reduction 5.5 MW(E)
- Expected project cost R 184 million
- Expected annual saving R 32 million
- Expected payback 4.6 Years

Other advantages

With a minimum amount of water flowing into and being pumped out of the mine, there will be savings in the maintenance costs of the complete mine cooling water system including turbines, pumps, dams, piping etc. All the equipment in the surface refrigeration plant will not be fully utilised hence the redundant equipment can be used as standby equipment.

Scenario 2 - Convert part of the surface refrigeration plant to produce ice

Part of the surface refrigeration plant is converted into a feed system for a new ice plant producing approximately 20 kg/s of ice. The ice is delivered to a new ice dam on Level 16. The underground air cooling system receives water at about 2.0 °C from the ice dam and returns the hot water back to the new Level 16 ice dam to melt the ice.

Results of financial assessment

- Expected power reduction 4.5 MW(E)
- Expected project cost R 88 million
- Expected annual saving R 28 million
- Expected payback 2.5 Years

Other advantages

With a reduced amount of water being distributed and pumped out of the mine, there will be savings in the maintenance costs of the whole mine cooling water system including turbines, pumps, dams, piping etc. The temperature of the cold water circulated from the Level 16 ice dam will be lower than in other options and this will result in savings in the capital requirements of the cooling distribution system.

Scenario 3 - Install underground refrigeration plant to provide the additional underground cooling and utilise all four turbines

This option involves making maximum use of all the installed equipment (including all four turbines and refrigeration machines.) New underground refrigeration machines are installed to provide the additional required cooling. There is no increase in the quantity of water handled by the return water pumping system to the surface.

Results of financial assessment

- Expected power reduction 3.5 MW(E)
- Expected project cost R 68 million
- Expected annual saving R 20 million
- Expected payback 2.5 Years

Other advantages

This is the lowest capital cost option and the work can be completed in the shortest time.

In Table 3 the financial assessment of the three scenarios considered are summarised.

Table 3 - Refrigeration and cooling option comparison

		Saving MW (E)	Capital Cost R Million	Saving R Million (per annum)	Payback years
1	Underground plants provide all underground cooling requirements	5.5	184	32	4.6
2	Convert surface plant to produce hard ice	4.5	88	28	2.5
3	Underground plant for additional underground cooling and all turbines operating	3.5	68	20	2.5

CONCLUSION AND RECOMMENDATION

After reviewing the various options, Ventilation Scenario 4, with the surface fans operating at 20% closed IGVs and the Level 21 booster fans stopped, is the recommended optimised ventilation option. Combined with this, Refrigeration and Cooling Scenario 3 is recommended due to the shorter implementation time, lowest implementation cost and least complexity.

The result of this study proves that, with careful planning, changes to current ventilation and refrigeration systems in deep level mines can result in major electricity operating cost savings. At Beatrix West Mine, the mine has already achieved energy savings of 10 400 MWhours per annum resulting in an energy cost saving of R 8 million per annum, by changing the inlet guide vane setting of the main surface fans. It would be possible for the mine to save an additional 3 300 MWhours and effect a further energy cost saving of R 4 million per annum by stopping an underground booster fan. The main penalty attached to these changes is that the underground air flow would reduce by nominally 35 m^3/s (total air flow is nominally 550 m^3/s.)

Significant energy saving is attainable by improving refrigeration positional efficiency and reducing the volume of cooling water that is pumped from the bottom of the mine to the surface. In Refrigeration and Cooling Scenario 3, the additional refrigeration and cooling water required for future mining will be produced by an underground plant, eliminating the pumping of 50 l/s over 2 000 m back to the surface, and by utilising the existing two energy recovery turbine stations. At Beatrix Gold Mine, the operational savings will be in the order of about R 20 million per annum. The cost of the required modification will be R 68 million with a capital payback of just more than three years.

ACKNOWLEDGEMENTS

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