Controlled Recirculation and Refrigeration at Vale's Taquari Potash Mine

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ABSTRACT

Taquari Vasouras potash mine (Vale Fertilizantes) has many interesting features including virgin rock temperatures of 50°C at depths of 700 m. The mine has a relatively small shaft system with limited ventilation carrying capacity, which was not adequate to exploit the full extent of the deposit. This limitation was overcome by installing two large-scale recirculation systems with underground reconditioning centres. This paper describes this unique mine ventilation and cooling system and some of its history over the past two decades. The two controlled recirculation systems have been operating safely for some ten years and the use of large-scale recirculation has been a fundamental component in the increase of production and extending the mining further-and-further from the shaft centre. The recirculation systems have played a huge role in the mine profitability and comprehensively extending the mine life. The paper also discusses a number of novel design and operating features such as reverse running pumps for energy recovery. The underground chilled water system design required a number of special safety features in order to minimise the risk of water leakage since this could be catastrophic in a potash mine. This paper describes a good example of a mine in which the final ventilation and cooling system design ends up very different to what was envisaged at the greenfields stage.

INTRODUCTION

Vale's Taquari Vasouras potash mine (Vale Fertilizantes) is located in Brazil in the northeast state of Sergipe, about 40 km from the city of Aracaju and 20 km from the coast on the latitude of about 10° south (Figure 1).

The mine, which is the sole producer of potash in Brazil, was started in 1979 by Petrobras but was taken over by Vale (then CVRD) in 1992. From then to the present, the mine has increased production and extended workings further and further away from the central shaft area. For example, the run-of-mine production increased from 0.9 Mt/a in 1993 to 2.8 Mt/a in 2006 and the workings have moved from within 2 km radius of the central shaft area to 5 km and beyond.

The geology consists of halite, sylvanite, carnallite and tachydrite overlaid by sandstone and limestone. The mining method is that of room-and-pillar using continuous miners, such as the Marietta 900 for production and Alpine road headers for development. The ore is transported by shuttle cars to feeder-breakers for primary crushing and then through a system of conveyor belts, in the return airway system, to the hoisting shaft. There is very limited use of diesel equipment and there are very few occasions when drill-and-blasting is required.

The underground working depths vary from 450 - 700 m and there are about 300 km of open galleries. The virgin rock temperatures reach 50°C and the surface design temperature conditions are generally 23°Cwb and higher.

The orebody is overlaid by an aquifer at a depth of about 375 m that comprises pockets of water within layers of sandstone over a vertical distance of about 50 m. This aquifer presents a huge problem for sinking new shafts or possibly using boreholes (for coolants) both of which would have relieved the ventilation and cooling problem. Indeed, the original shaft sink(s) were carried out with difficulty using ice to seal the water until concrete lining could be installed.

Figure 2 shows a typical working section; each production panel is served by:

- Marietta 900 continuous miner (rated 800 kW)
- Joy 15 ton shuttle car pairs (rated 2 × 110 kW)
- feeder breaker and conveyor belt section (rated 150 kW).

The production rates of each panel depend on the dip (which can vary up to 25°) and other local conditions. In favourable conditions, the typical rate will be about 2500 t/d per panel. The production galleries are mined with face headings of 55 m^2 and general face advances vary up to about 20 m/d.

The ventilation and cooling systems include a number of unique features, the most significant of which are two large underground recirculation systems. The first recirculation system was started in 2003 and the second in 2005 and have

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FIG 1 - Location.

operated safely and effectively for ten years and eight years respectively (excluding maintenance periods).

VENTILATION LIMITATION DUE TO SHAFT CAPACITIES

The mine has a single downcast shaft and single upcast shaft each of five metre diameter. Both shafts are equipped: the downcast with men and material conveyances and the upcast for rock hoisting. The primary ventilation capacity from surface is severely limited by this shaft sizing and maximum air speeds related to skip vibration and conveyance aerodynamic effects.

The limit is 300 kg/s (250 m^3/s, 13 m/s) and there is no potential of increasing this significantly.

Indeed this shaft-system limitation meant that the distance of mining from the shaft was also limited and hence there was the perception of a limited resource, even though the deposit was much larger. This constraint has been overcome by the large-scale underground controlled recirculation schemes as described later.

TEMPERATURE DESIGN CRITERIA

Virgin rock temperatures

The depth of the mine varies from 450 - 700 m with the deeper section to the north and the virgin rock temperature varies from 40 - 50°C (see Figure 3).

The orebody and immediate surrounding strata comprise halite and silvanite with general geothermal properties as follows:

- thermal conductivity 4.4 W/m°C
- specific heat 1230 J/kg°C
- density 2150 kg/m^3
- thermal diffusivity 1.7 × 10^{-6} m^2/s.

The overlaying rock strata are of sandstone and limestone with general geothermal properties as follows:

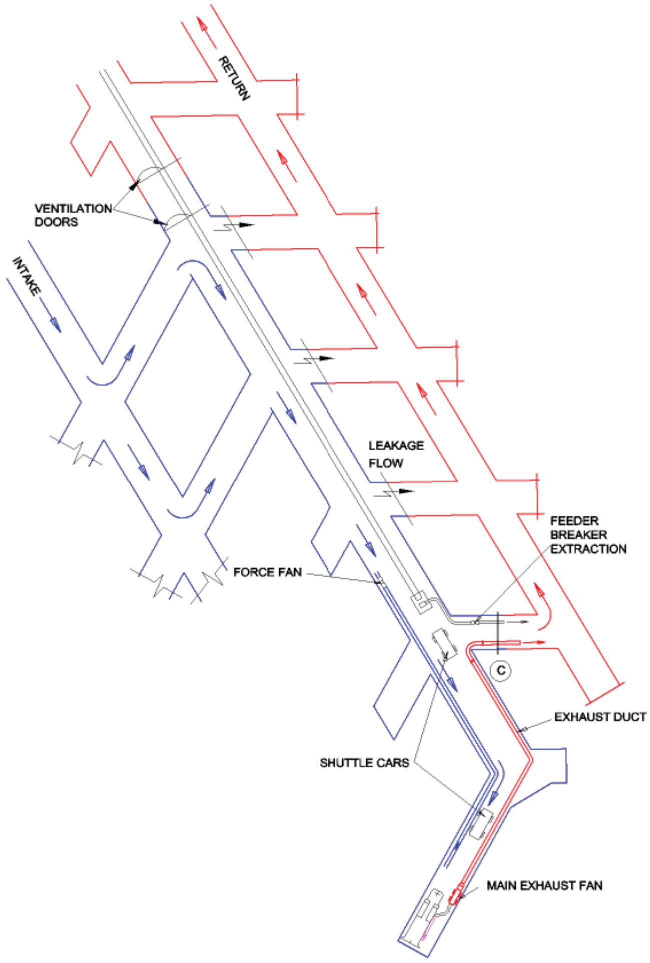

FIG 2 - Typical working section.

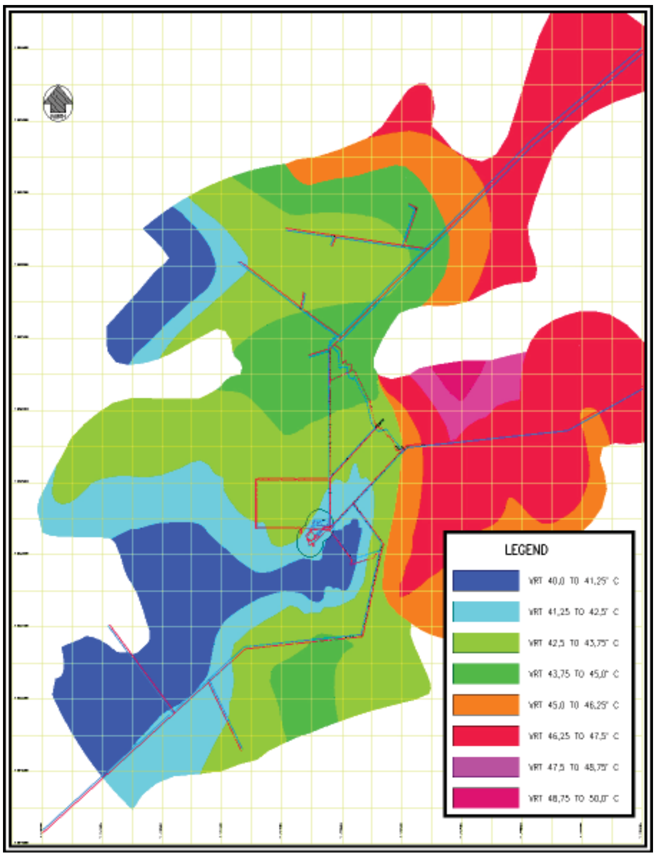

FIG 3 - Virgin rock temperatures.

- thermal conductivity 2.0 W/m°C
- specific heat 800 J/kg°C
- density 2300 kg/m^3
- thermal diffusivity 1.1 × 10^{-6} m^2/s.

Design surface temperature conditions

The surface process design temperature condition is generally 23°Cwb and this does not vary significantly from season to season. However, it does get higher during certain periods and some of the equipment selection was based on 24.5°Cwb.

Design underground temperature conditions

The mine has a very high regard for health and safety and there has been extensive debate regarding design temperature conditions with respect to both international and Brazilian standards. The various cooling power models (for example McPherson, 2009) were examined but, for on-the-job heat stress management, it was important to have a simple means of measuring the in-panel situations. The Brazilian law quoted WBGT concepts and, along these lines, the mine adopted the 'Effective Temperature' approach as defined by:

$$T_{eff} = 0.7 \times Twb + 0.3 \times Tdb - V\ (m/s)$$

The maximum T_{eff} was set at 30°C and an air speed of 0.3 m/s was adopted for global design purposes. For example, 26/42°Cwb/db and 0.3 m/s gives T_{eff} = 30°C. Note the underground climatic conditions are generally relatively dry in this (and most) potash mines.

ORIGINAL VENTILATION AND COOLING SYSTEM

The primary ventilation system is based on two main axial flow fans situated at the bottom of the downcast shaft forcing air through the mine.

The original refrigeration system included spot refrigeration plants (350 kW rated) situated in each of the production and development sections. This approach had numerous inefficiencies and constraints. The most important were that the refrigeration machines could not achieve adequate capacity because of high condensing conditions and that a significant fraction of intake air was 'stolen' to cool the refrigerant condensers. The spot plants were producing duties <200 kW (<60 per cent of rated) but the simulations and measurements at the time showed that, if the spot plant concept was to be used, much larger (+300 per cent) capacity spot plants would be needed in each panel. The forced fan operation with the spot plant air cooling coils created a heat gain about 25 per cent of the plant rated duty. In addition, the leakage of chilled air from the duct (up to 50 per cent) limited the effectiveness even further. The operation of these types of spot plants underground is inevitably inefficient because of high condensing temperatures, fouling of cooling coils and condensers, leakage of gas, etc. Furthermore, maintenance was difficult and costly and the plants had to be moved and re-established at least once a year.

It is interesting to note that in the 1950s spot refrigeration plants were relatively widely used in South African gold mines. However, for most of the reasons described above, they were all replaced by centralised refrigeration plant. Now there are very few spot refrigeration plants in South African mines in normal underground operations (although some have been used in shaft sinking and development operations).

In the 1990s, the concept of spot refrigeration plant had already been extended to its absolute limits at Taquari. Indeed, it had become a very good example of the misuse and in-effectiveness of the spot refrigeration plant concept (that is similarly abused and misused on many mines to this day).

Further increases in spot refrigeration plant duty were strongly advised against. Heat loads in the production panels would increase significantly as the production increased and the operations moved to deeper, hotter rock. Instead, it was recommended that centralised bulk air coolers should be used and that these air coolers should be served from a central surface refrigeration plant system (costs of spot plant systems were 250 per cent higher than central plant, per kilowatt cooling). There would be three bulk air coolers: one on surface chilling downcast air; one in an underground central location chilling recirculated air and one at a distant north location chilling recirculated air. The controlled recirculation underground of the ventilation (and its reconditioning) was the fundamental feature of this system.

CONTROLLED RECIRCULATION OF VENTILATION

The use of controlled recirculation in mines is not new. As mining takes place at greater distances from original intake shafts, the supply of primary ventilation becomes more difficult and more costly. In hot mines the cooling (and re-cooling) of intake air is expensive and supplying more air from surface directly influences shaft sizes and fan power requirements. The alternative is to increase the airflow in the workings by using controlled recirculation and this approach is an important part of this cooling system design. It is this feature and the application of refrigeration that has allowed mining beyond the originally perceived limited distances from the central shaft location.

Interest in recirculation in British coal mines (Robinson and Harrison, 1987; Pickering and Robinson, 1984) was motivated by the need to control gases, dust and heat. Early use of recirculation was aimed at increasing air cooling power at hot faces by increasing air velocities. It was also shown that recirculation reduced the risk of methane ignitions by better mixing and dispersal of methane layers. Later investigations were conducted into the use of recirculation and filtration for the control of dust levels.

In South Africa, there was extensive work carried out (Burton *et al*, 1984; Burton, 1988; Rose and Burton, 1992) on combining controlled recirculation with refrigeration and dust scrubbing to achieve improved temperatures and dust control. It was shown that, by supplying a minimum quantity of fresh air and using recirculation to increase the airflow to control temperatures and dust levels, the main fan power and shaft-airway infrastructure requirements can be minimised. The studies and the systems that were implemented showed that recirculation does not increase return air gas concentrations. Obviously all controlled recirculation schemes must have automatic safety systems that stop recirculation when a hazardous situation arises. Monitoring systems are required to detect products of combustion and shut off the recirculation so that the ventilation becomes a conventional once-through system. There have been a number of large-scale controlled recirculation schemes applied in mines in South Africa. In the recirculation systems, the returning air from the sections is reconditioned in underground spray chambers where it is cooled and cleaned. The air is then reintroduced into the intake system. The recirculation system designs need to satisfy general health and safety practices including heat, dust and gas dilution. It is important that recirculation zones receive the correct portion of air for dilution of contaminants at the point of use.

Taquari potash mine was a good candidate for large-scale controlled recirculation. The mine had a critical (and classical) shortage of primary ventilation capacity from surface due to limited shaft capacity, but furthermore the mine does not:

- experience any flammable gas
- use a large fleet of diesel equipment
- use large-scale drill and blasting operations
- experience quartzite, silica and derivatives in dust particles
- experience radon and derivatives.

As will be seen for Taquari, the primary ventilation system includes two recirculation systems allowing an overall ventilation duty of 560 kg/s, which is 87 per cent more than the limited downcast duty of 300 kg/s.

Note also that the first recirculation takes place near the base of the shafts (central system) and that the second recirculation (north system) is actually a 'recirculation-within-recirculation' system. The first recirculation system was started in 2003, the second in 2005 and both have operated safely ever since.

VUMA HEAT LOAD AND NETWORK ANALYSES

The specialised VUMA network software was used to model the various mine layouts and to simulate the different ventilation, recirculation and refrigeration strategies. The simulation is based on building up the layout as a network of heat sources and sinks such as tunnels, shafts, production sections, fans (recirculation and other) and air coolers (Figure 4). Within each building block, the heat flow from all sources is used to calculate the outlet air condition, which in turn, is the inlet condition to the next building block. Thus the interactions of all the components are examined. The simulation uses an iterative process to determine heat loads and cooling needs as well as the sizing and positioning of the air coolers and the refrigeration system components. The simulations take full account of the recirculation details. This software is unique in that it deals with the fundamentally important effects of broken rock and advancing rock faces. The variation of air density and barometric pressure with depth is also accurately examined.

These simulations acknowledged the unique set of circumstances prevailing at Taquari and, where necessary, special models were developed for these production sections. For example, the power absorbed by the continuous miner was measured at Taquari during a working shift and the work cycle is shown in Figure 5. The cycle takes less than ten minutes and the average absorbed power will provide a heat load – this was measured as 69 per cent of the total machine rating. This energy manifests itself as heat in broken rock and in ventilation air. Initially a portion of this energy goes to heating the broken rock; however, heat transfer then takes place between the broken rock and the ventilation air. Indeed, hand-held measurements at Taquari indicated that the broken rock had retained heat equivalent to 6°C and left the production zone at a higher temperature than the VRT (and thus served to remove some heat from the immediate workings).

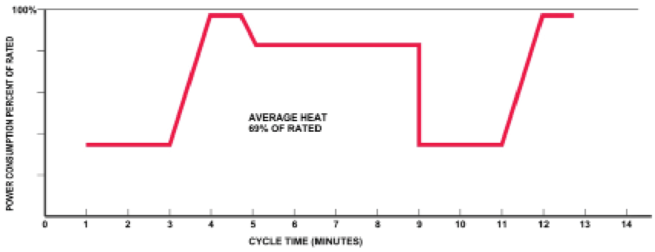

FIG 5 - Continuous miner work cycle.

Thus, the analysis takes account of the following (amongst other issues):

- effects of power utilisation of continuous miners including heat load to muck
- heat load effect of broken rock and advancing faces
- age and shape of excavations, production rate
- massive rock heat diffusion in shafts, airways and production zones

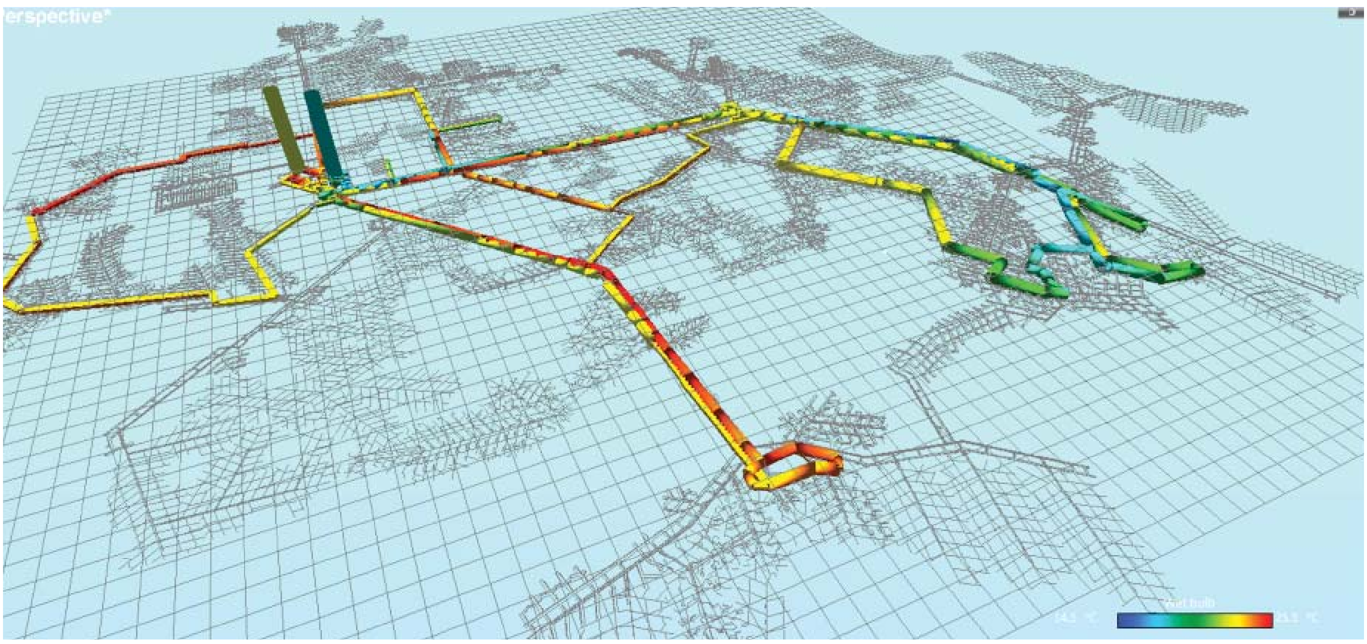

FIG 4 - Typical VUMA layout.

- leakage between duct and main airflow and leaks to return system
- heat transfer between ducts and main airflow
- heat from shuttle cars, feeder breakers, diesel utilities and production load-haul-dumps.

The general analysis procedures are widely published and well accepted internationally. The mine claimed measured accuracy of simulations of five to ten per cent in dry-bulb and wet-bulb temperature, relative humidity, speed and barometric pressure.

VENTILATION AND COOLING EXPANSION PROJECT

The expansion ventilation and cooling system design was based on the application of underground controlled recirculation and bulk air cooling. The selection of design flow rates for recirculation depended on:

- optimisation of energy loads such as:
  - main fan and recirculation fan power
  - underground air cooler water and pumping needs
  - surface air cooler capacity
- adequate fresh airflow if recirculation systems are shut down and acceptable ratio between fresh and recirculated air
- monitoring and safety systems.

Following VUMA simulation of many different scenarios (and some evolution with time), it was concluded that, for the ultimate duty, the primary ventilation system would include two recirculation systems as follows:

- downcast/upcast 300 kg/s
- recirculation at base of shafts (central system) 160 kg/s
- recirculation in north section (north system) 100 kg/s.

As noted, the overall ventilation of 560 kg/s is 87 per cent more than the downcast flow of 300 kg/s and, the 'first' recirculation takes place near main shaft station (central system) and 'second' recirculation (north system) is a 'recirculation-within-recirculation' system (Figure 6).

Ultimate process criteria

Before considering the specific needs for the individual systems, it is important to understand the overall system needs. The total ultimate cold air capacity (downcast and recirculation) is made-up cumulatively as shown in Table 1.

The refrigeration machine system produces 420 L/s of cold water, which is distributed as 230 L/s to the surface air cooler

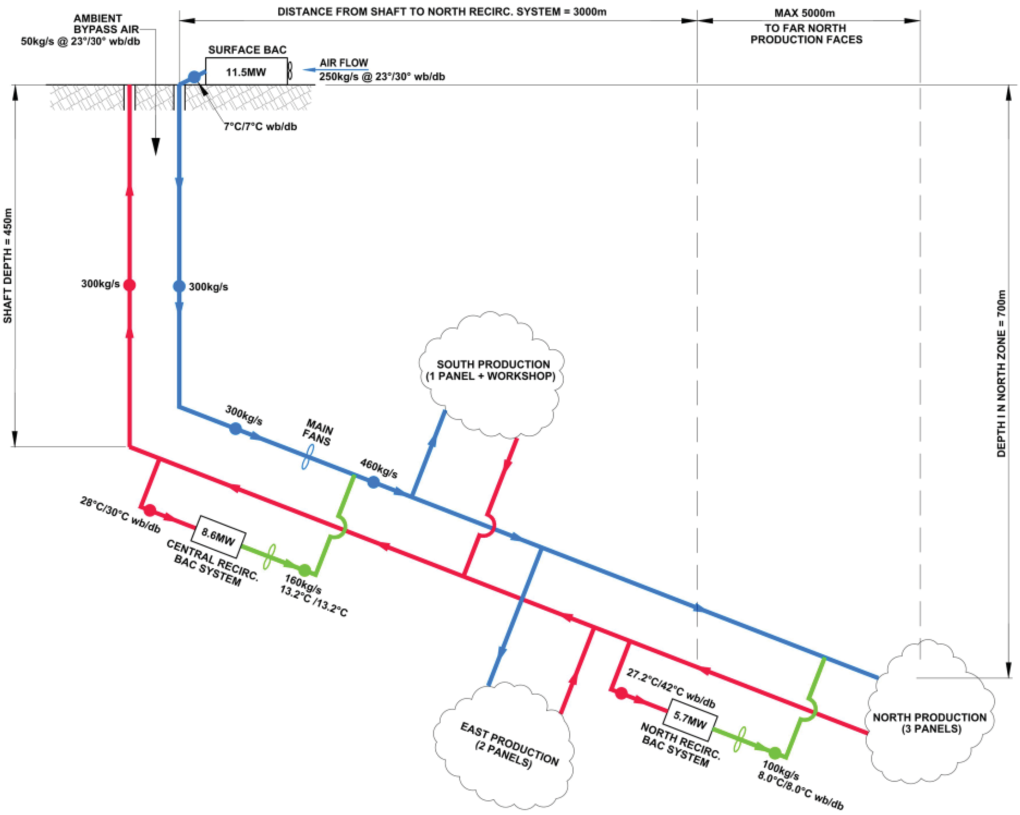

FIG 6 - Primary ventilation layout.

TABLE 1
Total ultimate cold air capacity (downcast and recirculation).

Air coolers	Total ventilation	Refrigeration process needs	Surface air cooler	Central air cooler	North air cooler	Underground water flow
Surface	300 kg/s	12.1 MW	11.5 MW	-	-	-
+ Central	460 kg/s	21.2 MW	11.5 MW	8.0 MW	-	90 L/s
+ North	560 kg/s	28.5 MW	11.5 MW	8.0 MW	5.7 MW	180 L/s

and 190 L/s to the cold dam (see Figure 7). From the dam, 180 L/s flows underground (10 L/s back passes for level control) with 90 L/s going to each of the underground bulk air coolers.

The water flows underground in an insulated 350 mm high-pressure shaft column system. At the underground station, the main pipe splits into two 250 mm pipe systems, one to each air cooler and, at each air cooler, safety shutdown valves (with dual backup) are installed to protect against flooding. Turbine sets are installed at each cooler site to reduce water pressure and provide energy recovery. From the turbine discharge, the water is piped to the first stage of the spray chamber. Turbine bypass arrangements with energy dissipaters are installed to allow operation without turbine. From the central and north air coolers, the return water is pumped to the warm water surface dam from which it flows to the sump of the surface air cooler and is then pump-returned to the refrigeration machines. There were many aspects of the underground water distribution system that required careful consideration and, in particular, detailed attention was given to water hammer, leak detection, control, monitoring and safety aspects.

Ultimate refrigeration machine arrangement

The ultimate required process refrigeration capacity was 28.5 MW and, with standby and redundancy provision of 18 per cent, the rated specifications are 33.6 MW.

The initial phase related to the surface air cooler and this included the installation of three NH_3 plants with a total process capacity of 12.1 MW (Figure 8). NH_3 plants were chosen at that stage because they can produce cold (1°C) water without freeze-up danger. However, with the introduction of the underground air coolers, the refrigeration system had to be extended and various combinations of refrigeration modules were examined. The selection of the best modules and tie-in layouts depended on many issues which, in addition to capital and running cost, included:

- control philosophy, flexibility and strategy for phase-in
- costs of individual modules versus size
- power costs for full life operation
- effects of machine failure on available cooling and standby needs
- size of available 'packaged' modules
- refrigeration machine type.

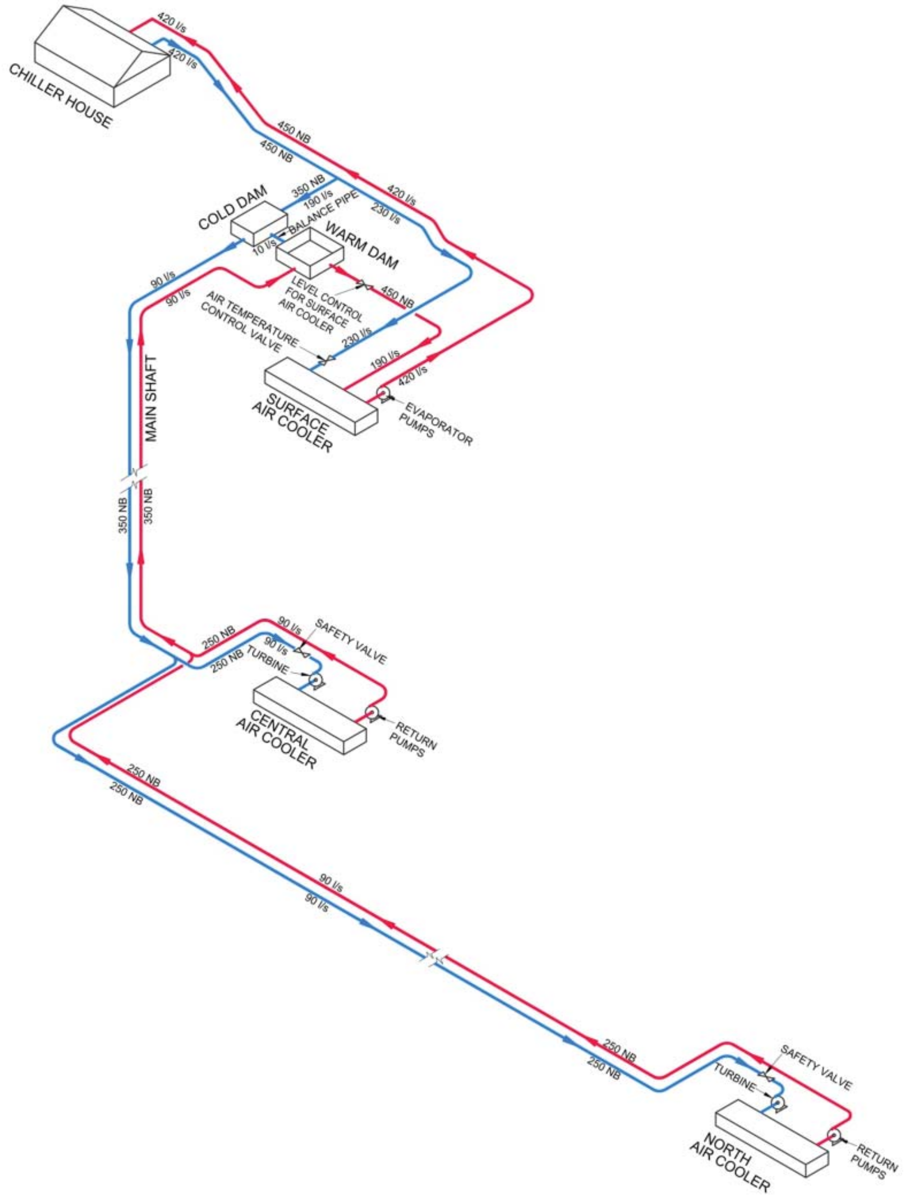

FIG 7 - Cold water distribution system.

FIG 8 - Refrigeration machines (NH_3) for first phase.

For the refrigeration plant extension, two types of refrigeration plant were relevant, namely screw compressors with NH_3 refrigerant with plate heat exchangers and single stage centrifugal compressors with R134a refrigerant with tube heat exchangers. The standard R134a centrifugal refrigeration packages are generally less expensive and, unlike NH_3, the refrigerant is not toxic. These plants are compact and packaged and are the most commonly used type in large-duty air conditioning applications worldwide. However, other main points of comparison are:

- Screw compressors plants (NH_3) have complex oil systems and potential operating problems with oil separator and return systems – the centrifugal compressors (R134a) do not have this problem.
- Centrifugal compressor plants (R134a) are significantly more compact than screw compressor plants (NH_3). For example, a 7 MW centrifugal compressor plant will be smaller than a 4 MW screw compressor plant. The centrifugal compressor (R134a) machines are much simpler and are fully factory packaged (preassembled) with minimum site assembly work.
- When water is sent underground to provide cooling it must be as cold as possible to maximise the cooling effect per kilogram and minimise pump costs. Screw compressor (NH_3) plants can produce 1°C water (without freeze-up danger) whereas centrifugal (R134a) plants can produce 3°C water (without freeze-up danger). Thus one consideration was to use R134a plants in series with the existing NH_3 plants.

After much consideration, 3 × 7 MW new centrifugal compressor packaged (R134a) plants were installed (Figure 9) in series with the earlier 3 × 4 MW screw compressor (NH_3) plants. In addition to the extended refrigeration machines, cooling towers, pumps, piping, instruments and control systems, it was necessary to construct a 500 m^3 holding dam on surface (Figure 10) for the underground air cooler operation.

SURFACE BULK AIR COOLER SYSTEM

The surface air cooler is located immediately next to the downcast shaft headgear building (Figures 11 and 12). The building was essentially enclosed but the required construction work to the original building included seals and doors, cut-away at the shaft brow for cold air entry to shaft and relocation of steel stairs, hand rails and walkways. The airflow is forced through the air cooler and delivered into the headgear enclosure by fans on the intake side of

FIG 9 - Refrigeration machines (R134a) for second phase.

FIG 10 - Cold water holding dam on surface.

the air cooler and the cold air is drawn into the shaft (along with some ambient air) by the main fans underground. The total downcast flow rate is higher than the flow through the surface air cooler. By design, the additional flow leaks into the system through the headgear enclosure (via louvres). The airflow rates have varied during the course of this project but the general process conditions are 250 kg/s through the air cooler and 50 kg/s of 'leakage' into the system through the headgear enclosure (total 300 kg/s downcast). The headgear enclosure is at a slight negative pressure and losses of cold air out of the headgear enclosure are not significant. The cold air density is higher than the ambient air and the cold air naturally tends to flow down the shaft.

The air cooler is a direct-contact spray heat exchanger in the form of two parallel spray chamber cells (Bluhm, Funnell and Smit, 2001). The heat transfer mechanisms in the spray chambers are discussed later.

The airflow is forced through the surface air cooler and into the headgear by four low-pressure axial fans (two per cell). These fans overcome the pressure drop through the spray chambers (including mist eliminator section) and into the shaft. Each fan is sized for 63 kg/s (54 m^3/s) and absorbs about 55 kW. The fan installation includes silencers, diffusers and non-return dampers (Figure 13).

The general thermal process conditions for the surface air cooler are:

- airflow — 250 kg/s
- inlet air temperature (before fans) — 23/30°Cwb/db
- outlet air temperature — 7°C sat
- mixed air temperature in shaft — 10°C sat

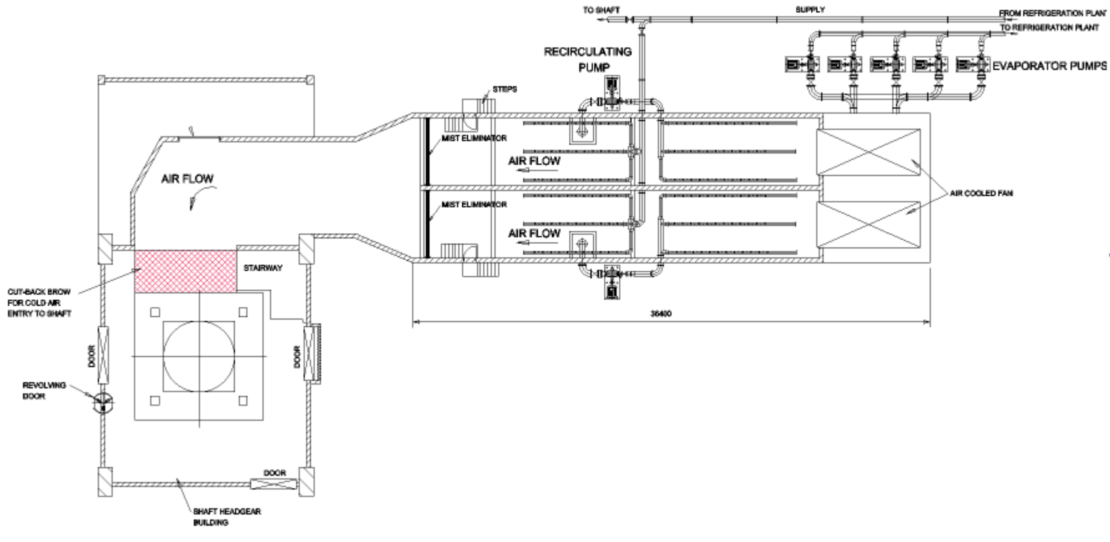

FIG 11 - Sketch of surface air cooler and headgear building.

FIG 12 - Surface air cooler joining headgear building.

FIG 13 - Surface air cooler fan installation.

- air cooling effect 11.5 MW
- water flow rate 230 L/s
- supply water temperature 2°C
- nominal return water temperature 14°C
- refrigeration machines 12.1 MW (process condition).

CENTRAL AIR COOLER SYSTEM

The central air cooler and reconditioning system is located underground near the shaft station (Figure 14). At the central air cooler, return ventilation is recirculated, cooled, reconditioned and mixed with fresh downcast air. The air cooler delivers reconditioned ventilation at the same temperature as fresh air arriving from surface, namely 13.2°Cwb. This provides mixed ventilation flow of 460 kg/s at 13.2°Cwb into the main intakes. The thermal process design parameters for the central air cooler are:

- airflow 160 kg/s
- inlet air temperature wb/db (before fan) 28.0°C/40.0°C
- outlet air temperature 13.2°C sat
- air cooling effect 8.0 MW
- water flow rate 90 L/s
- supply water temperature 2.4°C
- nominal return water temperature 25.5°C
- additional refrigeration machines 8.6 MW (process condition).

The construction of the central air cooler is based on a substantial concrete lining on the excavated rock surfaces.

NORTH AIR COOLER SYSTEM

The north air cooler and reconditioning system is located in the deeper, hotter north section of the mine some 3 km from the central shaft location. At the north air cooler site, return ventilation is recirculated, cooled, reconditioned and mixed with intake arriving from the central air cooler. In this system, 100 kg/s of return air is reconditioned and cooled to 8°Cwb (before fans). This recirculated air is then mixed with air arriving from the central system at 18.2°Cwb, thus providing a mixed ventilation flow of 320 kg/s at 15.6°Cwb. The thermal process design parameters for the north air cooler are:

- airflow 100 kg/s
- inlet air temperature wb/db 27/42°C
- outlet air temperature (before fans) 8°C sat
- air cooling effect 5.7 MW
- water flow rate 90 L/s
- supply water temperature 4.0°C
- nominal return water temperature 20.0°C
- additional refrigeration machines 7.3 MW (process condition).

The construction of the north air cooler is based on a fabricated steel 'box' type structure within the larger excavation (Figure 15). This was due to rock conditions in the north and the anticipated movement of the rock (and this is indeed what occurred over the period).

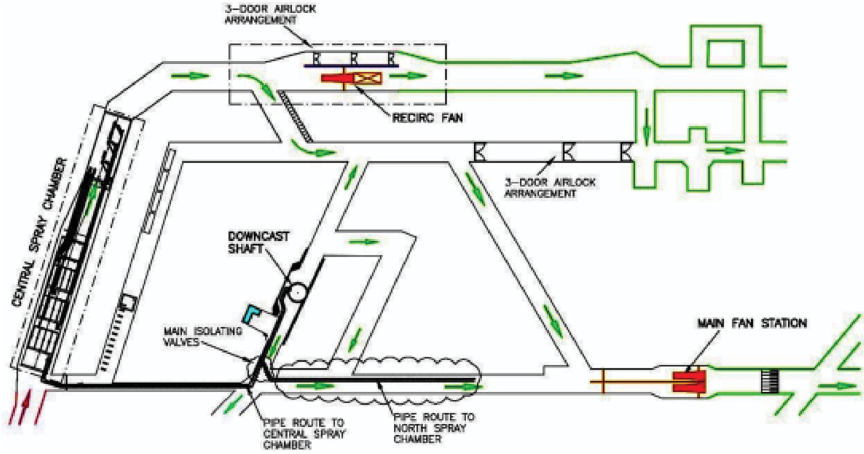

FIG 14 - Sketch of central air cooler.

FIG 15 - Photograph of north air cooler.

FIG 16 - Spray chamber internals.

TECHNICAL FEATURES OF UNDERGROUND BULK AIR COOLERS

The underground bulk air coolers are served by the following special equipment:

- spay chamber excavation, dam, civils, internals and mechanicals
- insulated supply and return piping in shaft and underground and control valves
- turbine-pump-motor set and bypass dissipater
- standby return pump-motor set
- ventilation recirculation fans
- instruments and recirculation control and safety system.

Spray chambers

The underground air coolers are both three-stage direct-contact spray chamber heat exchangers. In the spray chambers, cold water is sprayed upwards in a flat V-pattern into the warm air with distribution of water achieved by the correct selection and direction of nozzles (Figure 16). Heat exchange occurs directly across the large surface area of spray. Where the cool air emerges from the chambers, high performance mist eliminators (two banks) are fitted to ensure that no water is carried over. The spray chambers are versatile heat exchangers and it is relatively simple to change duty by increasing or decreasing the number of nozzles and the cold water flow as required. The spray chambers have three-stages of sprays arranged in counter flow to the airflow. Cold water from the refrigeration plant is sprayed in first stage and then collected and resprayed in the other stages prior to returning to the plant.

Note that although the air leaves the spray chambers in a saturated condition, the overall effect is one of dehumidification because water condenses from the air.

The spray chambers act as dust scrubbers and the return air from workings (and conveyor system) is scrubbed of most of its dust load. This increases the salinity of the water. The salinities are carefully monitored and fresh make-up water is required to control salinity and replace water loss by blow-down and evaporation.

Energy recovery turbines

The cold water flow from surface to the underground air coolers is delivered at a relatively high-pressure and energy recovery turbines are installed at both facilities (Figure 17). The turbines are of the reverse-pump back pressure type and are directly coupled to the main return pump-motor sets and run at two-pole speed (this arrangement removes the possibility of a runaway condition). Due to the high static head, both turbines are multi-stage centrifugal units with the north system turbine requiring additional stages (due to the higher head).

Water flow to the turbines is not regulated but is rather set by turbine selection and spray nozzle resistance. Energy dissipating devices are installed in parallel with the turbines

FIG 17 - Energy recovery turbine and return pump.

in a bypass pressure reducing branch that allows operation of the air coolers when the turbines are out of service. The energy dissipation devices are of the labyrinth or drag type, where pressure reduction is effected by constant velocity friction flow paths under all flow conditions. The turbine installations include monitoring, control and protection devices for turbine and dam. The information is transmitted and monitored at the control centre on surface.

For the north air cooler, careful consideration was given to whether the turbine should be located at the underground shaft station or at the north air cooler site. Originally, it was considered that a pelton-type turbine could be installed near the shaft station (with pelton turbines there is zero back pressure and it would have been necessary to have a turbine dam). It was eventually decided that a back pressure turbine located at the north air cooler was to be used (similar to central air cooler). The main reasons being:

- capital and operating costs favour the back pressure turbine systems
- gravity-feed of water to the north air cooler will be problematic (the north air cooler is 190 m below the shaft station elevation but the access roadway goes up and then down)
- complication of underground dam at shaft station
- additional pumps would be needed.

The turbine selection process conditions were as shown in Table 2.

For each underground air cooler system there is a return pump system comprising one operational unit (turbine-pump-motor set) and one standby unit (pump-motor set only). The pumps are multi-stage centrifugal units directly coupled to two-pole motors. The return pump selection process conditions are as shown in Table 3.

TABLE 2
Turbine selection process conditions.

	Central air cooler	North air cooler
Pressure delivered to turbine	4.20 MPa	5.70 MPa
Pressure off turbine (back pressure)	0.25 MPa	0.25 MPa
Design flow rate	90 L/s	90 L/s
Energy recovery	250 kW	340 kW

TABLE 3
Return pump selection process conditions.

	Central air cooler	North air cooler
Pressure discharge from pump	4.70 MPa	6.70 MPa
Design flow rate (+5 L/s control back pass)	90 L/s	90 L/s
Absorbed power without turbine	590 kW	850 kW
Absorbed power with turbine	340 kW	510 kW
Pump motor rating	680 kW	980 kW

Recirculation fans

The central and north recirculation systems utilise recirculation fans located on the discharge side of the spray chambers (Figure 18). The recirculation flow is controlled by these fans, which provide pressure to overcome air cooler resistance and other main network requirements. In an emergency situation such as a fire, the recirculation must be stopped and the fundamental action is to shut off the fans and ensure the non-return dampers shut with negligible leakage.

The fans are axial flow units with manually adjustable blades and directly coupled motors. The fan components were provided with corrosion protection, which was required to resist the corrosive/erosive effects of the harsh underground conditions. The fan-motor sets include bearing vibration, bearing and winding temperature monitoring as well as instrumentation for airflow and air pressure. The fan sets also have inlet screens, silencers, diffusers and non-return dampers. The process flow design selections for the recirculation fans were as follows.

The central recirculation system was constrained by space issues and a single axial fan was all that could be fitted. The nominal process selection conditions were:

- airflow 160 kg/s
- airflow 140 m^3/s
- fan static pressure 3.8 kPa
- absorbed power nominal 700 kW.

The north recirculation system did not have space constraints and two axial fans were installed. The process selection conditions were:

- airflow 2 × 50 kg/s
- airflow 2 × 40 m^3/s
- fan static pressure 2.3 kPa
- absorbed power nominal 2 × 125 kW.

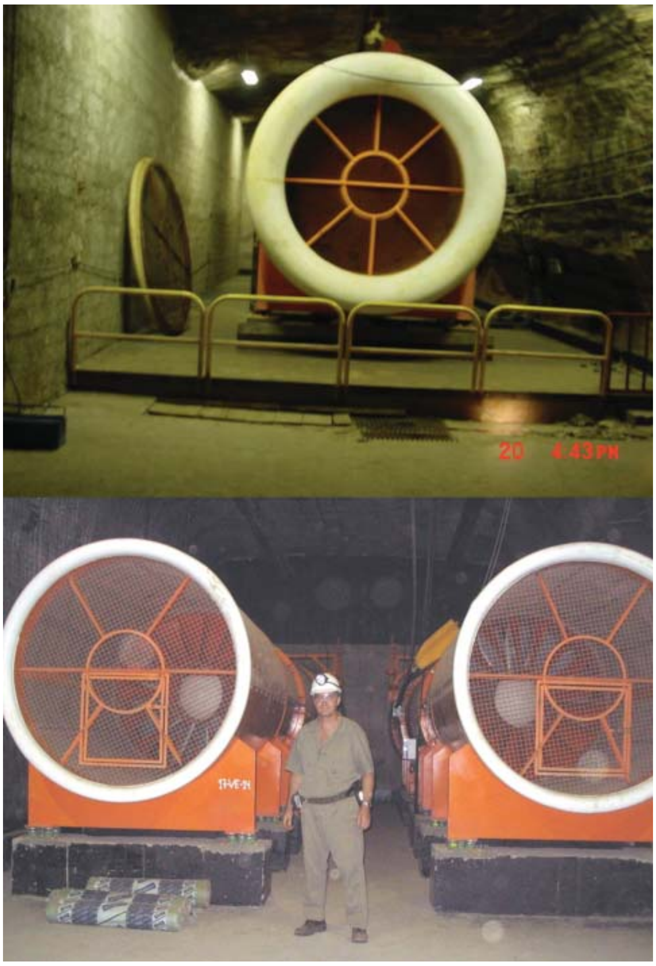

FIG 18 - Recirculation fans at the recirculation sites.

Control and safety system

Both the central and the north recirculation facilities have safety systems related to the risk of fire and smoke recirculation. The recirculation systems are equipped with monitoring facilities that transmit information to the control centre on surface and the secondary control centres located at the recirculation sites. In the event of a fire, the recirculation is stopped by shutting down the fans and ensuring that the non-return dampers are closed.

Each recirculation safety system includes three CO gas detector transducers, with one located before the spray chamber in dirty air and two CO detectors located after the spray chamber in clean air. The control logic is programmed into the PLC and SCADA system so that input levels of the majority of sensors will determine whether the recirculation system should be shut down. For example, if two CO detectors indicate a normal condition and one CO detector indicates an alarm condition then the overall status would be normal. The system status warning would be activated so that the discrepancy can be investigated. However, if any two CO detectors indicate an alarm condition then the overall status would be alarm and the recirculation system would be shut down. Mine personnel are then required to investigate the possible fire condition before the recirculation system can be restarted. The control and safety systems include the following functions:

- scan and record the following parameters continually: CO, fan motor current, winding and bearing temperatures, vibration, airflow and pressure differential
- display warning messages if any CO detector shows high condition (normal background condition is 2 ppm and alarm condition is set at >6 ppm)
- shut down air recirculation system if any two CO detectors show high condition
- spray chamber respray pumps are not shut down because the water sprays can remove some smoke particles (but not gas contaminants)
- warning messages/alarms remain active until they are acknowledged and investigated
- if any CO detector malfunctions (zero output), then any other detector indicating a high condition will result in an alarm condition.

CONCLUSION AND SUMMARY

The primary ventilation from surface is severely limited by maximum air speeds in the small down and upcast shafts. The limit is 300 kg/s and there is no potential of increasing this. This shaft-system limitation meant that the distance of mining from the shaft was also limited and hence there was the perception of a limited resource, even though the deposit was much larger. Due to an overlaid aquifer, the sinking of additional shafts was not an option but this ventilation constraint has been successfully overcome by large-scale controlled recirculation.

The original refrigeration system, in the 1990s, had a multiplicity of spot refrigeration plants that were generally ineffective. Back then, this was already a problem for the existing operation, which would be severely affected by increasing production with production centres moved further and further out. The concept of multiple spot plants could not be improved and this operation had become a good example of the misuse and ineffectiveness of the spot plant approach. It was recommended that large bulk air coolers should be used and they should be served from a central surface refrigeration plant. In addition to the surface bulk air cooler, two underground bulk air coolers for chilling recirculated ventilation were installed.

The overall ventilation duty is 560 kg/s, which is 87 per cent more than the downcast flow of 300 kg/s and the underground recirculation of air (and its reconditioning) was the fundamental feature of this design. These systems have been operating safely for about ten years and have played a huge role in the mine profitability and comprehensively extending the mine life (even with the limited shaft sizes).

The ventilation and cooling systems also have a number of other features of interest and uniqueness, which include:

- recirculation control and safety systems
- high-pressure chilled water pipe system in potash mine (with numerous safety devices)
- energy recovery turbines directly coupled to pump motor sets (recovering ~600 kW)
- R134a packaged refrigeration plants, which were favoured over NH_3 plants (in stage two).

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REFERENCES

Bluhm, S, Funnell, R and Smit, H, 2001. Horizontal spray chambers for surface bulk air cooling, in *Proceedings Seventh International Mine Ventilation Congress*, Krakow, Poland.

Burton, R C, 1988. Controlled recirculation in South African gold mines, in *Proceedings Fourth International Mine Ventilation Congress*, pp 275-279 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Burton, R C, Plenderleith, W, Stewart, J M, Pretorius, B C B and Holding, W, 1984. Recirculation of air in the ventilation and cooling of deep gold mines, in *Proceedings Third International Mine Ventilation Congress*, pp 291-301 (The Institution of Mining and Metallurgy: London).

McPherson, M, 2009. *Subsurface Ventilation Engineering*, second edition (MVS Inc: California).

Pickering, A J and Robinson, R, 1984. Application of controlled recirculation to auxiliary ventilation systems and mine district ventilation circuits, in *Proceedings Third International Mine Ventilation Congress*, pp 315-324 (The Institution of Mining and Metallurgy: London).

Robinson, R and Harrison, T, 1987. Controlled recirculation of air at Wearmouth Colliery, *Colliery Guardian*, 235(8):274-277.

Rose, H J M and Burton, R C, 1992. The optimization of a controlled recirculation system at Oryx Gold Mine, in *Proceedings Fifth International Mine Ventilation Congress* (ed: R Hemp) (Mine Ventilation Society of South Africa: Johannesburg).