

Modern cooling strategies for ultra-deep hydropower mines*

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Abstract

The increasing mining depths of South African gold mine deposits are resulting in ever-increasing heat loads associated with depth and the geothermal gradient. Together with changes in the mining horizons brought about by the depletion of older, shallower, high-grade reserves, this leads to the need for the continuous review and redesign of cooling requirements. Traditionally, cooling requirements were met by using a combination of cooling strategies, including bulk air cooling on surface and underground. If this proved to be insufficient, chilled service water and secondary remote air-cooling systems were introduced.

This paper reviews these practices in order to provide a cost-effective means of catering for the introduction of hydropower at the Gold Fields Ltd South African operations. Some of the equipment that has been developed to meet the requirements of both hydropower and refrigeration includes hydropower fans, cooling coils and in-stope venturis. These are individually described and discussed, together with their roles within the greater strategy.

The planned change in the cooling strategy and the employment of these technologies have effectively doubled the cooling available, from 10 MW to more than 20 MW, extracted from the hydropower water used to drive the mining equipment. In conclusion, the cooling strategy described allows a total heat load of approximately 52 MW to be successfully ventilated and cooled through the use of combined surface and underground refrigeration installations, and through the use of hydropower-chilled water.

Introduction

Traditionally, cooling requirements have been met by using a combination of cooling strategies, including chilled

service water. The use of hydropower as an energy source has resulted in the use of traditional cooling equipment, suited for lower water-pressure ranges and associated with the use of chilled service water, being limited.

The correct design will provide an underground working environment that is safe and that lends itself to a high level of work performance. This is particularly important for deep mines where the prevailing temperatures in the workings are not conducive to good work performance.

In this paper the use of a combination of cooling strategies, employing new technologies that utilise hydropower as effectively as traditional cooling equipment utilising chilled service water, is discussed. This strategy, combined with a re-examination of the cyclical nature of mining and of mine cooling associated with the use of chilled water, has resulted in the design presented here.

Reasons for using hydropower

Thompson and Carpentier Alting (1995) list some of the commonly claimed advantages of using hydropower instead of compressed air as follows:

- Hydropower equipment is considerably less noisy than pneumatics - and the noise generated is of a higher frequency - more easily dampened by earplugs or other forms of protection.
- Drills operate at a rate much faster than pneumatics, thereby increasing productivity.
- No oil is used, improving the working atmosphere and reducing worker exposure to oil mist.
- Cold hydropower water creates a microclimate that assists in workplace cooling.
- The use of drill rigs allows for more accurate drilling, less explosives-induced damage, fewer falls of ground and less scaling.
- Rigs are operated by one man, who is removed from the face (where most falls of ground [FOG] occur) and from the rock drill itself (avoiding noise and vibration-induced illnesses). The workload of the operator is lower and thus he suffers less fatigue.
- The water-powered loader is quiet and more productive than its compressed air counterpart.
- Water energy is virtually free as it is provided via potential energy gains.

In a subsequent study conducted by Fibiger (2004), he concluded that that, potentially, hydropower could impact positively on safety, productivity and energy costs.

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GFL cooling strategy

The selected cooling and refrigeration strategy is based on the provision of surface bulk air coolers (BACs) to reduce the overall in-mine cooling requirement by reducing the impact of auto compression. These BACs are designed to provide a mixed air temperature of 10°C immediately below the shaft collar. The service water must be supplied to the workings at a temperature of approximately 12°C and should provide a temperature differential of 15°C in the water at a maximum usage of 2 metric tons of water per metric ton of rock mined.

If the surface BAC and the chilled service water do not fulfil the design conditions, the additional air cooling required will be provided by first strategically placing major underground BACs, with a tertiary air-cooling system using closed-loop cooling coils reticulated through effectively insulated piping. This cooling will generally be provided from an underground refrigeration plant installed in such a position as to optimise the heat-rejection capacity of the return air.

All water fed from surface will be utilised in three-chamber pipe-feeder systems where the water quality is acceptable, or in energy-recovery turbines where the water quality could be problematic.

The use of chilled-water distribution systems from surface will be acceptable to a depth of 3300 m. Where mining operations take place below such a depth, ice could be considered as a cooling medium since 1 kg/s of ice can provide the same cooling as 10 l/s of chilled water.

Planning design parameters

The planning design parameters used by Gold Fields to draw up design conditions for the underground environment are as follows:

- The design reject wet-bulb temperature for stopes and development is 27.5°C, equivalent to a specific cooling power (Stewart, 1982) of 300 W/m² at a minimum velocity of 0.5 m/s.
- The design maximum wet-bulb temperature for achieving a similar specific cooling power at a minimum velocity at 1 m/s in all other areas is 28.5°C.
- Air quantities are to be selected to ensure that minimum air velocities can be met in all stopes and other areas.
- The development air quantities must be set at a minimum of 0.3 m³/s per m² of face.
- In-stope air utilisation must achieve 80 per cent, with 20 per cent allowed for the ventilation of centre and strike gullies.

Case study of Kloof No. 4 Shaft

Kloof Gold Mine is situated some 70 km west of Johannesburg near Carletonville in the Gauteng Province of South Africa. The site is accessed via the N12 freeway between Johannesburg and Kimberley. Geologically, it is located in the West Wits region of the Witwatersrand Basin.

Kloof No. 4 shaft is a deep-level gold mine that is accessed from surface through a combination of vertical shaft systems to some 3287 m below surface. A geographical layout of the mine is shown in Figure 1.



Figure 1: Geographical layout of Kloof No. 4 shaft

The mining layout at Kloof is based on breast stopping with closely spaced dip pillars. The mining layout is shown in Figure 2.

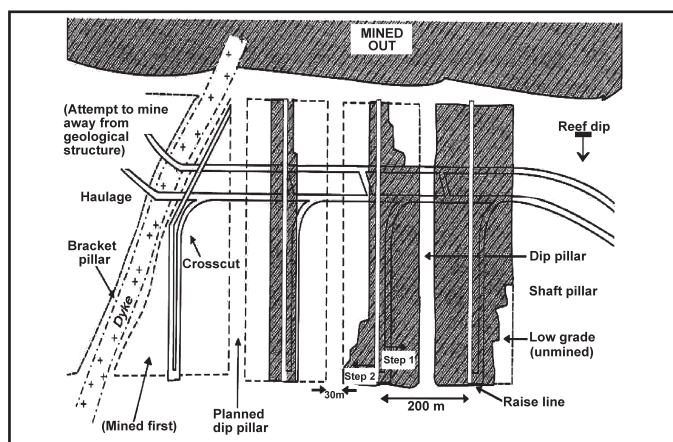


Figure 2: Mining layout at Kloof Mine

Heat load estimates for the Kloof No. 4 shaft operations were determined using the following parameters:

- A virgin rock temperature gradient of 15°C + 12.2°C per km of depth
- A heat load of 303 kW per thousand metric tons per month (Burrows et al., 1982, Figure 38.5, p 959)
- A base heat load from the air of 10 200 kW at 17 kJ/kg (Burrows et al., 1982, Figure 38.2, p 956)
- An artificial heat load from other sources of 4700 kW for 125 000 metric tons per month
- An air utilisation of 3.5 m³/s per thousand metric tons of rock broken, to remove pollutants and to transport cooling through the workings
- A closely spaced dip pillar mining layout, with breast panels being mined
- No backfill to be used.

From these parameters, the heat loads were calculated and can be summarised as follows:

Base heat load	37 875 kW
Artificial heat	4700 kW
Heat from auto compression	10 200 kW
Total estimated heat load	52 775 kW

EXISTING INFRASTRUCTURE AT NO. 4 SHAFT

Ventilation

The design capacity of the existing ventilation infrastructure of the upcast and downcast shafts is shown below.

Downcast facilities

No. 4 Shaft	8.7 m dia.
Air capacity	600 m ³ /s @ 10.2 m/s
No. 4 Sub-vertical shaft	7.9 m dia.
Air capacity	600 m ³ /s @ 12.2 m/s

Upcast facilities

No. 4 Ventilation shaft	7.3 m dia.
Air capacity	668 m ³ /s @ 16 m/s
No. 4 Sub-ventilation shaft	2 x 4.4 m dia.
Air capacity	660 m ³ /s @ 22 m/s

Main fans

Three Airtec Davidson SI W6 centrifugal fans are situated at the top of No. 4 ventilation shaft. Two fans are operating at 210 m³/s each at 6.8 kPa. These fans are installed in a parallel arrangement for operation. The nominal rating per fan unit is 210 m³/s at 7 kPa, requiring electrical input power of 2550 kW. Currently, the operating condition with two fans being utilised is 230 m³/s at 6.5 kPa per fan, giving a total of 460 m³/s at a density of 1.2 kg/m³. When the third fan comes into operation, the available circulating air will increase to 600 kg/s for mining and cooling purposes. The maximum available pressure is 9.0 kPa and at this pressure, each fan would course 140 m³/s through the shaft at 0.96 kg/m³ density.

Refrigeration plants

Refrigeration plants with a total capacity of 40 000 kW (nominal rating) are installed on surface. The system supplying hydropower water as service water is arranged to supercool 320 l/s from 18°C to 1.0°C. It consists of three 5300 kW York R134A machines, of 15 000 kW, and 10 000 kW ammonia plants. In addition, a further 15 000 kW (nominal rating) ammonia refrigeration plants are installed to provide 510 l/s of chilled water to feed the surface BAC described later in the paper.

There are two 5200 kW York refrigeration plants installed on 39 level which are used in a closed-loop chilled water reticulation system. There are plans to install an extra 12 000 kW of refrigeration plants (two nominally rated 6000 Kart York 134 A shell-and-tube machines) on 39 level, which will be included in the closed-loop cooling system arrangement. The total planned installed refrigeration capacity is therefore 62 000 kW.

COOLING DISTRIBUTION

Cooling from hydropower circuit

Hydropower was conceived as a means of providing energy for driving equipment in the workings efficiently, while at the same time introducing additional cooling. An important feature of chilled hydropower water is that it can provide more cooling power than hydraulic power, so that there is a net cooling benefit.

Hydropower cooling circuit

The distribution of the water is achieved as follows. The water is pumped from underground, filtered, then pumped through the pre-cooling towers (PCT) where it is cooled to 18 °C by the natural environment. The water (320 l/s) is then passed through refrigeration plants with a duty of 15 000 kW, cooling the water to 8°C. Thereafter the water is pumped into a dam kept at 8°C. From this dam, the water is then supercooled to 1.0°C by passing it through ammonia refrigeration plants with a duty of 10 000 kW.

The hydropower refrigeration network on surface is shown in Figure 3.

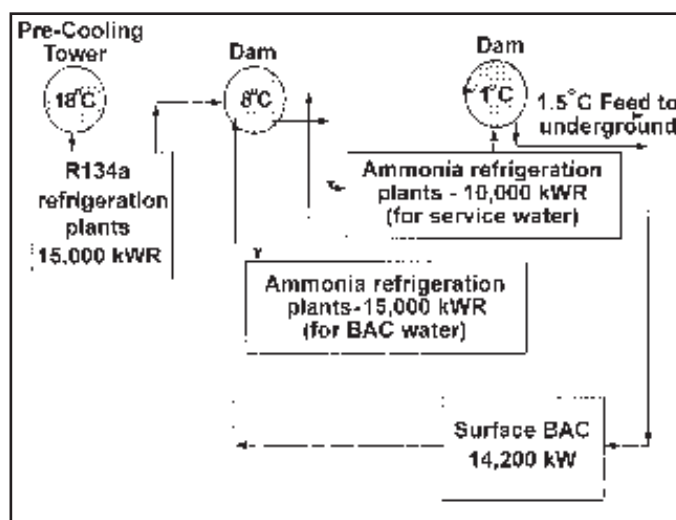


Figure 3: Distribution layout of the No. 4 shaft surface-chilled water

Underground distribution

Some 100 l/s of this hydropower water is used directly for air-cooling through the use of high-pressure closed-loop BACs designed to operate at normal hydropower pressure. These installations are on 41, 43 and 45 levels (which are the major production levels); an average water flow rate of 33 l/s results in a duty of 2000 kW per installation. The distribution of the water downstream of these BACs is as follows:

- 36 l/s to supply 24 venturis with water, providing additional face cooling in the wide raises
- 64 l/s which passes through hydropower rated spot-cooling units arranged in a closed-loop manner, coupled to the hydropower fans used to ventilate development ends.

The underground hydropower water distribution up to the individual levels is shown in Figure 4.

Using this design philosophy also helps to create a system that ensures the continuous flow of water through the pipes, assisting in creating a continuously cool work environment. The remaining 220 l/s is used directly as mine service water. The combined cooling effect of the 320 l/s is 21 000 kW, achieving an effective temperature difference of 15.7°C. This takes into account the 0.5°C loss in the surface dam and the 8.2°C loss down the shaft as a result of potential energy loss. The installation of the hydropower BACs, hydropower spot coolers, and hydropower fans and venturis assists in the more effective cooling of the air. Modular BACs utilising coil technology have the advantage over conventional spray-type coolers in that they can be installed in a

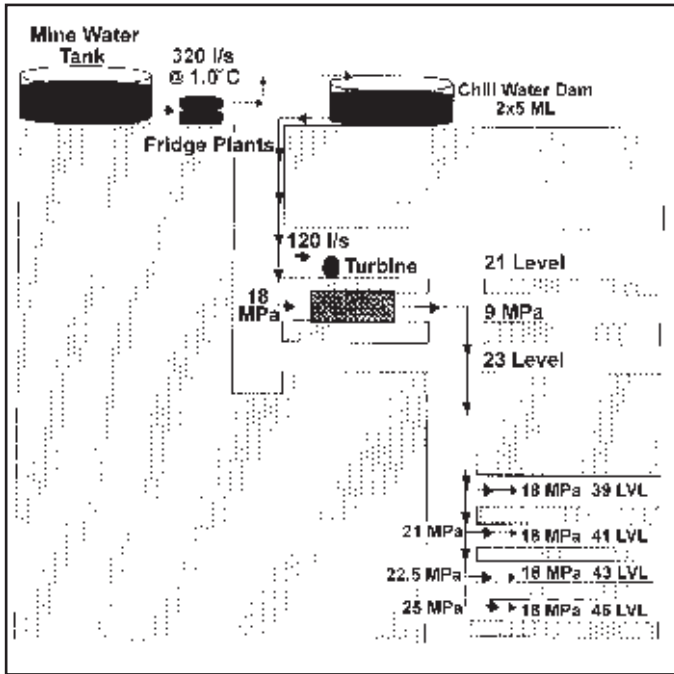


Figure 4: Hydropower water distribution layout

closed-loop system or chilled water can be redirected, after passing through the coolers, to be reused for production purposes without the need for additional pumping. The modular system allows for various duties, ranging from 1.0 MW to 10 MW installations. Below are some photographs (Figures 5, 6 and 7) showing the installation at Kloof No. 4 shaft, including the fans and self-closing doors. The bottom photo in Figure 5 shows the installation of the cooling coils, manifolds and self-cleaning systems. The coils are installed at an incline from roof to floor, with access provided in the centre.

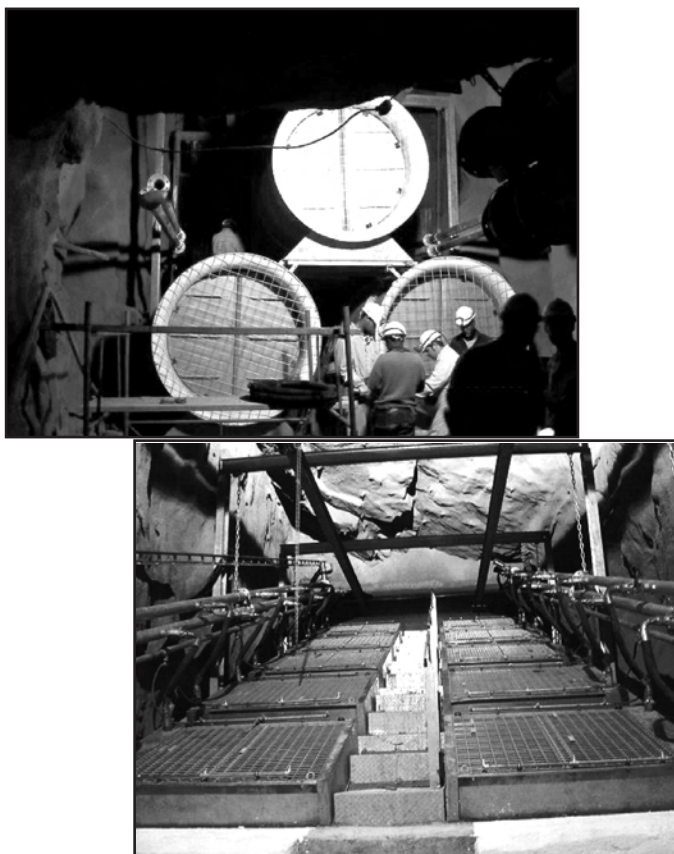


Figure 5: Hydropower BAC

The duties of the hydropower spot coolers are dependent on the intake water and air conditions, as well as on the amount of air and water available. The units used vary from 100 kW to 500 kW, with operating pressures of up to 19 MPa. An example of such a cooling coil unit is shown in Figure 6.

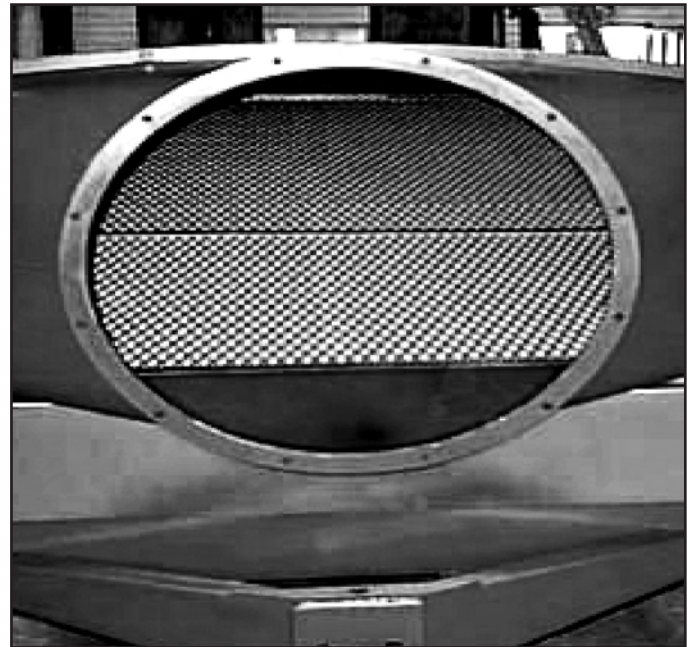


Figure 6: Hydropower spot cooler

The fan fits into a standard duct and has both fixed and rotating blades. A high-velocity jet of water drives an impulse turbine attached to the back of the rotating blades. The water discharging from the turbine mixes with the air, cools the air and is then collected in a special duct with a water-collection groove several metres downstream. The technical specifications for the hydropower fan are shown in Table 1.

Table 1: Technical specifications of the hydropower fans

	22 kW	15 kW
Nominal duct size	762 mm	570 mm
Air flow (1.2 kg/m ³)	8 m ³ /s @ 1700 Pa	5 m ³ /s @ 1400 Pa
	11 m ³ /s @ 0 Pa	7 m ³ /s @ 0 Pa
Water consumption	2.2 l/s @ 16 MPa	1.7 l/s @ 16 MPa
Cooling effect	50 - 100 kW	30 - 70 kW

In the venturi air coolers (see Figure 8 below) high-pressure water is exhausted through an energy dissipater and nozzle assembly, creating a venturi effect, which entrains air into a ventilation column. These are normally used in the stope face where water pressure of approximately 18 MPa is available. At the maximum water flow rate of 0.5 l/s, the venturi arrangement will entrain approximately 3 m³/s of air. The unit also provides a secondary cooling effect which is dependent on the temperatures of the intake water and air.

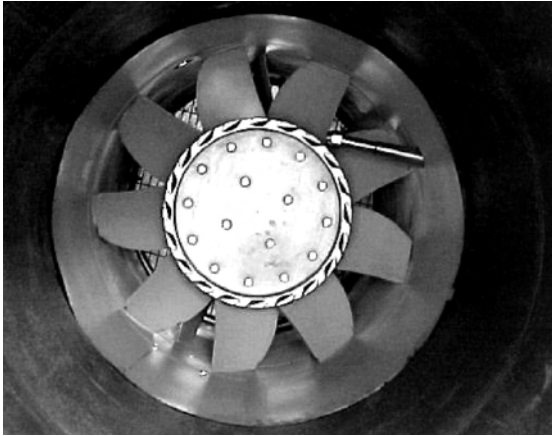


Figure 7. Hydropowered ventilation fan.



Figure 8: A hydropower venturi air cooler

Retrofitted surface Bulk Air Cooler (BAC)

Refrigeration plants giving a total of 15 000 kW (nominal rating) have been installed to provide a surface BAC with a water supply of 510 l/s and a design duty of 14 200 kW. The surface BAC ensures that intake conditions into the different stations meet acceptable standards. The design specifications for this installation are shown in Table 2.

Table 2: Surface BAC design specifications

Description	Specification
Duty	14 200 kW
Water flow	510 l/s
Water inlet temperature	1.5°C
Water outlet temperature	8.2°C
Airflow	450 kg/s
Air inlet temperature	18/28°C
Air outlet temperature	7/7°C
Barometric pressure	84 kPa
Factor of merit	0.51
Fill type	Splash fill

This water supply system is interlinked with the other dams on surface (see Figure 3). The use of the same dams will provide flexibility for maintenance on the plants during the winter months when ambient conditions will allow the surface BAC to be stopped. Both the ammonia plant installations feed into the insulated surface dam at 1.0 °C. This dam feeds both the surface BAC and the underground chilled service water system. A photograph of the installation during construction is shown in Figure 9.

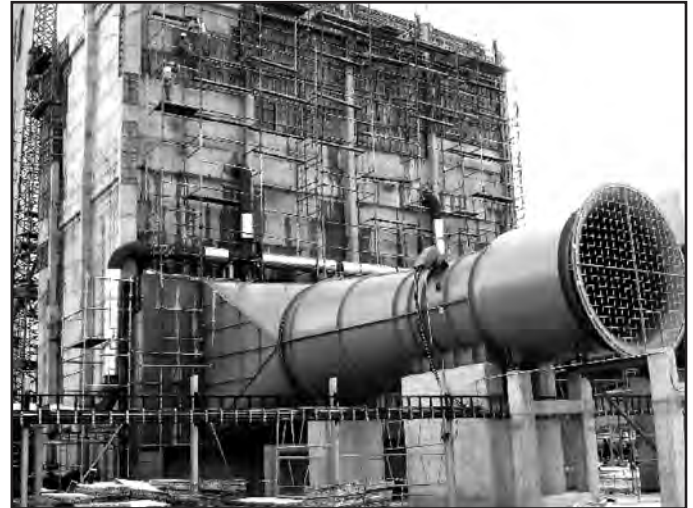


Figure 9: The surface BAC during construction

Underground refrigeration plant and closed-loop circuit

The maximum underground refrigeration capacity is based on the available air heat-rejection capacity of 45 kW/kg. This allows for 27 500 kW of condensing heat rejection and 22 000 kW of evaporator duty.

A 10 000 kW conventional underground refrigeration plant is installed on 39 level. This plant feeds the insulated closed-loop piping system that is used directly for cooling the air through cooling coils positioned in the mining sections, providing effective cooling of 9000 kW. The mine is in the process of installing a further two 6000 kW machines which will increase the underground capacity by between 12 000 kW and 22 000 kW. This will result in effective cooling of 20 000 kW from underground refrigeration installations.

These installations will provide chilled water for a series of 2000 kW BACs to be installed just before the stope horizons and for the additional installation of 400 kW spot coolers at the start of development end-sections using a water flow of 16.5 l/s. All of this cooling will be distributed in an insulated closed-loop configuration. A schematic diagram of the distribution is shown in Figure 10.

EFFECTIVE COOLING

The effective cooling power of the refrigeration that is installed is determined by calculating the amount of heat that the water will take out of the mine airflow. The chilled water that comes from the surface plants loses 8.2°C of its cooling power though the loss of potential energy. The use of hydropower prevents the need to install energy-recovery systems.

Another factor that has an influence on the effectiveness

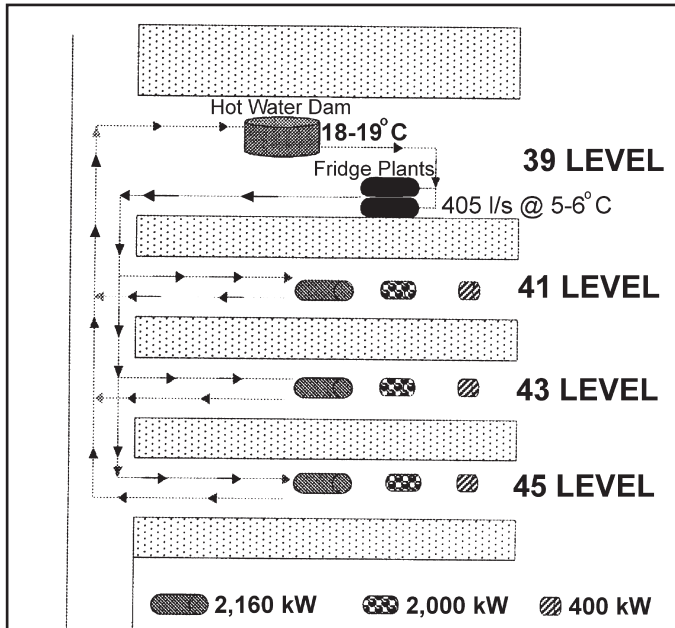


Figure 10: Underground closed-loop reticulation

of the cooling provided by chilled water is what the water is used for. For example, if the chilled water is used only as service chilled water for production purposes, then the water that reaches the working place and has direct contact with the hot rock will be very cold, drawing more heat from the rock and limiting the cooling of the ventilating air. Another aspect is that the amount of water that is used is dependent on the equipment and production needs; this amount is therefore cyclical in nature, again influencing the effectiveness of the cooling available. A summary of this is shown in Table 3.

Table 3: Effectiveness of cooling

Source of cooling	Planned effective temperature difference(°C)	Cooling effect(kW)
Surface refrigeration plants	15.7°C	21 000
39 level refrigeration plants	12.6°C	20 000
Surface BAC		11 600

The effectiveness of the cooling provided from surface has been ensured by installing the hydropower BACs, and the hydropower fans and coolers, as well as through the use of more production water. The increase in the cooling effect from the 39 level plants will be passed on as more pipes and coolers are installed, thus allowing more water to be used more effectively .

CONCLUSIONS

The ever-increasing depth of South African gold mining operations has necessitated a reappraisal of the use of resources available for cooling the working environment. The use of hydropower has also placed additional restrictions on the use of conventional equipment. This has been

overcome by redesigning the hydropower water reticulation system and through the subsequent development of equipment that can be used in the higher water pressure regime.

The planned change in the cooling strategy and the employment of these technologies have effectively doubled the cooling available, from 10 MW to more than 20 MW, extracted from the hydropower water used to drive the mining equipment. In conclusion, the cooling strategy described allows a total heat load of approximately 52 MW to be successfully ventilated and cooled through the use of combined surface and underground refrigeration installations and through the use of hydropower-chilled water.

By means of this approach, effective cooling of an ultra-deep mine has been achieved.

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