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Refrigeration and cooling concepts for ultra-deep platinum mining

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Impala are considering long-term strategies for mining below 2 000 m in the Rustenburg area. Below these depths, the virgin rock temperatures are greater than 70°C and refrigeration and cooling will play a major strategic role and have a dominant effect on project planning and indeed project viability. Future cooling strategies will involve the use of dedicated 'fridge' shafts for ultra-cold downcast, large quantities of chilled water fed underground through energy recovery facilities, secondary and tertiary (in-stope) air coolers, and ultimately even ice fed underground from surface. Furthermore, any future considerations must include sophisticated and well engineered power control and general energy management. This paper examines all these issues and discusses the relevant technologies. Also, through comparative modelling and life-cycle costing, the paper indicates at which depths the efficacy of fridge shafts runs-out and then at which depths the efficacy of more and more chilled water from surface shafts runs-out, and thus at which depth the use of ice becomes attractive.

Introduction

At present, the cooling of all the hot underground operations at Impala is achieved by providing refrigerated air from surface. However, the depth of a number of planned projects will approach 2 000 m below surface and other future proposed operations will extend to even deeper levels. Obviously these depths will approach the horizon where acceptable underground conditions can no longer be achieved by providing only refrigerated air from surface. At the deeper mining levels supplementary means of providing cooling will have to be implemented.

The objective of this paper is to provide a review of the 'supplementary' refrigeration technology for the 'ultra-deep' planned operations and suggest strategic recommendations in this regard. This paper includes a generic examination of the most cost-effective provision of cooling at depth and gives a summary of the strategic way forward for the future deep shafts and reviews the potential technologies to be applied.

Impala's operations have evolved through a number of generations in which the mining has become increasingly deeper and more ventilation and refrigeration has been applied. The cooling of all the second and third generation operations is achieved by providing refrigerated air from surface. In addition, all service water is cooled atmospherically in cooling towers on surface. Basically, the approach has been to provide more and more air and to make it colder as the depth has increased. For the more recent deeper projects this has included the use of a dedicated fridge shaft. Detailed trade-off studies indicated that this was a better approach to the alternatives of either making the main shafts bigger or introducing air cooling underground.

However, as operations get deeper and deeper, the concept of surface bulk air cooling becomes less and less positionally efficient until ultimately the depth is reached where it becomes cost-effective to start introducing supplementary underground air cooling rather than more and more surface air cooling (even in dedicated fridge shafts).

Generic phases of mine cooling implementation

Because of the unique features of each mine, there is a great diversity in the designs of the existing cooling systems in RSA platinum mines. Mine cooling is, and will be in the future, distributed by both surface and underground air cooler systems. There is also a great diversity of air cooler designs and uses of chilled water. But for global discussion purposes, a generic 'hierarchy-with-depth' for introducing cooling provides a very useful framework. This is shown graphically in Figure 1 starting with ventilation only, progressing to surface bulk air cooling, then underground air cooling, and ultimately ice-from-surface systems for the ultra-deep mines.

The first general guideline is to extend the ventilation-only period for as long as possible to delay the costs of refrigeration. However, cooling by ventilation alone is severely limited by auto-compression and the surface ambient temperatures. Depending on the selected design temperatures and mining methodology, the depth horizon at which ventilation alone can no longer provide adequate cooling will be about 600 m to 800 m (depending on design criteria) even with large quantities of air. Ultimately, the maximum air quantity is limited by the carrying capacity of the primary ventilation circuit, which is constrained by maximum air speeds in shafts. Below this ventilation-only horizon, and depending on the actual heat loads in the mine, refrigeration will be required to remove some part of the heat load.

The next general guideline is to extend the surface bulk air-cooling-only for as long as possible to delay the need for the introduction of underground cooling with an associated step change in complexity and cost.

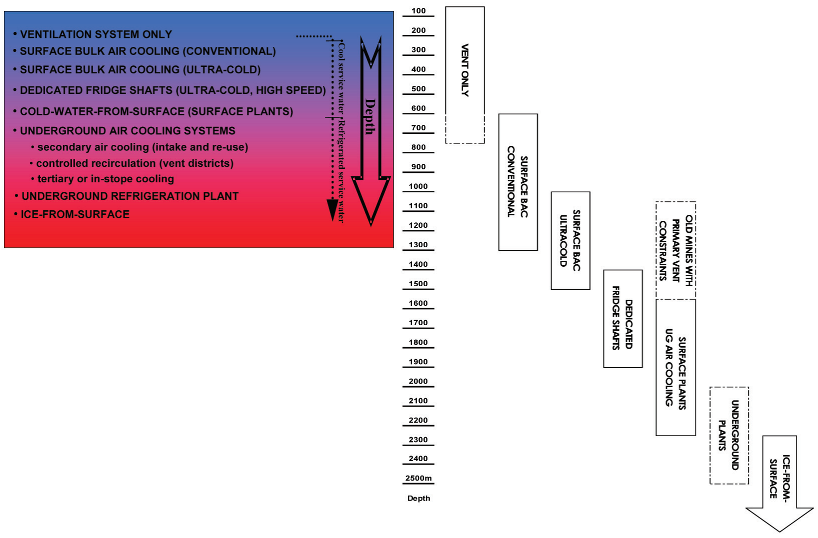

Figure 1. Hierarchy-with-depth and phase-in of refrigeration modes

Thus the optimum cooling strategies for the existing Impala mines maximize the surface bulk air cooling effect. The air temperature downcast from surface is the major factor—the lower the temperature to which air is cooled on surface, the greater the depth to which cooling can be achieved in this manner. Hence the approach of ultra-cold dedicated fridge shafts (operated at high air speeds) has great merits.

As mining gets deeper, ultimately it is inevitable that cost-effective cooling can no longer be provided by more and more cold ventilation from surface. There is a general 'break-even' depth that can be identified and, at that stage, underground cooling needs to be introduced. For this paper, models were set up to identify this break-even depth for the current set of circumstances.

In general, for platinum mines, underground air cooler systems (and service water systems) will be served with chilled water from surface-located refrigeration machinery. This is different from the 'generic' gold mine practice in terms of the hierarchy-with-depth framework. In general, by the time significant underground air cooling systems are needed in typical deep gold mines, they are so deep that the use of underground refrigeration machines is more cost-effective than those on surface because of cold water distribution positional efficiency issues.

For the Impala mining operations, surface-located refrigeration machines will be preferred in general. But there may be exceptions where there are problems installing in-shaft chilled water piping or where heat rejection opportunities are very conveniently located underground.

Continuing with the hierarchy-with-depth concept, as the mining gets even deeper, more and more chilled water will be required from surface and, notwithstanding energy recovery facilities, the return pumping costs will start becoming excessive.

Ultimately it is inevitable that cost-effective cooling can no longer be provided by more and more chilled water from surface. At that stage, in order to contain pumping costs, it will be necessary to seriously consider the use of surface ice-making plants and ice-to-underground cooling distribution systems. Again, there will be a general 'break-even' depth that can be identified at which ice should be considered. In the course of this work, models were set up to identify this break-even depth for the current set of circumstances.

Comparative modelling to identify break-even depths

It is important to understand the break-even depths for introducing chilled air-cooler-water from surface to underground and then for introducing ice from surface. Even though this requires various assumptions and the creation of 'model mines', the results are very useful, particularly when the various main sensitivities are examined. The two relevant basic comparisons are:

- Fridge shaft approach compared to chilled water from surface to underground air coolers
- Chilled water from surface as compared to ice from surface to underground air coolers

The model mine was set up with a mining block of 8 levels producing 255 kt/month. The mining depth was then increased in steps of 200 m from 1200 m to an ultimate depth of 3 000 m, see Figure 2. The heat load profile was generated as a function of depth by VUMA simulations and extrapolation. The different types of cooling systems were then sized and designed to fit each scenario and capital and operating cost comparisons were carried out.

Fridge shaft approach

This approach includes the main hoisting shaft of 10 m diameter downcasting ultra-cold (5.3°Cwb) ventilation. The modelling work shows that this resource can provide sufficient cooling capacity to cool the operation down to the 1 400 m depth scenario, but not beyond. At that stage, a fridge shaft downcasting at 3°Cwb is introduced to provide the remaining supplementary cooling capacity. The size of the fridge shaft and its refrigeration system (and the upcast shaft) must be increased as the operation gets deeper and heat loads increase. For example, for the scenario at a depth of 2 000 m, say, the required fridge shaft size will be about 7 m to 8 m diameter. As the depth approaches 3 000 m, these requirements become unreasonably high (see Figure 3) and clearly this approach is not viable at those depths.

Chilled water from surface to underground air coolers approach

Again, this approach includes the main hoisting shaft downcasting ultra-cold ventilation with this resource

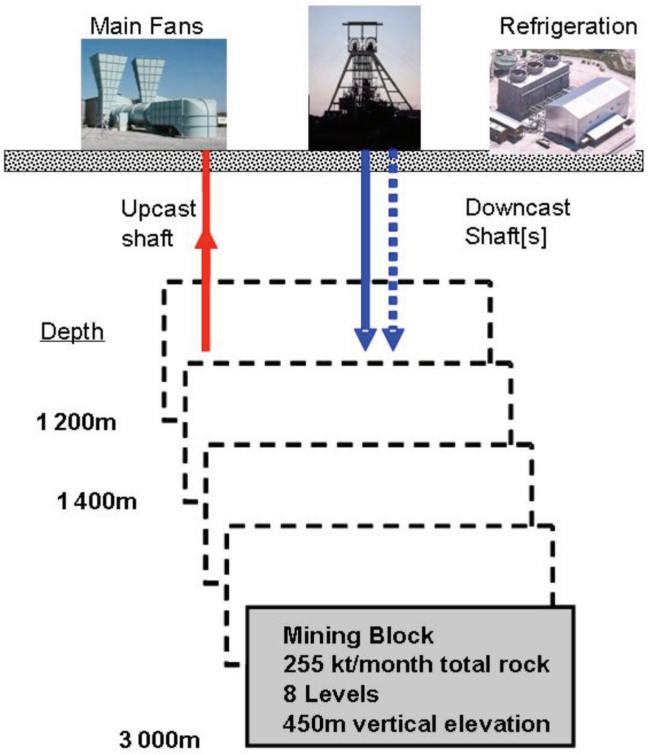

Figure 2. Schematic of model mine with increased depth

providing sufficient cooling down to the 1 400 m depth scenario, but not beyond. At that stage, chilled water from surface to underground air coolers will be introduced to provide the remaining supplementary cooling capacity. Figure 6 shows a basic schematic of this approach. The downcast capacity (and upcast shaft) remains unchanged but the amount of chilled water circulated into the mine (and pump returned) and the underground air cooler(s) capacity must be increased as the operation gets deeper and heat loads increase. For example, for the scenario at a depth of 2 000 m, say, the required chilled water flow rate to underground will be 500 ℓ/s (43 Mℓ/d) and the return pumping power will be 10 MW. As the depth approaches 3 000 m, these requirements increase further until eventually they obviously become excessive, see Figure 4.

Ice from surface approach

Again, this approach includes the main hoisting shaft downcasting ultra-cold ventilation with this resource providing sufficient cooling down to the 1 400 m depth scenario, but not beyond. At that stage and in this approach, ice from surface to underground ice melting dams (and hence to the air coolers) will be introduced to provide the remaining supplementary cooling capacity. The downcast capacity (and upcast shaft) remains unchanged but the amount of ice circulated into the mine (and pump-returned as water) and the underground air cooler(s) capacity must be increased as the operation gets deeper and heat loads

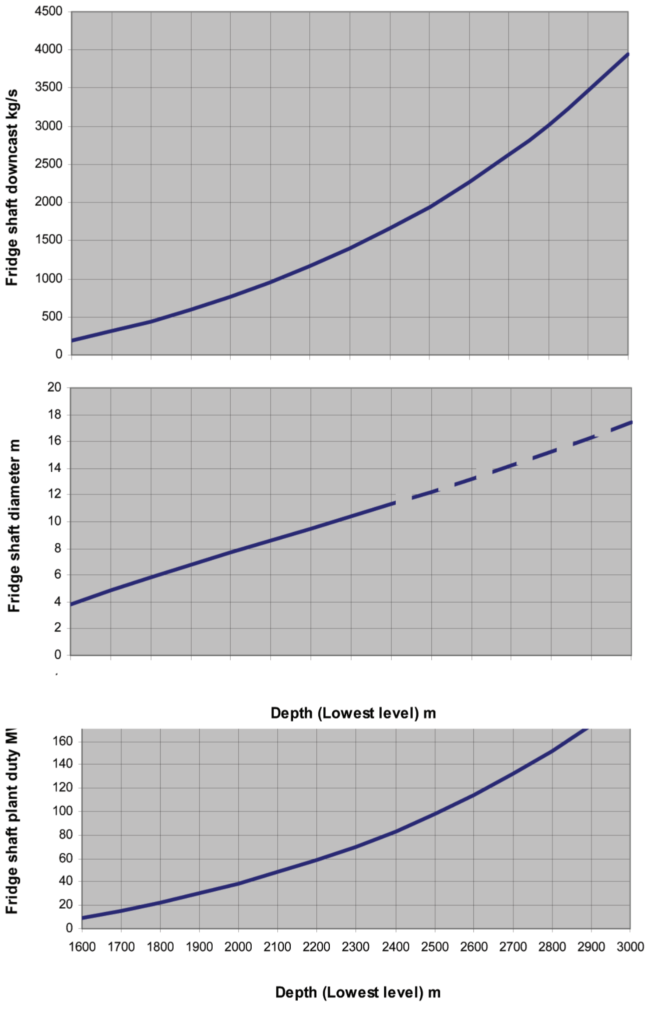

Figure 3. Trends for fridge shaft approach with increasing depth

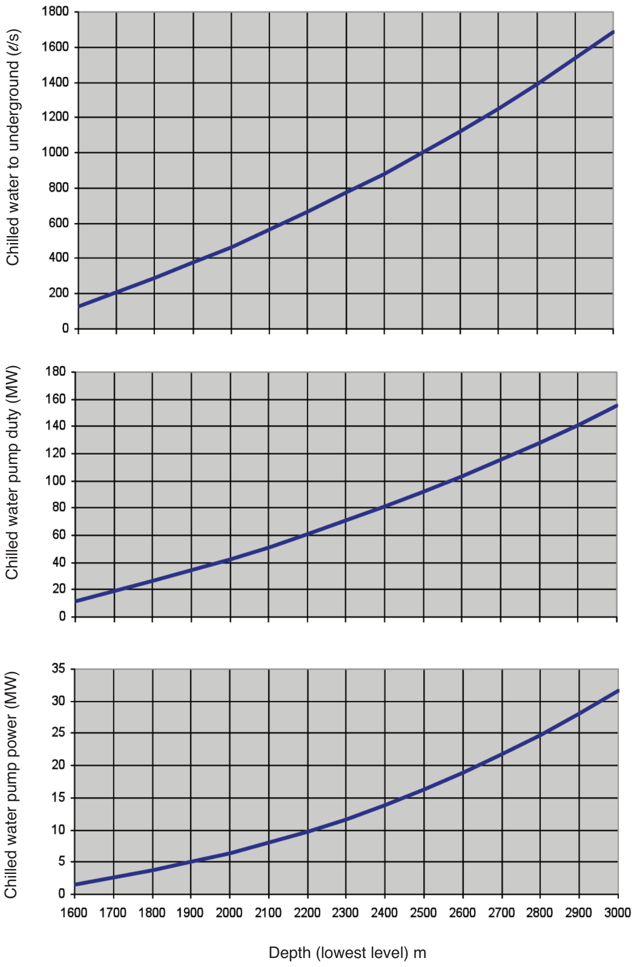

Figure 4. Trends for chilled water to underground approach with increasing depth

increase. For example, for the scenario at a depth of 2 000 m, say, the required ice flow rate to underground (at 94% ice mass fraction) will be 140 kg/s and the ice makers will have a refrigeration duty of 50 MW. As the depth approaches 3 000 m, these requirements are more attractive than the alternative of the chilled water from surface scenario. These trends are shown in Figure 5.

Cost components

Basic comparisons were carried out by examining the capital and operating costs. This was not a full-budget-estimating type analysis but, rather, selected costs were examined of the main components that changed relative to each other. These components were:

Capital cost components

- Shafts
- Airways
- Main fans
- Surface refrigeration plant for surface bulk air coolers
- Surface refrigeration plant for chilled water to underground
- Surface refrigeration plant and ice-making equipment (including feed water plant)
- Turbine-generator stations
- Pump stations
- Underground air cooler systems
- Insulated shaft pipes for chilled water
- Insulated underground pipes for chilled water
- Shaft pump columns
- Shaft ice columns and feeder conveyor systems
- Underground ice-melt dam(s) and secondary pumps.

Operating cost components

- Main fans power
- Surface refrigeration plant for surface bulk air coolers power
- Surface refrigeration plant for chilled water to underground power
- Surface refrigeration plant and ice-making equipment (including feed water plant) power
- Turbine-generator station power
- Pump stations power
- Secondary pumping power
- General maintenance allowance.

Comparison of fridge shaft and chilled water to underground approaches

The totals of the cost components (CAPEX and OPEX) for these two approaches are compared in Figure 6 and the following observations are relevant.

- For depths of about 2 200 m, the comparison is 'break-even' and sensitivity studies indicated that, depending on the variance in key assumptions, this value could be statistically within ± 100 m.
- For depths between 1 900 m and 2 300 m, the difference is not particularly significant.
- For depths greater than 2 300 m, the difference is significantly in favour of the chilled water to underground approach.
- For depths less than 1 900 m, the difference is significantly in favour of the fridge shaft approach.

It is also important to note that the:

- Fridge shaft approach is more capital intensive than the chilled water approach, but
- Fridge shaft approach is less power intensive than the chilled water approach.

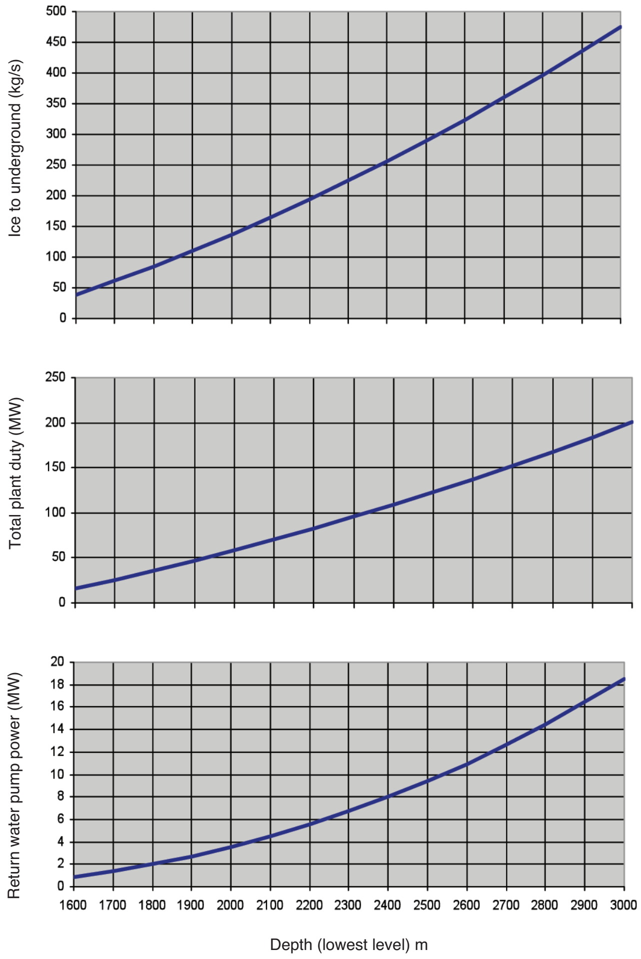

Figure 5. Trends for ice to underground approach with increasing depth

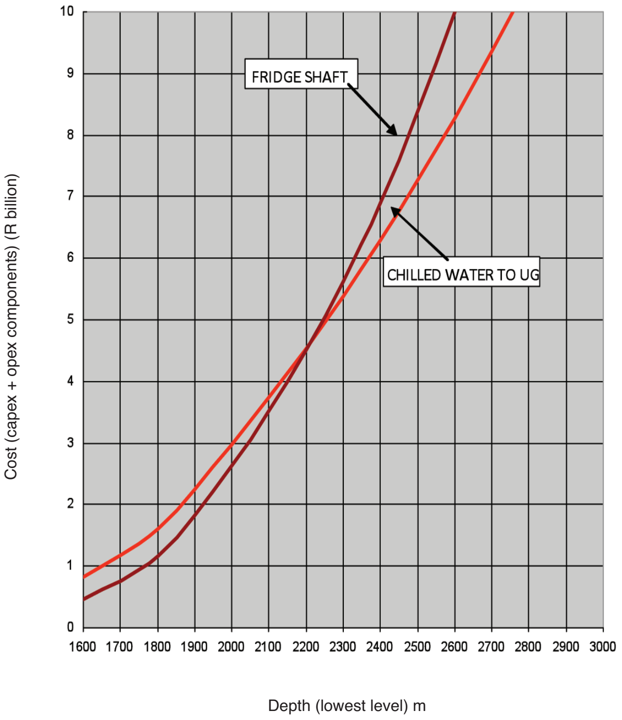

Figure 6. Cost comparison fridge shaft vs. chilled water

Comparison of chilled water or ice to underground approaches

The total of the cost components (CAPEX and OPEX) for these two approaches are compared in Figure 7 and the following observations are relevant:

- For depths of about 2 900 m, the comparison is 'break-even'.
- For depths between 2 400 m and 3 000 m, the difference is not particularly significant (indeed the relatively small difference at 2 400 m depth is a 'surprising' result of this work).
- For depths greater than 2 900 m, the difference will be in favour of adopting the ice approach.
- For depths less than 2 400 m, the difference is in favour of the chilled water option.

There is very little difference in the split between the capital cost and running cost components for either case.

Conclusions of comparisons and break-even depths

For depths between 1 900 m and 2 300 m depth, it will be a marginal decision as to whether to use more fridge shaft provision or to introduce chilled water from surface. The correct decision will depend on site-specific circumstances. However, it is noted that the chilled water scenario will have the attraction of being less capital intensive (but it is more power intensive).

Thus, for the deep platinum operations of the future there should be an introduction of chilled water from surface for underground air cooling and, with this, the following technologies may apply.

- Underground air cooling
  - Chilled service water
  - Secondary cooling of intake air
  - Controlled recirculation in vent districts and bulk air cooling
  - Tertiary or in-stope air cooling
- Pipe insulation
- Energy recovery systems
- High pressure 'U-tube' systems

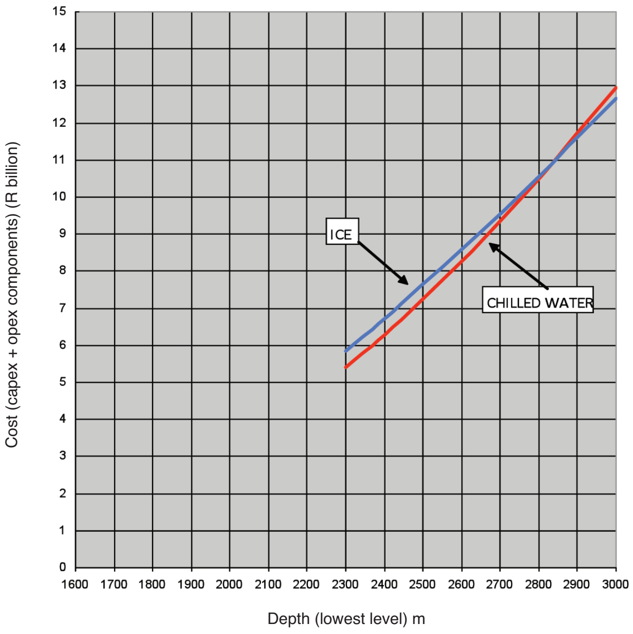

Figure 7. Cost comparison of chilled water vs. ice systems

These topics are each discussed below.

Underground cooling

Underground air cooling will be introduced by any or all of the following, depending on site-specific circumstances:

- Chilled service water
- Secondary air cooling of intake air
- Controlled recirculation in ventilation districts and related bulk air cooling
- Tertiary or in-stope air cooling.

Chilled service water

Platinum mining does not use large quantities of mine service water (with the exception of Northam) and, in terms of mine cooling, this is an important difference when compared to deep gold mines. Platinum mines in RSA generally use about 0.3 t/t to 0.6 t/t of service water whereas some gold mines use up to 3 t/t and more in deep operations. Thus, in these platinum operations, the amount of cooling that can be distributed by chilling the service water is relatively modest.

However, once the stage is reached that chilled water to underground is introduced, the first priority should apply to chilling the service water. When any chilled water is sent underground, the pipe system must be insulated and, once a well-insulated pipe network exists, it is very effective to refrigerate the service water to the lowest practically possible temperature. With the limited quantities involved, the effectiveness of distributing cooling by chilled service water is dependent on delivering genuinely cold water to the workings. The water must be refrigerated to close to 0°C and the distribution system must use well-insulated piping systems with a minimum number of dams.

Refrigerated service water (in an insulated pipe system) is a very effective way of distributing cooling. The cooling is applied directly in the hot workings and this approach has a very high positional efficiency.

Secondary cooling of intake air

Deep South African gold mines have long had similar applications for this type of air cooling and there has long been debate as to whether these installations should be direct-contact spray heat exchangers (Figure 8) or closed-circuit cooling-coil heat exchanger banks and cars (Figure 9). Direct-contact systems are thermally more

Figure 8. Direct-contact spray heat exchangers underground

Figure 9. Closed-circuit cooling-coil heat exchanger banks

efficient but suffer pumping penalties, whereas closed-circuit systems are thermally less efficient but have pumping advantages.

In practice, the selection is governed by the required size-capacity as well as site-specific circumstances. In general, the state-of-art is that, for up to about 1.5 MW duties, closed-circuit cooling-coil banks are used. With these systems, great care needs to be taken to ensure that well engineered water balancing systems and effective *in situ* external coil spray washing systems are applied. These installations will generally be moved and reused more than once during the life of the equipment.

For installations with duties greater than about 1.5 MW, direct-contact spray chambers are generally preferred. These installations will generally be two-stage designs but when the return pumping costs are high, three-stage installations will be used to achieve appropriately high water efficiency performance. These installations are generally not moved during the life-of-mine (but often the spray headers and mist eliminators can be reused).

Controlled recirculation in vent districts and bulk air cooling

The use of controlled recirculation within relatively large ventilation districts will play an important role in some of the future deep platinum mining applications.

Controlled recirculation is used to increase the flow of primary ventilation underground. It relates to the controlled and monitored recirculation of reconditioned return-air back into the primary ventilation supply. Controlled recirculation is implemented to increase the mass flow and cooling carrying capacity of the air flow. It is anticipated that the most effective controlled recirculation schemes will be relatively large and will circulate up to about 200 kg/s.

The driving force for controlled recirculation in deep gold mines is greater than that in platinum mines because of depth and auto-compression. Although some substantial systems were operated successfully for many years, the application of controlled recirculation in RSA gold mines has been limited. The main reason has been the increased awareness of the possible radiation hazard—however, this will not apply in RSA platinum mines.

Indeed, all the recent research related to ultra-deep gold mining again strongly emphasized the need for controlled recirculation in the future (even with the requirement of including radon ‘scrubbing’ treatment technology where relevant).

The application of controlled recirculation and ventilation districts also lends itself to dynamic control of the cooling and ventilation systems and this is considered a very important step in future developments and energy management for both deep platinum and gold mining.

Considerable research, field testing, and application of controlled recirculation was achieved in the gold mining industry in the 1980s and early 1990s. Where applicable, all of this technology and documented experience should be fully embraced by the platinum mining industry in RSA.

Tertiary or in-stope air cooling

In very high rock temperatures, the high temperature increases along the stope-back will sometimes prescribe the need for intermediate cooling of the air as it flows up the stope line. This is achieved in so-called tertiary air coolers and the objective of these coolers is to achieve a significant air cooling effect before the water is discharged to free flow over rock surfaces (and to drains).

The ultra-deep gold mining industry faces the same dilemma of high air temperature pick-up in stopes. The recent deep gold mining research programme identified the development of an effective in-stope cooler as an essential part of deep cooling strategies and an in-stope air cooler and fan unit was developed. Prototype units were manufactured and tested, and Figure 10 shows the general arrangement of a unit. Those tested underground performed

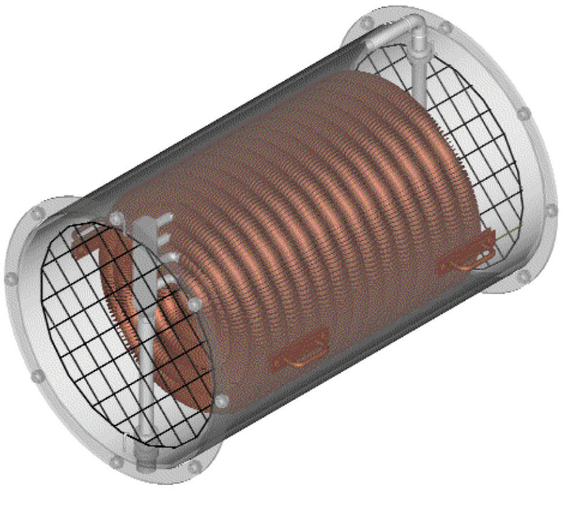

Figure 10. Prototype of an in-stope cooler

well but these units are not widely used in the gold mining industry at present and the design is not fully perfected. But, it is considered superior to the alternative of in-stope spray systems or Venturi cannons (particularly those requiring booster pumping). The great need for this type of product has not yet manifested itself in the gold mining industry but perhaps this will happen when the current wave of expansion projects mature. Apparently the IP and designs for the heat exchanger are openly available to any heat exchanger manufacturer and final development and application of these devices is to be encouraged. In the long term, for mining in very hot rock, these types of coolers will play an important role.

Pipe insulation

As noted, once chilled water to underground systems is introduced, it is essential that this is done in well-insulated piping systems. Chilled water pipe insulation systems comprise an insulation medium, vapour barrier, and outer mechanical cover. Newly installed insulated pipes can effectively contain cooling losses, but the mining environment is such that the insulation loses its effectiveness with time (sometimes very quickly). This is because it becomes damaged and even a small hole in the vapour barrier can lead to complete saturation.

For example, a 300 mm, high-quality insulated pipe system would typically lose about 5 kW per 100 m whereas a low-quality insulated pipe system would lose about 200 kW per 100 m. Considering that some of the future platinum mine systems will probably have more than 15 km of chilled water piping, the cooling losses through piping relate to very significant energy losses.

In general, the existing pipe insulation systems in mines do not perform well—the main problem being mechanical damage and water logging. It is clear that there is a great financial driving force for installing and maintaining high integrity and high quality pipe insulation systems. Significant expenditure in pipe insulation (including maintenance) will be a sound investment in the overall context. By far the most important issue is the specification of the mechanical protection barrier without which the insulation will be almost useless in a very short period of time. With an adequate mechanical barrier, the insulation material itself does not need to be sophisticated, and phenolic foam is widely used underground because of its favourable fire characteristics.

Energy recovery devices

There can be no doubt that the use of water energy recovery systems will ultimately be an important feature for deep hot platinum mines. State-of-art energy efficient systems will be essential for controlling operational costs (again past errors made in the gold mining industry should not be repeated).

There has been much debate over the last two decades comparing turbine generator systems (Figure 11) to hydro-lift systems or three-pipe feeder systems (Figure 12). The comparison of turbines with hydro-lift systems is dominated by the overall effectiveness of energy recovery and pumping efficiency.

For the turbine systems, the effectiveness* is considered to be in a band of data of 70% for an 'upper' scenario and 60% for a 'lower' scenario. Also inherent in the overall system is an assumed pumping efficiency of 75%. Thus, in an overall sense, the energy conversion with turbines can be considered as 53% and 45% for the 'upper' and 'lower' scenarios respectively.

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* 'Effectiveness' term refers to the product of: availability factor, utilisation factor, hydraulic efficiency, mechanical efficiency, thermodynamic efficiency and electrical efficiency (in case of generator).

Figure 11. Typical turbine generator systems (5 MW rating)

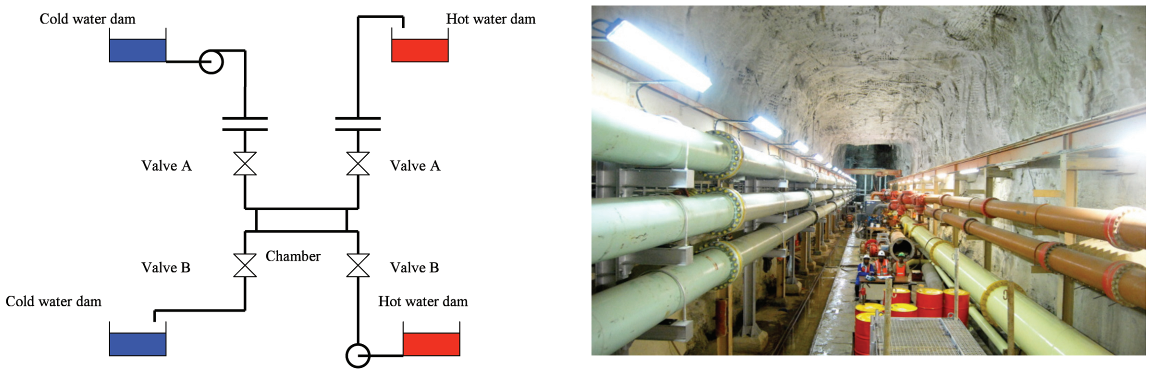

Figure 12. Hydro-lift system

For the hydro-lift system, the effectiveness* is considered to be in a band of data of 80% for an 'upper' scenario and 50% for a 'lower' scenario. In this case, these values include the pumping needs (but, with hydro-lifts, the evaluation must include standby pump capital provision).

The many comparative studies that have been done to examine the specific characteristics of each type of equipment in terms of energy efficiency and capital costs. But, in addition to this, it is informative to examine the losses on an overall minewide basis (because of system 'knock-on' effects). The life-cycle present-value cost differences must be examined for an entire cooling system. This includes capital estimates of refrigeration plants, dams, pumps, pipes, energy recovery equipment, standby equipment and all related infrastructure, as well as operating estimates for all power components (plants, pumps, etc.), maintenance costs, replacement spares, consumables, water treatment, etc. Based on this approach, the hydro-lift systems are generally found to be more favourable.

Indeed, if hydro-lift systems can be proven to be reliable in a fully operational sense, they will offer significant benefits over turbine systems. Hydro-lift systems deserve detailed consideration and the renewed interest in this concept (in deep gold mines) should soon produce the much needed practical operating histories. While hydro-lift systems are conceptually elegant, a long-term sustained operational effectiveness factor of the order of 80% may be difficult to achieve considering the low effectiveness of existing (and past) energy recovery systems and the failure in the past of direct-coupled turbine/pump systems (where 'up' and 'down' water flows needed to be matched).

In a 'two-year-view', the decision on using hydro-lifts would not be clear. But, following more operational information from the gold mine systems presently being installed, it is possible that a five-year-view will fully support the hydro-lift option.

High pressure 'U-tube' system

The viability of using high pressure 'U-tube' systems and high pressure heat exchangers to distribute cooling from surface depends very strongly on depth.

In these systems, chilled water is circulated from surface in high pressure pipes in closed circuit with underground heat exchangers either in the form of high pressure air cooling coils or high pressure water-to-water heat exchangers. However, neither of these approaches is widely used.

Feasibility studies on the use of high pressure closed circuits with cooling coils have concluded that these systems are generally not viable at depths greater than about 1 000 m. Indeed, one platinum mine makes use of high pressure air-to-water heat exchanger systems down to depths of about 1 000 m. Furthermore, high pressure air-to-water heat exchanger systems for pressures up to 500 m are relatively common in RSA gold mines where chilled water is fed from a central underground plant. The only applications at depths much greater than 1 000 m are found in mines that use hydro-power and where minewide high pressure water reticulation systems exist for other reasons.

High pressure water-to-water heat exchanger systems suffer the thermodynamic disadvantage of incorporating an additional cooling medium and inevitably there will be a temperature difference of a few degrees between the cold water in the high pressure system and the low pressure system. One of the few mines that tried this system, without long-term success, was Western Deep Levels in the late 1970s.

Thus, although there have been isolated applications of this approach, it has never been widely applied. However, with new generations of plate and shell heat exchangers this approach will deserve examination in certain applications.

Conclusions

For depths between 1 900 m and 2 300 m depth, it will be marginal as to whether additional fridge shaft provision or whether the introduction of chilled water from surface is more cost-effective. The correct decision will depend on site-specific circumstances.

Thus, the relatively near future should see the introduction of chilled water from surface for underground air cooling and, with this, the following will be important.

- Underground air cooling
  - Chilled service water—first priority with chilled water underground
  - Secondary cooling of intake air—mainly bulk air cooler spray chambers but possibly a limited number of cooling cars
- High quality pipe insulation systems will be essential
- Energy recovery systems will also be extremely important.

This paper has provided a review of this refrigeration technology.

It is also concluded that, on a general basis, serious consideration of the use of ice systems need only to be applied for depths greater than 2 500 m and this will only be a longer-term consideration. However, there may be unusual site-specific circumstances that may establish the exception to this.

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