Refrigeration and ventilation systems for ultra-deep platinum mining in the bushveld igneous complex

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ABSTRACT: Impala Platinum has been examining the viability of a number of deep mining options and it is clear that the cooling of the deeper platinum mines presents one of the greatest challenges to the financial viability of future projects. The paper addresses the cooling of a green-fields project with a depth of 2150m and virgin rock temperatures approaching 70°C. A survey of proven technology, VUMA modelling and a technical/economic trade-off studies were used to evaluate the range of cooling options including: ultra cold chilled air from surface; chilled water from surface with energy recovery; underground refrigeration and ice from surface. The financial analysis favours the concept of using ice from surface which, for this depth, was an unexpected outcome since the break-even depth for the introduction of ice was historically considered to be deeper. This is a manifestation of the large increase in power costs and a rationalisation of ice maker costs - both of which support the ice option. The paper then turns to the specific application of ice for the cooling of a decline extension to a depth of 1760m at one of Impala's operating shafts. There are a number of circumstances that support the use of ice in this application, the most important being that the cooling system will have to be retrofitted into an existing operating mine. The concept of surface ice-to-underground will require the least in terms of shaft piping and underground excavations and it was favoured in minimising disruptions to the existing mine. The paper describes the logic as well as the design of this overall cooling system.

1 INTRODUCTION

At present, chilled air from surface is used as the only cooling medium in all the refrigeration systems at Impala Platinum Rustenburg. The deepest project currently in execution is No.17 Shaft which is 1820m deep and which will be cooled by 1300 kg/s (5 kg/s per kt/mnth) of refrigerated air from surface. There will be 40% of this ventilation downcast in a dedicated ‘fridge’ shaft in an ultra-cold condition at high air speed. While this approach may be optimal for this project, once the mining gets much deeper eventually underground air cooling must be introduced. There is a “hierarchy with depth” for cooling technology at Impala that was proposed by Mackay et al (2010), indicating that chilled water from surface and ultimately ice would be required to cool deeper future operations.

Ice-from-surface for mine cooling was pioneered in the 1980s with hard ice plants at Harmony and ERPM mines that operated until the mines closed. Soft ice plants have operated at Mponeng since 1993 and recently both Mponeng and Phakisa mines have installed hard ice plants. The viability of using ice plants was established in numerous feasibility studies done in the 1980, 1990 and 2000 decades. The main driving force favouring the use of ice is that less pumping is needed and clearly as depth increases the use of ice becomes more favourable. The many feasibility studies done in the past repeatedly indicated that ice would be viable at depths of greater than 2500m. However, there have been two fairly recent trends that have moved this breakeven depth to lesser depths.

The first is the new generation of hard ice makers which are more cost effective but the second and more important trend has been the cost of power. The power tariff in South Africa cost has increased by more than 400%. in a period of six years and this has fundamentally modified the design and operating approaches for mine refrigeration systems and particularly has made ice more attractive at lesser depths.

The Impala Platinum resource boundary extends to a depth of 2350m in virgin rock temperature of 75°C. Similarly, the Anglo Platinum resource boundary is limited to a virgin rock temperature of 75°C (Smith, 2011). Mining at depth in the Bushveld Igneous Complex is limited to the Northam hydro-powered mine, at a depth of 2115m (Northam, 2012) and a virgin rock temperature of 70°C. Whilst chilled water is the default choice for cooling in a hydro-powered mine, there are other alternatives available for non-hydro-powered mines, including chilled air from surface via dedicated 'Fridge' shafts, underground refrigeration plants or ice-from-surface. Selecting the appropriate cooling and ventilation scheme for deeper mines is central to the financial viability of future deeper mines.

Impala carried-out a prefeasibility study into the so-called Impala No.16 Lower project, planned to a maximum depth of 2150m and this presented an ideal case study to evaluate cooling options at depth. This paper examines this case study and concludes in favour of using an ice-from-surface system. Although the overall project was found to be unfeasible, in the present economic climate, the ice observation was a very important conclusion. Following the No.16 Lower study, Impala then examined a decline extension below the existing No.16 Shaft operation. This would operate down to a depth of 1760m and there are a number of circumstances that support the use of ice in this application, the most important being that the cooling system will have to be retrofitted onto an existing operating mine. Surface plant with ice-to-underground will require the least in terms of shaft piping and underground excavations and it was favoured in minimising disruptions to the existing mine. The paper describes this logic as well as the design of this overall cooling system.

2 GREEN-FIELD DEEP-MINE CASE STUDY

The key features of the project case study are that it will be a green field project for Merensky and UG2 reef production of 200 kt/mnth with main access being via a vertical shaft system, with horizontal cross-cuts to reef, foot wall drives on strike, with cross cuts and travelling ways to the reef plane.

The following cooling strategies are proven in the deeper Witwatersrand gold mines and were considered for this study:

- Option 1: Chilled air from surface - dedicated 'Fridge' shaft.
- Option 2: Chilled water from surface (with energy recovery) supplementing basic surface bulk air cooling.
- Option 3: Underground refrigeration supplementing basic surface bulk air cooling.
- Option 4: Ice from surface supplementing basic surface bulk air cooling.

2.1 *VUMA heat load modeling*

VUMA modeling was used to determine the total heat load for all cooling options and the cooling required by each option for a maximum design reject wet bulb temperature of 28.5°C.

The heat load for Option 1 (chilled air from surface) will be higher than that for Options 2 to 4 due to the greater surface area of exposed rock (additional and/or larger excavations) as well as the greater temperature driving force between the rock and chilled air.

For Option 1, the total cooling requirement will be 81.8 MW and of this 38.5 MW will be provided by 'normal' chilled air from surface via the main hoisting shaft. The remaining cooling requirement of 43.3 MW must therefore be applied by additional chilled air down cast via a dedicated 'Fridge' shaft.

For Option 2 to 4, the total cooling requirement will be 79.5 MW and again of this 38.5 MW will be provided by 'normal' chilled air from surface via the main hoisting shaft. The remaining cooling requirement of 41.0 MW must therefore be obtained from underground cooling of air. The VUMA modeling again confirmed that the underground air coolers will be most effective when placed close to the stoping horizon, as the air temperatures in the main cross-cuts remains low due to the basic main shaft surface bulk air cooler.

2.1.1 *Cooling Option 1: Dedicated fridge shaft*

The use of an unequipped dedicated, high speed, 'Fridge' shaft to convey ultra-cold air (typically at 3°Cwb), offers an extension to the use of surface bulk air cooling at greater depth (Biffi et al, 2007). Option 1 will feature chilled air at 3°Cwb, downcast via the dedicated Fridge shaft at >15 m/s to the deeper levels, Figure 1. The object is to deliver this ultra-cold ventilation right where it is needed and the Fridge shaft will report to the deepest levels only (there will be no other ventilation connections to the fridge shaft system). This ultra-cold air delivery is wholly dedicated to the deepest levels and this gives a positional efficiency effect not usually associated with surface bulk air cooling. This option also results in larger and/or additional return airways due to the significant increase in total air flow.

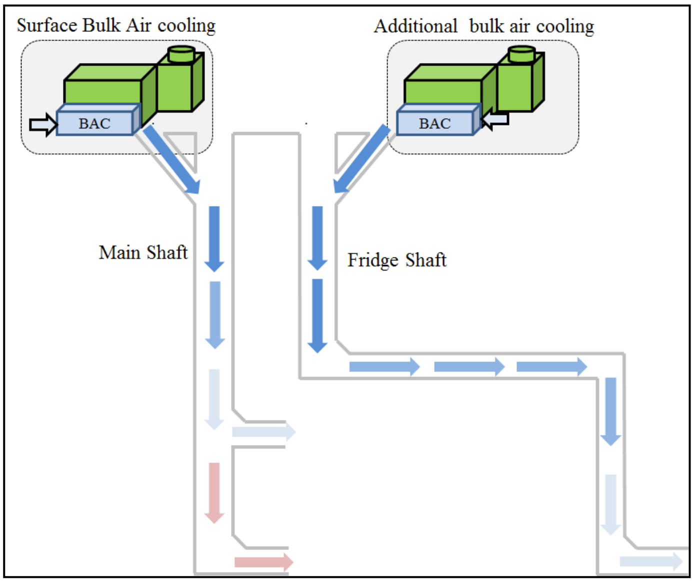

Figure 1 Schematic of Option 1 (Fridge shaft)

2.1.2 *Cooling Option 2: Chilled water from surface*

This option involves the use of surface refrigeration plant producing chilled water which is distributed to underground air cooling systems, Figure 2.

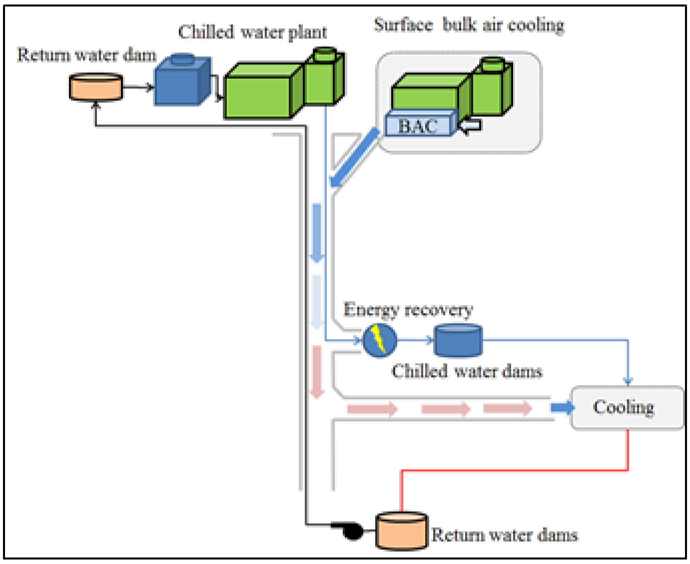

Figure 2 Schematic of Option 2 (chilled water from surface)

The chilled water is produced by surface refrigeration plant at 1.5°C and flows under gravity in insulated columns in the main shaft to energy recovery station (1851mbs). From there, the chilled water will be distributed to air coolers in the form of bulk air cooler spray chambers and cooling cars. The return water from each cooler is allowed to flow under gravity to the main pump station (2200mbs). The water is returned out the mine and delivered to pre-cooling towers at the surface refrigeration plant.

In this study, both a pelton turbine system and a three chamber pipe feeder system were considered as options for energy recovery. Within the accuracy of this evaluation and based on these present assumptions there was no real significant difference in the overall power profile for either of these systems and a debate on the finer differences is not given here.

2.1.3 *Cooling Option 3: Underground refrigeration machines*

Early gold mining refrigeration plants were located underground, either as scattered small units or large central plants close to shaft systems. Intuitively, the significant cost of return water pumping associated with surface plants, would tend to favor underground installations. However, this cost can be offset by:

- Use of energy recovery systems.
- Pre-cooling of water in cooling towers on surface.
- Economy of scale of surface plants cannot be done underground due to excavation constraints.
- Maintenance on surface is of a better quality.
- Coefficients of performance of underground plants will be about 3.3 while those for surface plants will be about 5.7.
- Maintaining water quality in underground plants condenser circuits, using return ventilation for heat rejection, is difficult as the heat rejection sprays have a scrubbing effect (amount of blow down water required to be pumped out mine often exceeds planned values).

The schematic layout of this option is shown in Figure 3. The underground refrigeration plant system (1851mbs) produces cold water that is distributed to the various cooler locations. The distribution system, air cooler system and return water system to main pump station level is similar to the chilled water Option 2. The return water is pumped from the main pump station level to the return water dam located at the underground refrigeration plant.

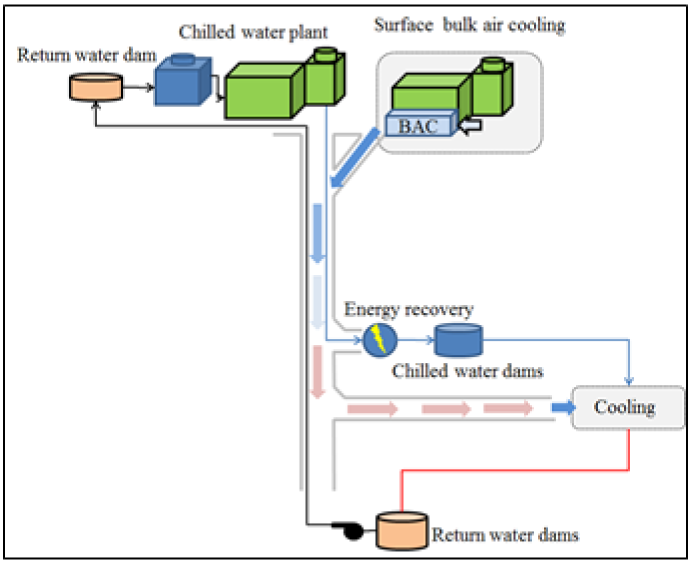

Figure 3 Schematic of Option 3 (underground refrigeration plant)

The blow-down from the heat rejection system circuit is pumped to an intermediate pump station from where it is pumped to surface. The energy consumption, related to pumping of blow-down to surface is dependent on the underground water treatment. Make-up water to replace blow down and evaporative losses is gravity fed from surface to the refrigeration plant.

2.1.4 *Cooling Option 4: Ice to underground system*

The main advantage of using ice is derived from its latent heat of melting which means that ice can provide four to five times more cooling than chilled water per kg. Ice is produced in a surface plant and sent underground in shaft ice column to an underground ice melting dam, where return cooling water is re-cooled to a temperature close to 0°C, Figure 4. Although there can be some debate between the merits of hard ice and soft ice, this study has adopted the hard ice system because of the high ice mass fraction and the fact that hard ice systems have recently been installed at a number of deeper gold mines.

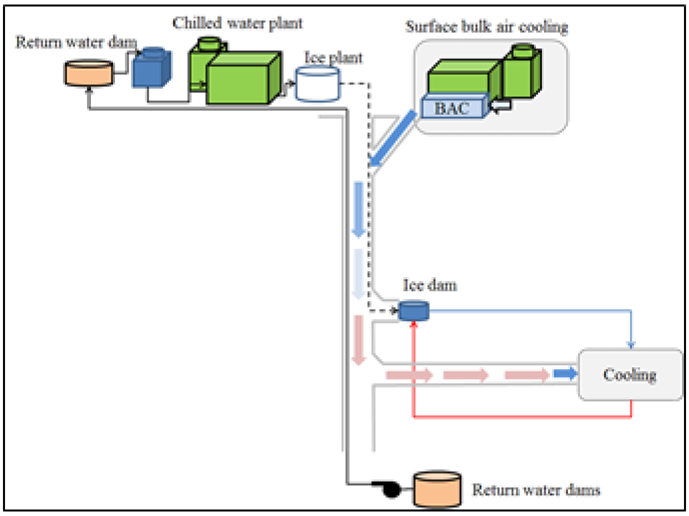

Figure 4 Schematic of Option 4 (ice from surface)

In this system, the surface ice-making plant will produce hard ice, conveyed on surface to the shaft head by belt conveyor and fed by a uPVC column down the shaft to an ice dam, located (1851mbs).
The chilled water at 1.5°C will be circulated from the ice dam to the suite of bulk air coolers and cooling cars (as per the chilled water and underground refrigeration plant options). The return water from the air coolers on each level will be returned to the shaft on the particular level and gravity fed to a central dam near the main pump station. The water from this dam is circulated back to the ice dam. The excess water, arising from the addition of ice to the ice dam, is pumped to the intermediate pump station and, from there, back to the surface return water dam.

3 COMPARISON OF FOUR OPTIONS

The four options were compared on a power basis, with Option 1 (dedicated Fridge shaft) proving to be most energy efficient and Option 2 (underground refrigeration) the least efficient. The comparison of the power requirements of all four options can be seen in Table 1.

Table 1 Comparison of power requirements

	Option 1 Fridge Shaft MW	Option 2 Surface Plant MW	Option 3 U/G Plant MW	Option 4 Ice Plant MW
Chilled air	9.2			
Main fan	7.9			
Chilled water		12.5	23.6	1.7
Pumping		10.8	3.5	5.6
Ice plant			13.1	
Total cooling	43.3	41.0	41.0	41.0
CoP	2.53	1.76	1.51	2.01

In addition to the power comparison, an overall financial analysis was also carried out. The negative Net Present Value (NPV) at a discount rate of 14% and a 20 year life-of-mine was determined for capital cost, maintenance cost and electricity and is compared in Figure 5.

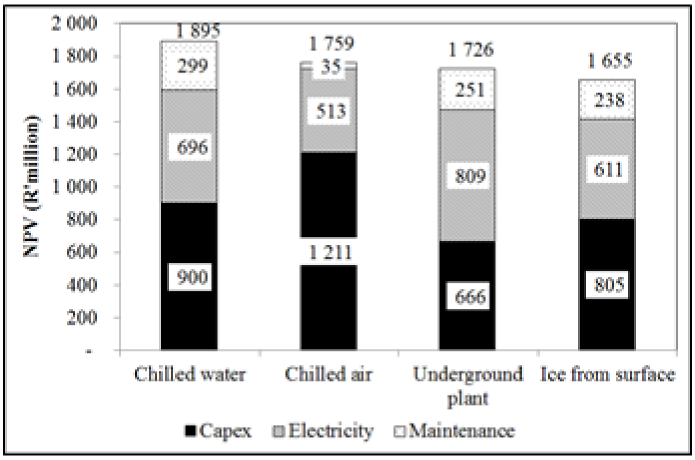

Figure 5 Negative net present value (NPV) comparison

Based on the financial analysis, Option 2 (chilled water from surface) is the least preferred, while Option 4 (ice from surface) yields the lowest negative NPV. Although the differential NPV between ice and the most expensive Option 1 is only 13%, it offers the following additional advantages:

- Surface plant is major portion of capital spend, where the risk of capital overrun is lower than with underground installations.
- Ice plants are generally also built as turnkey installations, with limited risk of cost overruns to the client.

- Lower risk of schedule overruns, as it requires limited mining excavations, which are generally on the critical path of mining projects.
- Ability to automate ice plant control and limited underground maintenance requirements.
- Ability to phase in ice plant modules over the life-of-mine, yielding greater capital efficiency.
- Improved positional efficiency, as ice can be transported both vertically and horizontally (to a certain extent) underground and ice dams can be position on more than one level.

In conclusion, of the four proven technological options considered, ice from surface presents the lowest negative NPV over a 20 year life of mine. Ice also presents the lowest risk to capital and schedule overruns. The fact that the cost analysis favoured the concept of using ice from surface, for this depth, was an unexpected outcome since the break-even depth for the introduction of ice has been historically considered to be deeper. The many feasibility studies done in the past repeatedly indicated that ice would be viable at depths of greater than 2500m. However, there have been two fairly recent trends that have moved this breakeven depth up.

The first trend is the new generation of hard ice makers which are more cost effective but the second and more important trend is the cost of power. The power tariff for South African mines has, in recent years, increased dramatically e.g. 2008 - 46%; 2009 - 38%; 2010 - 25%; 2011 - 26%; 2012 - 17% and 2013 - 9%. Thus, in a period of six years, this power cost increased by more than 400%. These changes have fundamentally modified the design and operating approaches for South African mine refrigeration systems and particularly have made ice more attractive at lesser depths than generally considered.

4 NO. 16 DECLINE PROJECT

The No.16 Lower project(described above), planned to a depth of 2150m, presented an ideal case study to evaluate cooling options at depth. Although the overall project was found to be unfeasible, in the present economic climate, the ice observation was a very important conclusion. Following the No.16 Lower project study, Impala then examined the feasibility of a Decline extension below the existing No.16 Shaft operation. The decline could support four levels of Merensky and UG2 production (120 kt/mnth reef) as replacement tonnage thus extending the full production at the shaft for at least 8 years. The decline will operate down to a depth of 1760m and there are a number of aspects that support the use of ice to supplement the existing system. The most important aspect being that the supplementary cooling system will have to be retrofitted onto an existing operating mine.

Although additional cooling resources can be achieved by upgrading the existing refrigeration system at No.16 Shaft, this will not adequately cool the full Decline project. To achieve the extra cooling, a (supplementary) ice-from-surface system will be installed.

Before selecting the ice-from-surface option, there were a number of different approaches considered which again included underground refrigeration plant with heat rejection underground and surface refrigeration plant with chilled water to underground via energy recovery turbines. There were also a number of derivatives examined such as: three pipe feeders instead of turbines, ultra high pressure air coolers with chilled water in closed circuit from surface, slurry ice systems and glycol systems. The selection of the best system depends on many issues but in this case the judgment was dominated by the outcome of the No.16 Lower study discussed above and the fact that this system will have to be retrofitted into an existing mine which creates a number of constraints.

- Underground refrigeration plant with heat rejection underground will require a number of large chambers to be excavated near the existing shaft bottom for plant room, cooling towers, pump rooms and sub-stations.
- Surface refrigeration plant with chilled water-to-underground will require relatively large insulated shaft columns to be installed in an existing operating shaft. Furthermore, this approach will also require relatively large excavations for energy recovery equipment with dam and return pump chamber with dam and sub-station.
- Surface plant with ice-to-underground will require the least in terms of shaft piping and underground excavations and was favoured in terms of minimum disruptions when retrofitted into the existing mine. This approach also reduces the cost of pumping water to surface.

Hence, the hard ice-from-surface system was selected to serve 18.3 MW of air cooling duty in the underground workings. This ice-to-underground system will serve the following underground:

• 29 level BACs	9.9 MW	128 l/s
• Development end coolers	2.0 MW	27 l/s
• Chilled service water	3.3 MW	40 l/s
• Heat losses from pipes	3.1 MW	
• Total underground cooling	18.3 MW	

The ice plant will provide 45 kg/s of ice to the mine and will consist of a pre-chiller (R134a) and ice-making modules (ammonia) rejecting heat to a common bank of CCTs. The ice plant will deliver ice to a pipe conveyer that will transport the ice to the shaft system. The overall ice system process flow diagram is given in Figure 6.

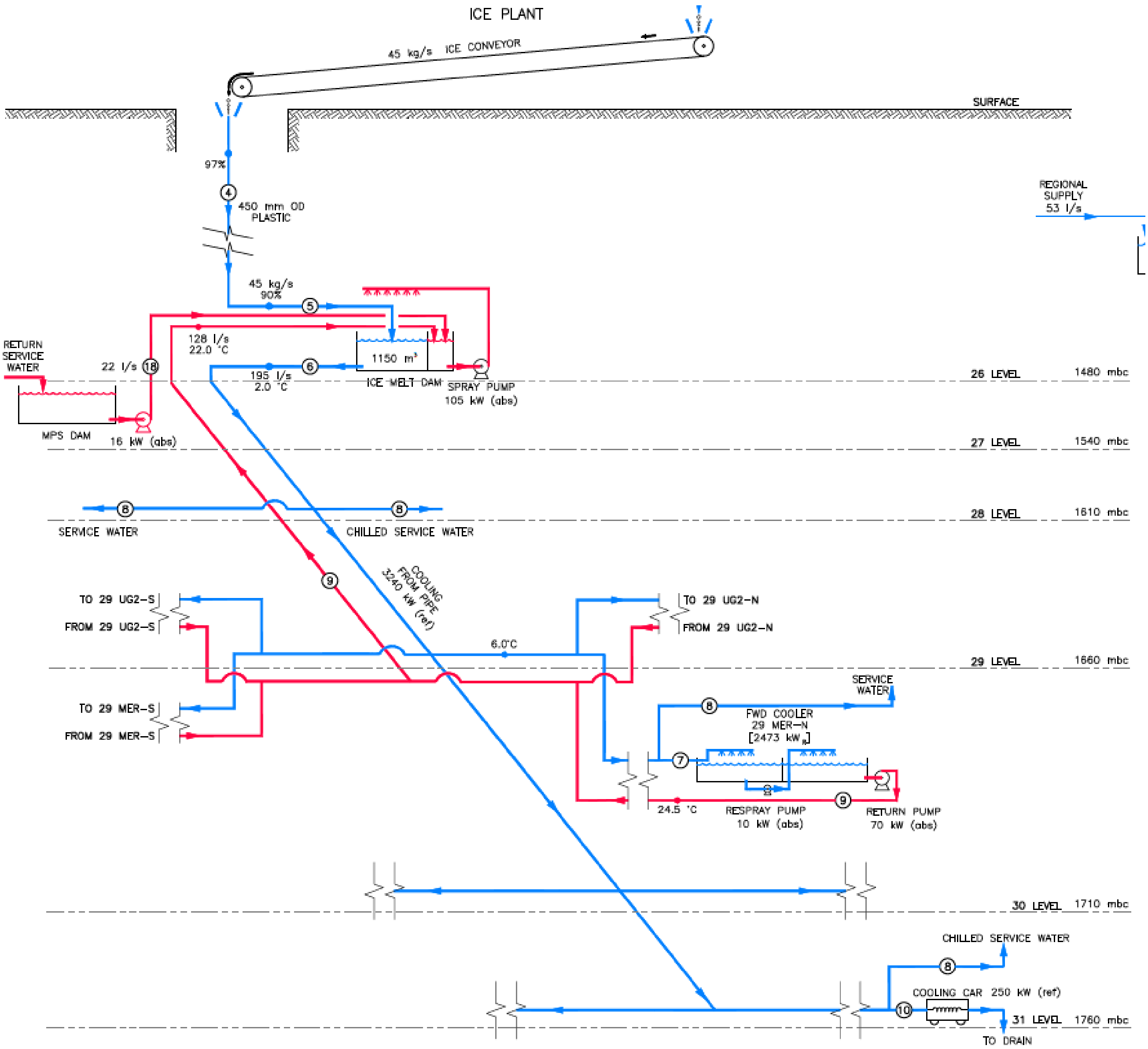

Figure 6 Ice system process flow diagram

The ice makers will be either plate or tube type hard ice machines. The ice will be harvested from the ice makers by defrost to fall via chutes onto a lateral belt conveyer which will transport the ice out of the ice plant to the main pipe conveyer.

The ice will be transported on a closed pipe conveyer which will deliver the product to a funnel feeder at the shaft system. The general arrangement and overall site layout for the ice system can be seen in Figure 7 and Figure 8 respectively.

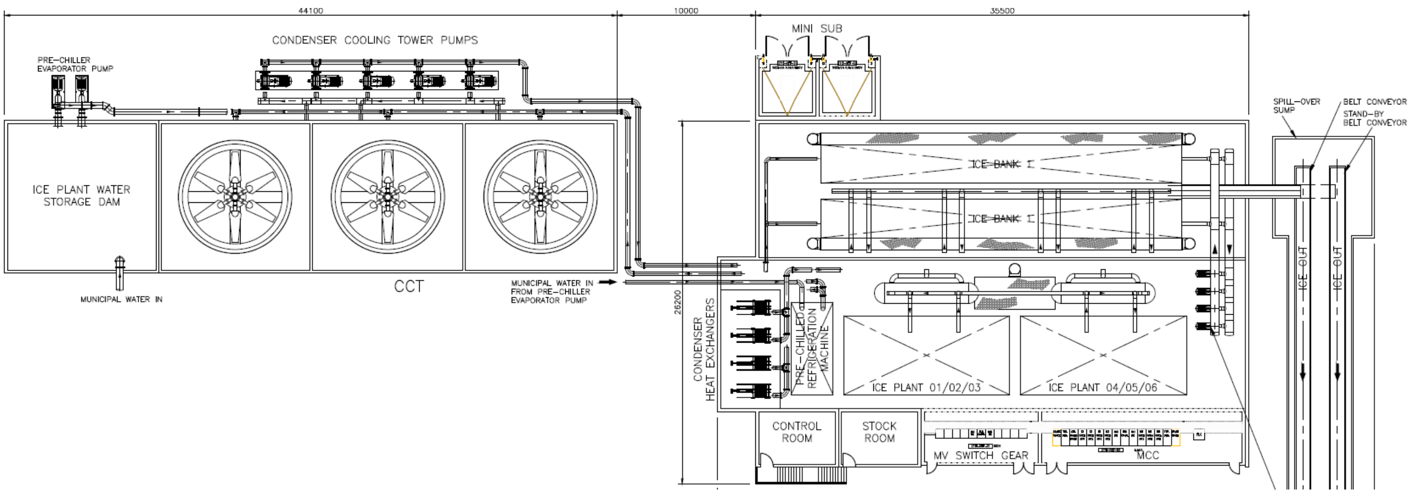

Figure 7 Ice plant general arrangement

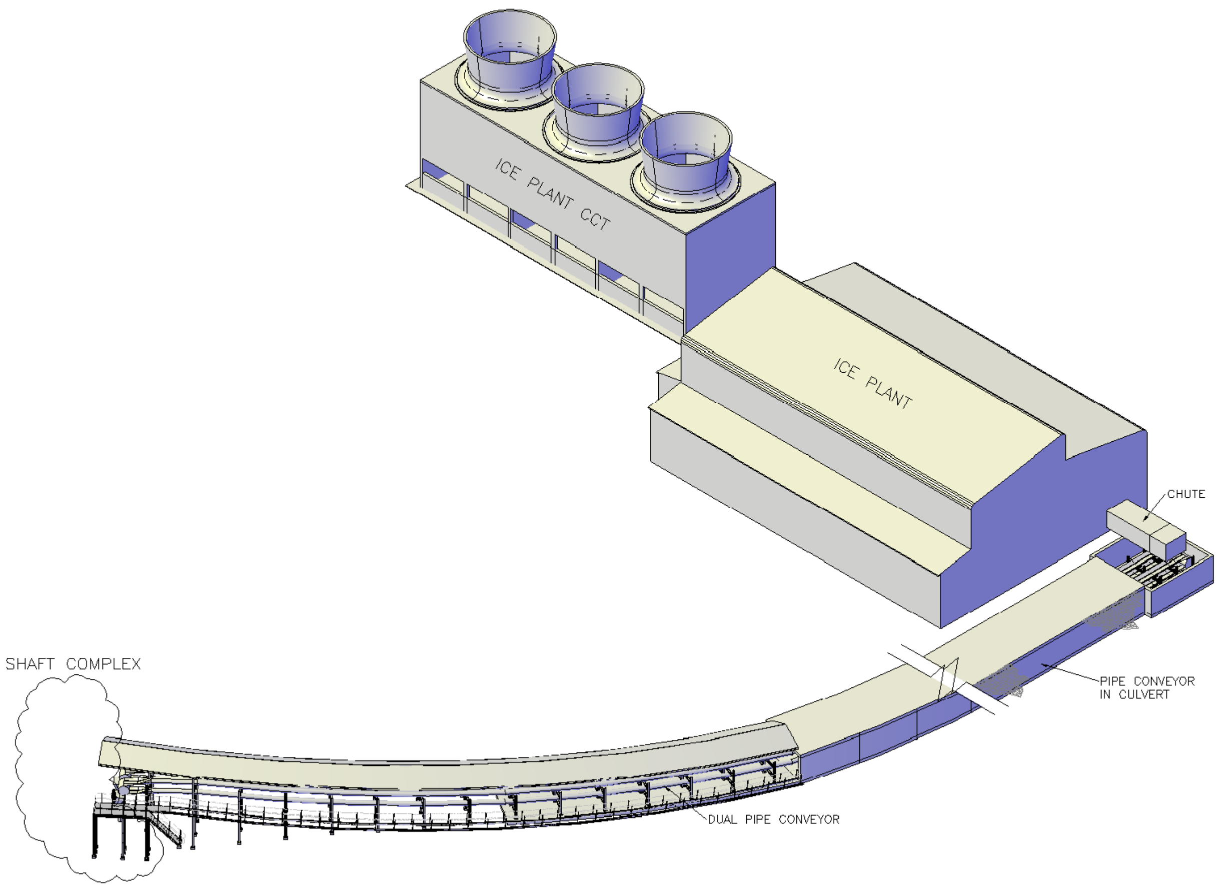

Figure 8 Site layout of ice plant, CCTs and conveyer system

Once the ice arrives at the shaft it will gravity feed through a funnel into a 450mm plastic pipe which will run to 24 level (1370mbs) where the pipe will change direction and will enter a 600mm hole at an angle of 30° to vertical to flow down to an ice dam on 26 level (1480mbs).

The ice melt dam will receive 45 kg/s of ice and 150 l/s of warm return water. The water will be circulated in the ice melt dam by a pump feeding a spray system above the ice dam to assist the ice melting process. The ice dam will supply a total chilled water flow of 195 l/s at 2°C in a pipe in the Decline which will feed out on all four levels to provide additional cooling to the Decline operation.

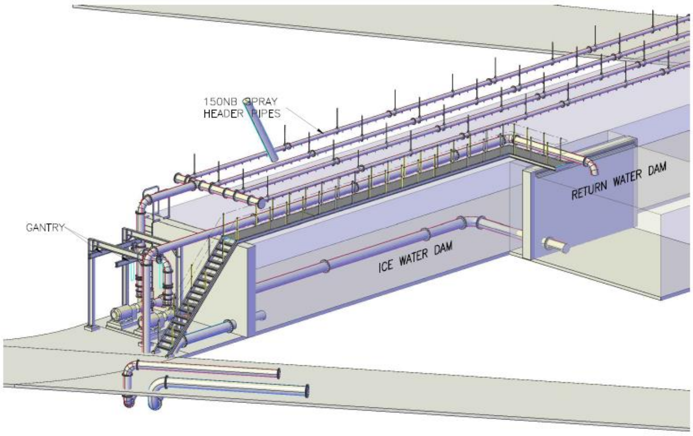

Figure 9 Ice melt dam

The majority of the water (128 l/s) will feed to 29 level foot wall drives bulk air coolers (BACs) with the balance being utilised as service water (40 l/s) and providing cooling in cooling cars (27 l/s) on the lower level drives.

The BACs will be used to distribute the majority of the cooling underground and this will be a first in the Impala group. There will be four BACs installed on 29 level (Merensky north+south, UG2 north+south). The BACs will re-cool air from 30 level after it has cooled the deeper working areas.

The BACs will be in the form of a horizontal spray chambers in which cold water will be sprayed upwards in a flat V-configuration into the horizontal airflow. Within the sprays, heat exchange will occur across the large surface area of drops. Re-spray systems will be used to achieve high thermal efficiency and these installations will be two-stage spray chambers. Mist eliminators will be installed where cold air emerges from each spray chamber cell. The four BACs will be designed for an average duty of 2.5 MW each using 32 l/s of chilled water, with the potential to provide a maximum duty of 3.3 MW using 43 l/s of chilled water if required.

In addition to the BACs, cooling cars will be utilised on the two lowest levels (31 level and 30 level) to cool air at the development sections. The cooling cars will be located in cubbies that will subsequently be utilised for electrical mini-subs.

The operation of each cooling car will include an auxiliary mine fan and duct system to draw air through the cooling coil and down the drive. The spent water will be allowed to fall to drain after it has passed through the cooling coils and the water will provide a little more cooling as it flows down the drive. The total air cooling duty from all the cooling car system will be about 2 MW require the use of about 27 l/s of chilled water from the ice dam and chilled water reticulation system.

Finally the chilled service water will provide the remaining cooling capacity as it is applied in the working places with a high positional efficiency.

5 CONCLUSION

The paper has discussed the planned cooling of a green-fields project with a depth of 2150m and virgin rock temperatures approaching 70°C. Technical/economic trade-off studies were used to evaluate the range of cooling options including: ultra cold chilled air from surface in Fridge shafts; chilled water from surface with energy recovery; underground refrigeration and ice from surface. The financial analysis favoured the concept of using ice from surface which, for this depth, was an unexpected outcome since the break-even depth for the introduction of ice was historically considered to be deeper. This is a manifestation of the large increase in power costs and a rationalisation of ice maker costs - both of which support the ice option.

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