The design of cooling systems for mining at a depth of 4 000 m

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ABSTRACT: This paper presents an overview of the design of the ventilation, cooling and refrigeration requirements for mining activities at Gold Fields Driefontein Mine No.9 Shaft for mining at a depth of almost 4 000 m below surface with virgin rock temperatures of 56°C. The paper describes the early modelling, the logic and the latest philosophies behind the design, including energy saving facilities, and briefly summarises the components of the cooling system selected.

1 INRODUCTION

Mining activities are to resume at Gold Fields' Driefontein Mine's No.9 Shaft. The block of ground extends from 3 316 m to 3 820 m below surface with VRTs ranging from 51°C to 56°C. The primary surface shafts are more or less complete and the sub-vertical shaft has been partially sunk to a depth of 2 950 m. Target production is 200 ktpm (total).

The design work for the ventilation and cooling system required the following:

- Determination of in-stope ventilation and cooling requirements for selected mining method, including sensitivity studies.
- Assessment of air carrying capacity of existing primary infrastructure.
- Design of ventilation infrastructure for life-of-mine requirements and interim scenarios.
- VUMA-network modelling and examination of proposed cooling strategies.
- Determination of heat loads and cooling requirements over life-of-mine.
- Verification of best location and sizing of cooling systems such as: ice melting centres, mix of ice and chilled water from surface, secondary/tertiary cooling.
- Investigate energy management options such as thermal storage and time-of-use strategies and integrate into designs.
- Preliminary first-order costing (capex and opex) of primary components to perform initial trade-off studies relating to cooling system structure.
    - surface bulk air cooler and refrigeration system
    - surface chilled service water refrigeration system
    - pumping installations and shaft columns
    - energy recovery systems (Pelton turbines and 3-chamber system)
    - surface ice-maker system
    - ice conveying to shaft and in-shaft ice pipe system (size ice dams)
    - underground bulk air coolers
    - underground refrigeration plant and circulation system
- Selection of optimum ventilation and cooling system for full production scenarios over life-of-mine.
- Definition of phase-in profile of the refrigeration systems over life-of-mine, with due regard for access and timing issues relating to underground installations.

This paper focuses on the philosophies and outcomes of the economic studies for the ventilation and cooling system structure. The specific details of underground bulk air coolers, secondary air coolers and tertiary air coolers – apart from assessing the overall required capacities of each – have been excluded.

Established concepts have been selected for each of the cooling sub-systems. The design concepts are in keeping with the findings of the DeepMine-FutureMine work and are based on state-of-art practical current thinking on cooling deep mines. Further trade-off studies relating to individual components and sub-systems and final optimisation work will be performed during the detailed engineering design phase.

Energy management considerations were included as an important part of the work. It is advisable to provide versatile facilities for possible implementation of any number of energy management tactics. At present, this would include load shifting for Eskom DSM purposes; i.e. tariff vs. load cycle optimisation and diurnal cooling load damping. In the future this emphasis may change and these facilities must give management of the day a versatile capability for energy control. Of particular interest are the concepts of ‘ventilation-on-demand’ and ‘cooling-on-demand’ which are currently being researched.

For the design work described in this paper, the No.9 Shaft complex has been considered as a stand-alone project and has not included any possible long-term synergy with the neighbouring No.5 Shaft infrastructure. Any optimisation possibilities will form the basis of future investigations.

2 PRIMARY DESIGN CRITERIA

The primary design criteria are summarised as follows. It is important to note that some of these relate to existing infrastructure.

Production rate	200 ktpm (reef & waste)
Mining method	Closely spaced dip pillar
Production raise lines	7 off
Ledging raise lines	2 off
No.9 Main Shaft (downcast)	9.15 m dia.
No.9 Sub-vertical Shaft (downcast)	9.15 m dia.
No.9 Ventilation Shaft (upcast)	7.00 m dia.
Upcast raise bore holes to 40 Lev	4 off 3.8 m dia.
Primary airflow	840 kg/s (3.5 kg/s per ktpm)
Shaft air speed (downcast)	12 m/s
Shaft air speed (upcast)	21 m/s
Surface ambient temperature	18/28°Cwb/db
Underground reject temperature	28.5°Cwb
Service water (2 t/t)	175 l/s average
Fissure water expectation (0.3 t/t)	30 l/s
Backfill	65% coverage
Leakage assumed	20% of total downcast
Platform Level (23 Level)	1 983 mbc, 37°C VRT
Upper mining level (50 Level)	3 316 mbc, 51°C VRT
Lowest mining level (57 Level)	3 820 mbc, 56°C VRT

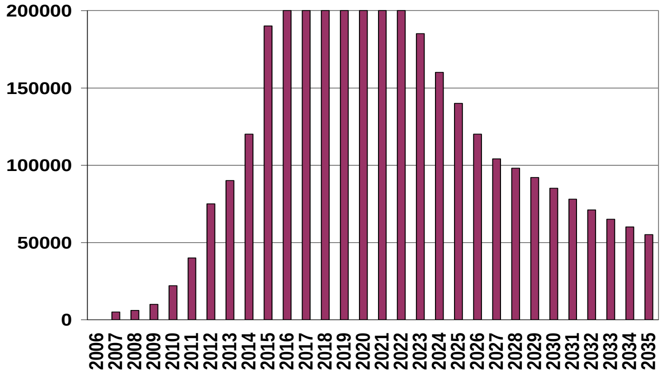

Figure 1. Production profile for No.9 Shaft

Whilst the peak tonnage is only sustained for a period of 9 years, the cooling demand will not reduce as rapidly as the tonnage due to the increasing mean rock-breaking depth and distance on strike.

2.1 *Existing infrastructure*

The existing infrastructure is indicated in solid in figure 2. No.9 Main Shaft (men and material) and No.9 Ventilation Shaft are more or less complete and No.9 Sub-vertical shaft has been partially sunk to a depth of 2 950 m (43 Level) and equipped down to 42 Level.

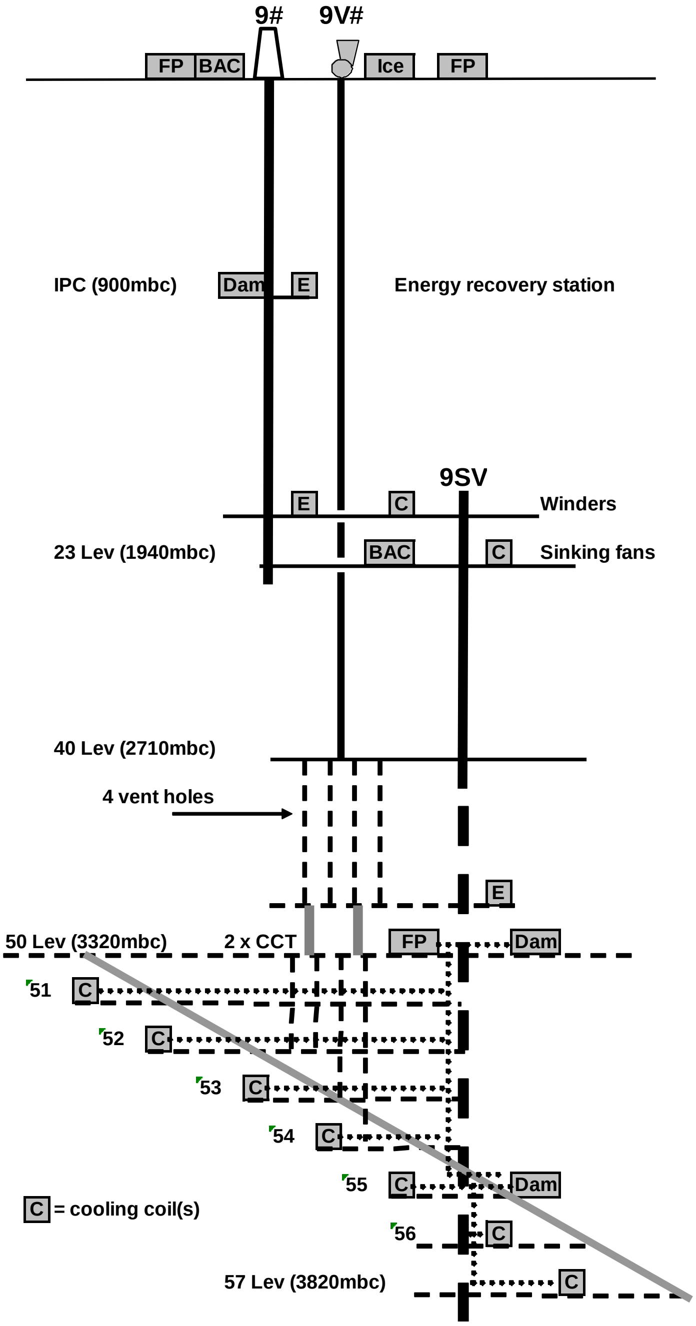

Figure 2. Section of No.9 Shaft and cooling system

3 MODELLING, ENERGY BALANCES AND AIR COOLING TACTICS

Initial modelling was required of the primary intake infrastructure and of generic stopes. The intake models were used to ascertain typical air temperatures into stope cross-cuts for the various cooling strategies that were considered. Being a brownfields project, the primary air quantities were dictated by existing infrastructure. The stope models were used to understand and explore in-stope air and cooling requirements and to conduct sensitivity studies of the various mine design criteria affecting these requirements.

Two significant periods in the life-of-mine were then selected for detailed modelling purposes. The first, when full production is first achieved; the second, when full production is still maintained, but at the extremities of the mine (depth and strike).

- Design Scenario 1 year 2015
- Strike distance up to 1.2 km (east and west).
- Deepest operating level 57 Level
- MRBD 3 480 m
- This is an **interim scenario** to establish the phase-in profile of cooling equipment.

- Design Scenario 2 year 2023
- Strike distance up to 2.4 km (east)
- Deepest operating level 57 Level
- MRBD 3 650 m
- This is the **peak scenario** for which the system must be designed and optimised.

Detailed VUMA-network modelling of the complete mining block and airways were carried out and global cooling balances were evaluated for these scenarios.

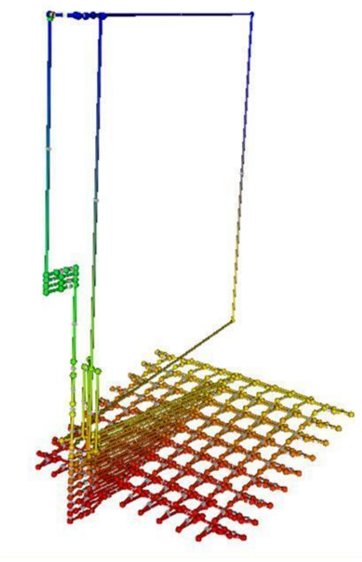

Figure 3. Preliminary VUMA model of No.9 Shaft

The mine-wide energy balance can usually be satisfied by different combinations of air quantities and cooling arrangements. However, in this case, the options are limited by the sizes of the existing shafts which set the primary ventilation rate to 840 kg/s. This equates to an overall air factor of 3.5 kg/s per ktpm (reef & waste). (Note: this is one aspect of the design where it will be possible to explore future synergies with the neighbouring No.5 Shaft mining area).

For this set of circumstances, the optimum ventilation/cooling philosophy is to operate the system at the maximum primary ventilation capacity and then introduce refrigeration capacity as the underground heat load increases. A special design condition is required for shaft sinking and station development operations – discussed below.

The VUMA-network modelling allows the location and size of the cooling installations (bulk air coolers and cooling cars/coils) to be selected to achieve the required ventilation conditions in each scenario. The cooling effect of service water is also taken into account.

For the ultimate design, Scenario 2, the VUMA-network models indicate that the global mine energy balance will be satisfied by a total distributed air cooling duty of 93 MW_R. For the interim Scenario 1, the required total distributed air cooling duty will be 78 MW_R. The air cooling requirements can be summarised as follows:

Scenario	**1**	**2**
Surface bulk air cooler	20 MW_R	20 MW_R
Coolers for u/g equipment	1 MW_R	1 MW_R
Main u/g BACs	21 MW_R	36 MW_R
Tertiary air coolers	11 MW_R	11 MW_R
In-stope air coolers	25 MW_R	25 MW_R
Total cooling	**78 MW_R**	**93 MW_R**

Note that these are the duties at the air cooling locations. These air coolers and the chilled service water will be served by a matching chilled water circulation and refrigeration system. Using well-established performance specifications regarding the characteristics of air coolers, pipe insulation, energy recovery systems, open drains, dams, etc, as well as average versus peak duties, allows these refrigeration needs to be determined. Thus the following refrigeration systems have been calculated for the ultimate operating Scenario 2:

Surface bulk air cooler system	20 MW_R
Mine water refrigeration system	28 MW_R
Underground refrigeration plant	40 MW_R
Surface hard-ice makers	23 MW_R
Total refrigeration machine duty	**111 MW_R**

A specific scenario during shaft sinking was also modelled with VUMA in order to determine the initial refrigeration requirements. From this and the main models, the required phase-in can be predicted. Figure 4 (see below) summarises the global energy balance in the form of the life-of-mine profile of the basic cooling needs.

4 COOLING SYSTEM PHILOSOPHY

The design concepts for the overall refrigeration and cooling distribution system were based on current thinking for cooling deep mines and are consistent with the findings and philosophies of the DeepMine and FutureMine programmes.

The first phase of cooling incorporates surface bulk air cooling. In operating shafts the surface downcast air temperature is limited to about 10/12°C(wb/db). The peak duty during life-of-mine will reach 20 MW_R. The initial duty at the lower air flow rate during shaft sinking and station development in the sub-vertical shaft will be about 10 MW_R.

Surface bulk air cooling will be augmented by chilled water from surface for distributed cooling. There is an economic limit to the quantity of chilled water from surface. This depends on the ultimate sizing of the underground refrigeration plant and future ice strategies. From the initial studies for this project, the quantity of chilled water from surface will be 300 l/s (~ 3,5 t/t), which includes 175 l/s of genuine mine service water. The balance will be utilised in tertiary open circuit (free discharge) air coolers. All this water must return to the shaft in pipes so as to avoid the harmful heat transfer from open drains into intake air. The ultimate surface mine water refrigeration system will be sized for 28 MW_R. The initial duty will be about 10 MW_R.

Chilled water from surface will be fed underground in insulated steel pipe columns. To reduce the high energy costs associated with returning this water to surface and to minimise water temperature increases due to the Joules-Thomson effect, energy recovery systems will be employed. Three-chamber systems potentially offer the greatest savings for water transport given current improvements in both capital cost and operational reliability. Alternatively Pelton turbines will be installed. These systems will be cascaded vertically to match the pumping system layout.

As the production from this mining area increases and once the permanent return airway system is fully established, the next priority will be an underground refrigeration plant to make maximum use of heat rejection capacity into the return air. For No.9 Sub-vertical Shaft, the underground plant will be located on 50 Level with a duty of 40 MW_R supplying chilled water to two closed networks of cooling coils ranging from 3 000 kW_R bulk air cooling stations down to individual 350 kW_R secondary cooling cars. The circulating pumps and dams will be located on 50 Level and 55 Level. The system will be split to avoid excessive pressures on the lower levels and to accommodate the introduction of ice at a later stage.

Finally, once the mine heat load exceeds the capacity of the underground plant, hard ice from surface will be introduced. The current design work indicates that this plant will have a rating of 23 MW_R and produce 68 kg/s (5 900 t/d) of hard-ice. This ice will be delivered to the deepest practical location which will eventually be 55 Level.

The overall design also includes state-of-the-art energy management considerations. On surface, thermal (ice) storage facilities will be provided for both the bulk air cooler system and the mine water refrigeration system. In both these facilities, one refrigeration machine will cool glycol to sub-zero temperatures which will be circulated through submerged coil bundles. Ice will form on the coils during optimal periods and will be melted (from the outside) by circulating water over the ice to provide extra cooling during other strategic periods. This will provide a versatile resource for implementing a variety of energy management tactics. At present, this would include load shift for Eskom DSM purposes; tariff vs. load cycle optimisation and diurnal cooling load damping. In the future this emphasis may change and this resource will give the management of the day a versatile capability for energy control.

Further energy management will be possible by providing storage capacity in the 55 Level underground ice dam to allow strategic stop/start of the surface hard ice-makers at optimum times. In many cases a small amount of capital can be justified by future savings in operating costs and other incentives.

Current research is also looking at the possibilities and benefits of ‘ventilation-on-demand’ and ‘cooling-on-demand’. The strategies involve minimising the provision of excessive ventilation and cooling during periods of inactivity.

Another concept combines live modelling of ventilation networks with feedback from underground monitoring stations to allow intelligent control of ventilation and cooling systems. By carefully selecting the locations of a few monitoring stations the model can determine conditions throughout the mine and adjust the settings of control elements to suit the current activities, with obvious energy savings.

The design logic and principles regarding standby equipment are:

- Each system will comprise a multiplicity of similar equipment modules.
- Surface mine water refrigeration system will have an additional refrigeration machine for standby and maintenance needs.

- All key pumps will have fully piped-in standbys.
- Two in-shaft ice pipes (2 x 400 mm) will be installed. (Although the minimum requirement is only 1 x 150 mm and 1 x 400 mm, two larger pipes will give greater flexibility, standby capacity and capacity for possible future expansion).

In summary, for the ultimate design scenario, the overall refrigeration and cooling distribution will comprise the following:

Surface bulk air cooler system	20 MW_R
Mine water refrigeration system*	28 MW_R
Three pipe feeder system (3 off cascade)	380 l/s
Underground refrigeration plant	40 MW_R
Surface hard-ice makers (68 kg/s)	23 MW_R
In-shaft ice-columns	2 x 400 mm

5 DESCRIPTION OF SURFACE BULK AIR COOLER AND PLANT

The surface bulk air cooler will have a nominal design capacity of 20 MW_R. This will create a downcast ventilation temperature of about 10/12°Cwb/db (surface in-shaft mixed). This system will be separate and independent of the mine water refrigeration system with benefits for water quality management and equipment specifications.

This cooling system, installed on surface at bank elevation, will comprise of a bulk air cooler connected to a sub-bank cold air duct, refrigeration modules, plant building, condenser cooling towers and associated pumps etc. The design provides for active energy management with the inclusion of thermal storage facilities in the form of glycol ice banks. This facility will operate automatically and will be monitored remotely without the need for permanent on-site operators.

5.1 *Bulk air cooler*

The bulk air cooler will cool 630 kg/s which will mix in the shaft with 210 kg/s of warm ambient air from the surface brow to provide the total downcast of 840 kg/s. The air cooler will be a horizontal spray chamber constructed in concrete in which cold water is sprayed into the horizontal airflow, with a re-spray stage to achieve high thermal efficiency. Mist eliminators will provide 100% separation of droplets from the outlet air stream. Air will be forced through the cooler and sub-bank to the shaft by four low pressure axial flow fans.

5.2 *Refrigeration machines for surface BAC*

The refrigeration system for the BAC will comprise three refrigeration machines with a nominal duty of 7 MW_R each. These will be standard, packaged, factory assembled R134a plants with centrifugal compressors and shell-and-tube heat exchangers.

Two of the refrigeration machines will chill the water from the BAC in a series (evaporator) arrangement. The chilled water will then flow to the thermal storage dam where it will be in direct-contact with ice surfaces and will leave the dam at close to 0°C. The third refrigeration machine will chill a glycol-water mixture to sub-zero temperatures which will be circulated through submerged coils in the thermal storage dam. Ice will form on the coils during optimal periods and will be melted (from the outside) by the water circulating over the ice to provide extra cooling during peak demand and other selected strategic periods.

The condenser heat exchangers of the three refrigeration machines will be connected in parallel, served by a three-cell induced-draught counter-flow cooling tower.

6 DESCRIPTION OF MINE WATER REFRIGERATION SYSTEM

Water from underground returns to two existing 5 Ml surface mine water dams. From these dams the warm mine water will be circulated through a bank of pre-cooling towers. From the pre-cooled water sump, the water will be chilled in a bank refrigeration machines with the final stage being a new ice thermal storage facility from which the mine water will be delivered to the existing surface cold mine water dam (5 Ml) and hence to the mine.

The quantity of mine water includes the 300 l/s fed to the shaft (service water and some cooling water) plus the (future) 68 l/s feed water to the surface hard-ice makers.

The design of the mine water refrigeration system includes for active energy management through an ice thermal storage facility (glycol ice banks) that will allow energy control strategies. In addition, the pre-cooling towers will be operated at higher loads during cooler periods of the day (see below).

6.1 *Pre-cooling tower system (existing)*

The existing pre-cooling tower system can process a higher instantaneous flow rate than the 368 l/s average. The pre-cooling system will be set up to allow a return flow of water from the cooling tower sump back to the mine water dams, thus providing a larger combined storage capacity. In this manner, the pre-cooling tower system can be operated at a higher capacity during the cooler parts of the day thus maximising this cooling effect as well as increasing overall system efficiency. The temperature of the water off the pre-cooling tower system will be closer to the daily average and the peaks will be damped out.

6.2 *Mine water refrigeration machines*

In order to minimise underground pumping costs and the power consumption of the ammonia hard ice maker, it is very important to deliver the mine water as cold as practically possible. In the proposed system design, with ice thermal storage, it will be possible to genuinely deliver the water at close to 0°C (say 1°C for design purposes). Thus the mine water refrigeration system will be required to chill the flow rate of 368 l/s to 1°C.

The mine water refrigeration plant will comprise 4 off (plus 1 off standby) identical refrigeration machines. These will be standard, packaged, factory assembled R134a plants with centrifugal compressors and shell-and-tube heat exchangers.

Three of the refrigeration machines will chill the water flow in a series arrangement. From these machines, the chilled water will flow to the thermal storage dam where it will be in direct contact with the ice surface and leave the thermal storage dam at close to 0°C. The fourth refrigeration machine will chill a glycol-water mixture to sub-zero temperatures which will be circulated through submerged coils in the thermal storage dam as described above.

All these refrigeration machines will be identical. At the summer day average design condition, the three water chillers will have nominal duties of 8 MW_R, 7 MW_R and 6 MW_R. The thermal storage will provide a peak cooling duty of 8 MW_R. The glycol chiller will have a nominal duty of 4.7 MW_R. The total absorbed compressor power will be 4.2 MW_E. The existing refrigeration plant house and associated infrastructure will be extended. The ice thermal storage dam will be integrated into the new chilled water dam

The condenser heat exchangers of the four (plus standby) refrigeration machines will be connected in parallel and will be served by a bank of parallel cooling tower cells. The four existing cells will be inadequate for the ultimate requirements. The new cooling towers will be as described above for the BAC refrigeration system.

7 DESCRIPTION OF UNDERGROUND REFRIGERATION SYSTEM

The underground refrigeration system will be installed on 50 Level (uppermost mining level) with a nominal duty of 40 MW_R produced by 5 off refrigeration machines, similar to the system at No.5 Sub-Vertical Shaft.. This refrigeration system will provide 600 l/s at 5°C to a closed-circuit network of cooling-coil air coolers on the lower levels.

7.1 *Underground refrigeration machines*

The underground refrigeration plant will comprise 5 off identical 8.0 MW_R refrigeration machines, similar to those installed underground at No.5 Shaft. The machines will be standard R134a machines comprising three-stage centrifugal compressors, economisers and shell-and-tube heat exchangers. The chilled water within this system will remain separate and independent of the mine service water system so as to minimise the load on the settlers, reduce water treatment costs and to maintain a high thermal efficiency demanded by the low return water temperature from the closed circuit.

7.2 *Condenser cooling towers*

The condenser heat exchangers of the five refrigeration machines, connected in parallel, will be served by two vertical, counterflow, cooling towers between 50 Level and 49 Level. Return, upcast ventilation air, drawn by the main surface fans, will be routed through the cooling towers.

7.3 *Closed circuit cooling system and pumps*

The closed-circuit chilled water systems with cooling coils will comprise a conventional arrangement with twin pipes (supply and return) down the shaft (or travelling ways) and out and back on the levels. However, to limit the pressures in these networks to 64 bar and with the possibility of future, deeper, extensions, it is proposed that the system be split, with an upper system supplying coils on 50 Level down to 54 Level and a lower system supplying coils on 55 Level and below. This will necessitate a set of dams and pumps on 55 Level.

The evaporator water pumps at the refrigeration plant on 50 Level will draw water from the warm return water dam, pump through the evaporator heat exchangers of the refrigeration machines and into the backbone of the upper closed-circuit cooling system, returning to the same warm water dam.

The lower closed-circuit system will have circulating pumps on 55 Level. In the early stages the underground refrigeration plant will have sufficient cooling capacity for both the upper and the lower closed-circuit cooling systems. The lower system will draw water out of the upper system on 54 Level and into the cold water supply dam on 55 Level. The circulating pumps will pump through the network of cooling coils with the water returning to the warm water dam on 55 Level. Warm water pumps will be required to return the water from 55 Level back to the warm water dam on 50 Level. (see figure 2).

In the ultimate scenario, the underground refrigeration plant on 50 Level will be fully committed to supply the upper closed-circuit system (down to 54 Level). Cooling for the lower closed-circuit system will be provided by ice from surface and the cold water dam on 55 Level will become an ice melt dam. This will have the advantage of supplying very cold water to the lower cooling circuit at a time when the heat load is at its greatest and at the extremities of the system. Although the circulating pumps on 55 Level will continue to circulate the full cooling requirements, the warm water return pumps to 50 Level will only have to pump a quantity equivalent to the ice supplied.

8 DESCRIPTION OF UNDERGROUND AIR COOLER STATIONS

The ultimate requirement for underground air coolers will comprise the following:

Main underground bulk air coolers	36 MW_R
Coolers for u/g equipment	1 MW_R
Open circuit tertiary air coolers	11 MW_R
Stope air coolers (closed circuit)	25 MW_R

For the present purposes, it is considered that all air coolers, including underground bulk air coolers will be made up of cooling coil modules, although the option of spray-type for the larger bulk air coolers will be considered during the detailed engineering phase.

8.1 *Cooling coils*

The cooling coil cars will be manufactured from 3CR12 fitted with stainless steel inlet and outlet water manifolds. The coils will be to the standard Gold Fields Specifications. Axial fans will bolt directly to the cooling cars.

8.2 *Underground bulk air cooler stations*

Underground bulk air cooler stations will have capacities ranging generally from 2.0 MW_R to 3.0 MW_R and ultimately have a total rating of some 36 MW_R. All these underground bulk air coolers will be connected to closed-circuit water systems fed from underground cooling centres (i.e. underground refrigeration machines or ice melting centre). The underground bulk air coolers will be made up of multiple coil units (e.g. 6 off modules for 3 MW_R station). The modules will be installed with manifold piping and steel cowling in permanent civil structures. Arrangements will be provided for automated in-situ washing (outside of tubes) and drainage.

8.3 *Secondary and tertiary air cooling units*

Secondary and tertiary air cooling units will have capacities ranging generally from 350 kW_R to 500 kW_R and ultimately have a total rating of some 36 MW_R, of which 70%, mostly 500 kW_R units, will be connected to the closed-circuit water systems.

The other 30% will be 350 kW_R units connected to the open-circuit and located predominantly at the development ends on all levels. The open-circuit chilled water requirements are included in the mine service water (300l/s) discussed above and will be pumped by the planned pumping system.

9 DESCRIPTION OF ICE PLANT AND CONVEYING SYSTEM TO SHAFT

The preferred ice-making process, at this stage, uses plate ice-makers similar to those at ERPM No.5 ice plant. However, developments in ice-making technology will be keenly monitored ahead of the 2016 installation date. The outputs of these ice-making units range from 20 kg/s to 24 kg/s ice capacity. Therefore, including stand-by capacity, four units will be required.

9.1 *Ice-makers*

These ice-making machines form ice on the outside surface of a number of hollow plates through which refrigerant circulates. The process is cyclical and to harvest ice produced during the freeze, warm refrigerant gas is introduced to the ice-making plates. The load on the compressors is smoothed out by having multiple modules arranged either side of a screw conveyor.

For the ice-makers to operate satisfactorily they will require feed water (from the surface refrigeration plant) supplied at below 5°C. To avoid build up of salts and associated problems, the quality of the water circulated over the plates must be monitored and controlled by means of a blow-down.

The ice-making modules will be housed in a well-insulated plant room.

9.2 *Compressors and condensing plant*

The cooling effect for each ice-maker will be supplied from ammonia screw compressors drawing from a common surge drum and rejecting heat into water-cooled plate heat exchangers arranged in parallel and served by parallel cooling towers. The condenser cooling towers will be similar to those proposed for the refrigeration plant. All equipment will be selected to ensure satisfactory operation of the plant up to 21°C wet bulb and 32°C condensing.

9.3 *Surface ice conveying*

During the harvest cycle, ice falls from the ice-making plates into hoppers and shatters on impact into convenient sized pieces. The hoppers serve two purposes:

- separate water from the ice to supply dry ice to the conveying system.
- feed ice onto the double screw conveyors that will move the ice onto a trunk conveyor belt.

A central collector conveyor belt running underneath the four ice-making units and extending beyond the ice-maker building will deliver ice onto the main conveyor belt to the shaft where the ice will discharge into a funnel/chute feeding directly into the shaft columns down to the underground cooling centres. There will be no ice storage facility on surface.

It should be noted that the capacity of the ice-makers and the surface transportation system, including stand-by, will be sized in order to implement future energy management considerations for load smoothing and load shifting. These systems may involve making additional ice during low tariff periods and storing it underground in the melting dams.

9.4 *Ice columns in shafts*

Each column will be sized for the full quantity of ice which will include standby capacity to allow for future energy management considerations i.e. approximately 85 kg/s. The PVC pipes will be 400 mm diameter, one to deliver ice to the 49 Level ice melting dam and the other to the 55 Level ice melting dam. The route of the continuous pipelines will involve a short horizontal transfer section from No.9 Shaft across to No.9 Sub-vertical Shaft.

9.5 *Ice melting dams*

The underground ice melting dams will be configured horizontally with a large surface area. To ensure efficient melting and stable temperatures within the dam, return water will be distributed uniformly through a manifold. The dams will be monitored with CCTV cameras to provide feed back to surface on the ice volume and distribution in the dams.

10 PHASE-IN PHILOSOPHY

To re-cap, the main sub-systems of the overall refrigeration and cooling system are:

Surface bulk air cooler system	20 MW_R	18%
Mine water refrigeration system	28 MW_R	25%
Underground refrigeration plant	40 MW_R	36%
Surface hard-ice-makers	23 MW_R	21%

Whilst the cooling system must be designed for the full production scenario, the sequence of construction will depend on accessibility of underground locations and any special requirements during sinking and build-up phases. Interim scenarios should ensure that the cooling demands of the system components do not exceed their ultimate capacities/duties.

The phase-in of the refrigeration and cooling facilities has been planned as follows:

Phase A	2007	Surface BAC (70% capacity)
Phase B	2010	Surface BAC (30% capacity)
Phase C	2011	Mine-water (70% capacity)
		Shaft columns and energy recovery
		U/ground coolers start (15% capacity)
Phase D	2013	Mine-water (30% capacity)
		U/ground coolers next (10% capacity)
Phase E	2014	U/ground plant (100% capacity)
		Shaft columns in u/g pipe raises & levels
		U/ground coolers next (45% capacity)
Phase F	2016	Surface ice makers (70% capacity)
		Ice columns from surface
		U/ground coolers next (20% capacity)
Phase G	2019	Surface ice makers (30% capacity)
		U/ground coolers next (10% capacity)

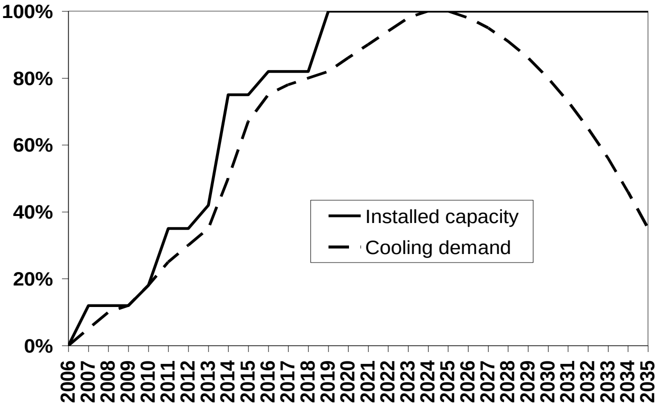

Figure 4. Phase-in of cooling requirements

The predicted life-of-mine profile of the cooling loads and refrigeration requirements is given in Figure 4.

11 DESCRIPTION OF VENTILATION FOR SINKING AND EARLY DEVELOPMENT.

No.9 Sub-vertical Shaft is currently sunk to 43 Level and equipped down to 42 Level. The ultimate depth of the shaft will be ± 3 900 m, requiring that through ventilation and cooling during shaft sinking (and station development) operations be carried as far as possible. For the early sinking period this will be 40 Level but the sinking fans will stay on 23 Level due to space limitations.

The shaft bottom will be force ventilated and a four-gate system will be fitted to the sinking fans to avoid exposing the sinking crew to blasting fumes while travelling in the shaft. The installation will include a diesel-powered emergency fan ($20m^3/s$).

Space constraints in the equipped portion of the shaft limit the ventilation columns to 2 x 1 000 mm diameter and the quantity of air delivered to shaft bottom will eventually reduce to 35 m^3/s. This will place a greater reliance on cooling provisions and the sinking fans will be fitted with 500 kW_R cooling cars using chilled water from surface.

Mid-way cooling (3 000 kW_R on 23 Level) will be required for station development in the sinking phase and surface bulk air cooling (10 000 kW_R) will be required by the time the shaft reaches a depth of ± 3 300m (50 Level). To create through ventilation, the first upcast ventilation hole (3.8 m dia.) must be drilled in parallel with the shaft sinking.

Surface bulk air cooler	**10 MW_R**
Sinking coolers	1 MW_R
Mid-way cooler	3 MW_R
Cooler for winders	0.5 MW_R
Cooler for development on 50 Level	0.5 MW_R
Underground cooling required	**5 MW_R**
Distribution losses (15%)	0.75 MW_R
Service water cooling	0.75 MW_R
Initial surface refrigeration	**6.5 MW_R**

11.1 *Programme of work for ventilation and cooling of sinking operations*

Before sinking can commence the ventilation shaft will be capped and sealed in order to create a complete upcast system. The surface fan will be recommissioned. A new diesel-powered emergency fan will be installed in the drift.

The first phase of the surface refrigeration plant will be required immediately to provide chilled water for underground coolers and service water.

The first phase of the Surface BAC will also be required for the shaft sinking phase. At least 40-50% of the BAC duty will be required when the shaft sinking passes 50 Level. The Surface BAC was not part of the original planning and will require cutting a new sub-bank airway into the shaft.

The various underground coolers will be assembled from coil-type cooling cars supplied with chilled water from surface.

12 CONCLUSION

The capital expenditure for the refrigeration and cooling systems for this project is estimated at R550m.over the next twelve years.

Shaft sinking phase	6 000
Surface Bulk Air Cooler System	75 000
Surface Mine Water Refrigeration System (including ice plant feed)	80 000
Underground Refrigeration System(s)	140 000
Underground BACs and tertiarycoolers	60 000
Ice plant and ice conveying to shaft	180 000
Ice conveying in shaft to u/ground dams	15 000

This project has been approved by the Gold Fields Board and preparation for sinking and initial infrastructure is underway.

The planning, scheduling and implementation of the designed strategy is the key to the success of such a project. In this case-study many of the design risks have been identified. At depth, cooling and ventilation are major cost items and the successful and efficient operation of these cooling installations is of the utmost importance. The capital expenditure on refrigeration and cooling is about 46% of the total cost of the project.

As the project develops, continuous reviews of the original design will be done and changes made as and when required. This is the major challenge facing any ventilation engineer as the planned environment changes continuously.

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