BIFFI, M. and STANTON, D.J. Cooling power for a new age. *Third International Platinum Conference 'Platinum in Transformation',* The Southern African Institute of Mining and Metallurgy, 2008.

Cooling power for a new age

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Anglo Platinum is in the process of introducing a number of initiatives, varied in nature, on a scale that will impact operations in the short, medium and long-term. The advent of mechanization on a large scale and the introduction of new mining technologies therefore require a different approach to the design of ventilation and cooling systems. In addition, the ventilation and cooling systems serving increasingly deeper operations will place a greater demand on electrical power consumption—this in an environment where power generation is limited and increasingly expensive.

Ventilation and cooling systems currently being employed in platinum operations have evolved from practices first pioneered in deep level gold mines. However, in modern and future platinum mines, deepening of operations will take place in a somewhat different environment—particularly in terms of geothermal settings and electrical power utilization. This provides the opportunities to devise novel and energy-efficient ventilation and cooling strategies tailor-made to meet these challenges.

The need for refrigeration and cooling at depth will increase the capital and operational cost component of ventilation systems and the medium-term limitations on the availability of electrical power will require the provision of innovative systems. The increased use of diesel-powered vehicles underground, the viability of energy recovery and feasibility of thermal storage opportunities are discussed in this paper. Some of the challenges and the solutions currently proposed in terms of ventilation system design, refrigeration plant selection and chilled water distribution methodologies are described. Changes in strategies core to this discipline that affect the health and safety of employees and the profitability of modern operations are deemed necessary to support the transformations that are envisaged.

Introduction

Ventilation, cooling and refrigeration systems will play an increasingly significant role in future platinum mining operations. The increasing depth of operations will result in escalating heat loads having to be handled by expanding ventilation and cooling systems. Considering that the performance of these systems is measured principally by the air wet bulb temperature and (arguably) air cooling power achieved, the most effective strategy to counter the increasing demand lies in providing adequate air quantities supported by effective cooling strategies.

Even if, for some reason, deepening of current operations were not to occur, the role of ventilation and cooling systems will continue to have a bearing on the standard of underground conditions and the profitability of operations. The mean rock breaking depth of current operations will increase, thereby raising the heat load to be handled and extending the magnitude of airway infrastructure to the edge of the existing lease areas. This will result in increased air leakage, airway age and resistance. These aspects have to be evaluated against the increasing age of the capital equipment and infrastructure serving these operations requiring increased maintenance and repairs and generally deteriorating in efficiency.

The increasing cost of powering these systems must be considered. Indications are that power consumption costs will double in the next three to five years and the outlook beyond this horizon is indicative that the age of 'cheap' power in South Africa is over. Given the ageing infrastructure and equipment it must be expected that, unchecked, any deterioration will result in lower efficiencies and in an increased cost burden to the operations.

The intended extended use of mechanized mining methods, irrespective of whether this will occur at greater depths or not, is a reality that must be addressed by the design of future ventilation and cooling systems. Standards regulating emissions from diesel-powered engines and, more importantly, worker exposure to diesel particulate matter present in the exhaust emissions from these vehicles are being revised both internationally and locally. At this stage, indications are that exposure limits will be reduced considerably and that therefore, if increased dilution of these fumes is selected as a control strategy, the capacity of current systems would have to be increased significantly.

Irrespective of the above considerations relating specifically to diesel-powered equipment, the introduction of low and extra-low profile electro-hydraulic machinery in the reef horizon will introduce heat loads that until now were not present and that will raise significantly the heat load experienced in the stoping cycle.

The above factors are deemed to be primary drivers in determining the capacity and effectiveness of future ventilation and cooling systems. However, the most significant aspects on the design of these systems are the sequence and rate at which the orebody is mined that are related to the extraction schedule and degree of concentration of mining operations respectively. The extraction sequence determines the number of stopes and geometry of the airway system serving them. The fact that stopes are to be ventilated simultaneously all of the time—a prerequisite in terms of Anglo Platinum standards—dictates to a large extent the air quantity and degree of re-cooling that are required to satisfy this condition. Also, it has been shown consistently that concentrating mining operations will decrease the size of the ventilation and cooling systems.

This paper discusses the above-mentioned aspects against the background of the foreseen expansion of operations in the next ten to fifteen years and proposes a number of design solutions aimed individually or as part of a co-ordinated approach at providing effective, efficient and viable ventilation and cooling systems together with the associated refrigeration infrastructure.

New mining methodologies and new challenges

From a functional perspective, modern ventilation and cooling systems have to be fit for purpose in terms of both design and operation. These systems must support the principal mining methods while being flexible enough to cater for variations in mining strategies. Furthermore, they must adapt to changing mining engineering requirements dictated by geological structures and the need for economically viable extraction of the orebody.

Of immediate impact on existing and brownfield projects is the increasing rock breaking depth and increasing age of current infrastructures. In the Western Limb, operations have reached an advanced stage in their life. Existing infrastructures will be used to ventilate the extraction of the UG2 reef from the original Merensky Reef network while current Merensky operations will be deepened. In some cases, this entails the introduction of tertiary extensions to existing shaft-decline cluster combinations or the sinking of altogether new shafts to enable, on average, mining at depths varying between 1 300 m and 1 800 m below surface. The corresponding virgin rock temperature (VRT) will range between 51°C and 62°C.

The introduction of mechanized mining methods, both in an absolute or hybrid fashion, will have a significant impact on the capacity and design of future in-stope ventilation systems. Also, Anglo Platinum is extending the introduction of electrically-powered blast-hole drills in stopes while the use of hydro-electrical pumps will also be increased. The intent is a reduction in the use of massive and inefficient compressed air distribution systems in order to diminish operational costs.

From a ventilation perspective, the introduction of alternative electrically-powered units in stopes and in haulages close thereto, many of which convey fresh air to these, means that all of the energy consumed by this machinery will be released directly in the underground environment. In contrast, the expanding compressed air used by pneumatically-powered machinery provides a limited and localized cooling effect. This aspect will be discussed in greater detail later in this paper.

The extension of current operations will result in increase system resistance to airflow, will have a greater propensity to air leakage due to the larger number of sealed-off areas and higher pressure differential across these, and will be highly susceptible to an uncontrolled deterioration of the return airway conditions.

Ventilation strategy

Ventilation systems currently operating in modern platinum operations have evolved from strategies pioneered in narrow reef South African gold mining operations. Typically, ventilation systems make use of the mining infrastructure consisting of a primary vertical shaft or decline clusters developed to an economically advantageous primary horizon.

As the mine is deepened, through the development of a sub-vertical decline cluster or by deepening the existing main decline infrastructure, the ventilation system must be extended accordingly.

The number of production, ledging and vamping stopes determines the air quantity drawn into each half-level. Fresh air is also provided for the on-going development operations on that level. The strategy of drawing air through the mine to a return airway system operated by main surface fans is tried and tested and almost universal in South African mining operations. Controls of these systems are more effective and leakage may be managed more effectively. Most importantly, this tactic precludes the use of trap-doors in the intake airway system and relegates the heat energy generated by the main fans outside of the mine airway circuit. It is unlikely that future mine ventilation systems will deviate from this architecture.

Heat loads

Having outlined briefly the role played by ventilating air, it is suggested that the effect of heat energy resulting from the anticipated expansion of mining operations in Anglo Platinum will have the greatest impact on the design of future ventilation system design. It must be added at this stage that the need for higher dilution levels required to counter the increasing use of diesel-powered equipment and the exposure limits (such as those recently legislated in the USA) might overshadow this consideration altogether.

The use of low profile machinery on the reef horizon as part of a hybrid or fully mechanized stoping suite of equipment is a large contributor to the heat load. For fully mechanized operations, it is estimated that the suite of vehicles required for a production rate of 12 000 tons per month from a single-sided stope, exclusive of the heat energy contributed by conveyor belts and utility vehicles, will increase the heat load from 5.7 MJ/t (contribution by electrical winches only) to 15.4 MJ/t. This means an average increase in heat energy absorption rate from 33.6 kW (over a 24 hour cycle) to 90.9 kW for the same cycle. On average, the contribution seems modest. However, when peak loads that occur during the production shift are considered, this amounts to 195 kW for conventional scraper cleaning combined with electric drilling, against a load of 625 kW for mechanised operations. This contribution is not insignificant and will lead to high panel temperatures if not controlled.

The use of electric-powered drills for blast-hole preparation in stopes will result in a net increase in the heat energy absorbed by the air. Compressed air drills contribute to a net cooling load while all the electrical power supplied to an electric drill will be liberated as heat energy in the immediate environment. It is estimated that for each electrical drill there will be a net heat energy increase of

5.25 kW that the system will have to absorb (inclusive of the cooling effect of the pneumatic drill of 3.5 kW). Globally this effect is of secondary value. However, during a drilling shift the gain dry bulb air temperature in a panel will vary between 0.3°C (at a flow rate of 20 kg/s) and 0.7°C (at a flow rate of 10 kg/s).

The introduction of these novel mining systems will improve the efficiency of the production cycle and will reduce the overall power consumption. However, the heat energy released by this machinery, particularly in the reef horizon, will be significant and must be countered by means of effective ventilation and cooling strategies.

Design standards

In terms of the thermal environment, it is required to use air so that the maximum reject temperature at a minimum air speed of 0.4 m/s is 27.5°C. For naturally acclimatised workers, this relates to an air cooling power (ACP) of 280 W/m^2 which is considered to be an absolute ACP minimum. Air cooling power is principally a function of air wet bulb temperature and air speed (clothing and skin wetness are also parameters that contribute to ACP but for this discussion are considered to be outside the realm of occupational environment control). Figure 1 shows the relationship between air speed and wet bulb temperatures up to 29.5°C for an equivalent ACP value of 280 W/m^2. This implies that environments within the envelope shown have equivalent ACPs and for practical purposes are deemed acceptable in planning and managing conditions in stopes.

The ACP plot indicates that higher wet bulb temperatures may be tolerated as long as higher face air speeds are attained.

An increase in panel air speed also reduces the rate at which air temperature increases in stopes at depth. Figures 2, 3 and 4 show the wet bulb temperature variation experienced as air passes through three in-line stopes. These temperatures were obtained from software models. These have been obtained for stopes located at depths varying between 400 m and 1800 m below surface for operations typically located in the Western Limb. Figure 2 shows the air wet bulb temperature variation for air entering the bottom crosscut of each four model stopes at a wet bulb temperature of 25.0°C. The stopes are at a depth between 400 m and 1 000 m below surface. The air quantity and air utilization in each case has been adjusted for an effective panel air speed of 0.4 m/s. The graph clearly indicates that up to a depth of 600 m the wet bulb temperature will remain below 30.0°C. The decrease in wet bulb temperature shown in the upper stope is as a combination of a number of secondary effects:

Figure 3 shows the same results for stopes to a depth of 1 800 m below surface. In these models, however, the air speeds used for the models were differentiated as indicated in Table I.

The results summarized in Figure 3 indicate that the increased (differentiated) air speeds result in decreased intermediate reject temperatures for the same inlet and operational conditions. In order to make this comparison

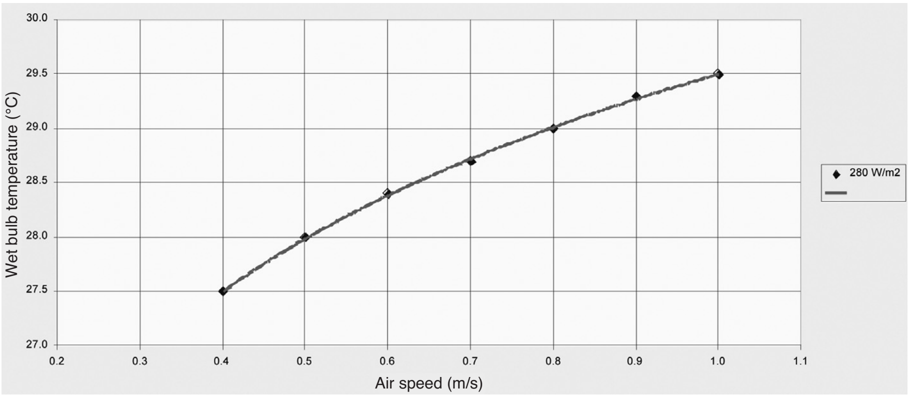

Figure 1. Equivalent air cooling power

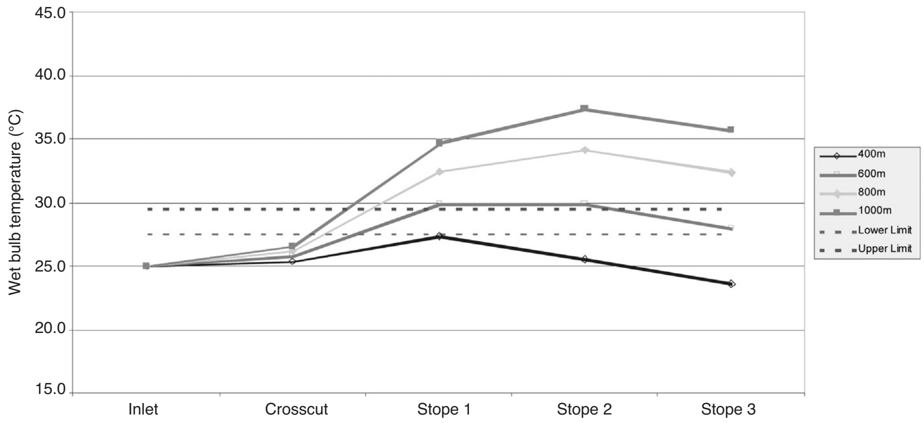

Figure 2. Wet bulb temperature variation

Table I
Differentiated air speeds

Stope depth (m BS)	Air speed (m/s)
400	0.40
600	0.40
800	0.60
1000	0;60
1400	0;80
1800	0.80

even more realistic, cooling was introduced for the model stopes located at 800 m and deeper. The cooling was simulated to reduce the inlet wet bulb temperature to 20.0°C saturated (which is deemed realistic if not slightly conservative). The results are acceptable for operations to 1 000 m below surface as shown in Figure 4.

Other simulations (not shown here) reveal that even if the air were cooled to an unrealistic 0.0°C at the inlet to the first stope, the temperature at the top of stope 3 will be higher than the design limit.

This comparison is demonstrative in nature but shows certain principles that hold true in reality. These are:

- In order to delay the use of secondary cooling below a depth of 600 m, the panel design air speeds should be maximized (an economic optimum should be sought).
- Ventilation of more than three stopes in line, particularly below 600 m, is not recommended.
- Below 800 m, secondary cooling (at stope entrance) will be necessary.
- Irrespective of the degree of secondary air cooling, the effectiveness of the heat energy absorption process reaches an optimum below which increased secondary air cooling will have few overall benefits
- Following from this, below a certain critical horizon (possibly 1 000 m) tertiary cooling of the air in the stoping horizon will be necessary.

Figure 5 shows the temperature envelope for models that include differentiated air speeds, secondary cooling at inlet to the bottom stope and tertiary cooling in Stopes 2 and 3.

These results demonstrate the evolution of a feasible stope air distribution and cooling strategy. It is recommended that simulations of systems based on the gradual introduction of individual parameters be performed to verify the validity of these postulates and to maximize the effect of any optimization.

New methods

This section of the paper outlines strategies that are proposed generically and conceptually for future applications. These are based on the foregoing analyses and on considerations aimed at improving the efficiency and effectiveness of air conditioning processes.

In-stope ventilation controls

An important system attribute that will maximize both efficiency and effectiveness is the proper utilization of air in the stoping horizon. Whereas the primary distribution system is designed to deliver on adequate quantity of cool air to the entrance of the stope, effective ventilation walls and gully brattices will direct the fresh air to the face and reduce leakage in gullies.

Currently pilot projects are being evaluated in order to select viable combinations of methods and materials that can be used in the construction of these control structures.

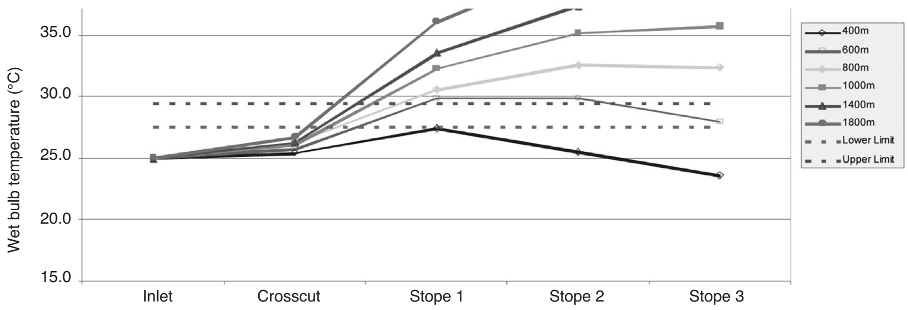

Figure 3. Wet bulb temperature variation with differentiated panel air speeds

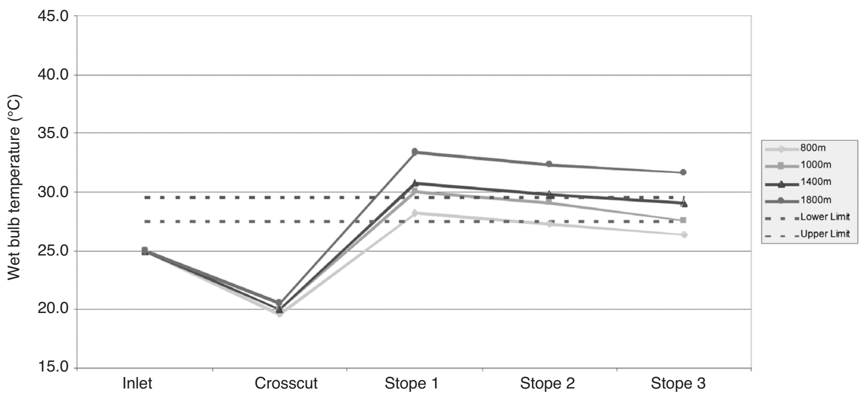

Figure 4. Effect of secondary cooling on wet bulb temperature variation

Preliminary results from these projects indicate the effectiveness of solid cement ventilation walling or paddocks cast in containment bags, suspended along gullies to improve stope air utilization.

Further testing at the deeper shafts in Rustenburg is also aimed at determining whether the postulated reduction in heat energy flux, expected from the effective isolation of worked-out areas by these paddocks from the ventilated face, will be achieved.

In addition, technologically advanced air curtain systems are also being tested and developed at these sites. The aim of this tactic is to enable aerodynamic systems to provide air barriers in gullies while not interfering with the transport of rock and materials.

Air distribution strategies

For deeper operations, observations from projects indicate that, in general, working places located at depths in excess of 600 m below surface and further than 1 500 m from a surface shaft or decline cluster (at the top of which a bulk air cooler is operational) require secondary cooling. Alternatively, the injection of an ultra-cold air stream from surface at strategic positions close to the advancing production front may be a viable alternative to the use of chilled water in secondary heat exchangers. This alternative is of value particularly for operations that will be replaced by new shaft infrastructures in future expansions.

Another alternative being evaluated is controlled recirculation of air coupled to secondary cooling of the recirculated air stream. This requires the provision of chilled service water to air cooling stations located at strategic sites underground that favour the connection between the return airway and section intake infrastructure. Up to 40% of the air quantity being returned to surface from a ventilation district is drawn into the air cooling station, reconditioned and reintroduced into the fresh air stream serving that district. The balance of the air is returned to surface.

On a large scale, there is a potential for decreasing the dimensions of the intake and return airways. This obvious advantage must be offset by the cost of introducing a secondary cooling infrastructure and the need to scrub all contaminants from the recirculated portion of the air before reintroduction into the intake airway system. This may be problematic where carbon monoxide liberated in mechanized sections buildsup as the result of the recirculation.

For safety reasons, the recirculation loop is monitored continuously by means of gas sensors that will stop the recirculating fans should noxious or flammable gases be detected in the return air stream. Also, PLC logic controlling the system will interrupt the recirculating loop at blasting time until the blast fumes are cleared.

Cooling and refrigeration strategies

Air cooling is achieved by generating cold water in a refrigeration plant and circulating this to direct or indirect contact heat exchangers where it is made to absorb heat energy from the air stream. Primary cooling occurs in surface bulk air coolers that handle up to 90% of the downcast air quantity in a shaft. Typically these units are of the direct contact, evaporative type and are used to lower the wet bulb temperature of the air stream to temperatures between 6°C and 9°C. The principal function of these air coolers is to ensure that the air temperature is maintained within a narrow, constant and comfortable range irrespective of surface cyclical weather conditions. In addition, primary cooling systems are designed to counter the effect of auto-compression and heat absorbed from the surrounding rock mass as the air stream descends through the shaft and declines. Ideally, a primary air cooling system will provide this constant air temperature envelope to a predetermined depth below surface and distance along strike.

As the mines advance beyond this critical boundary, additional cooling will be required. This may be achieved in one of two ways. If the mine is relatively shallow and conditions and environmental considerations allow it, 'injection' of extremely cold air from additional surface bulk air cooling plants may be considered. This requires the generation of air at a temperature of not more than 5°C by means of ammonia refrigeration plants or melting ice dams generated from glycol or ammonia plants. Alternatively, and more conventionally, secondary air coolers can be located at strategic underground sites fed through dedicated pipelines or sharing chilled service water off the main distribution network. Typically the air coolers can be conveniently positioned at the top of sub-vertical decline clusters so as to condition the air serving the production areas below this critical horizon.

Presently the use of secondary bulk air cooling is limited to the deeper operational shafts but this strategy will become increasingly widespread in the near future as mean rock breaking depths increase. Cooling systems serving controlled air recirculation sites are defined as secondary air coolers.

Cooling water required for secondary air cooling may be sourced from refrigeration plants located on surface or underground.

Surface refrigeration plants are easily accessible for maintenance and repairs. More importantly, they reject the absorbed heat energy directly to the atmosphere. This means that the coefficient of performance is hig, implying that for each unit of input power to the plant, it can transfer up to six units of heat energy. The penalty for this is a reduced 'positional efficiency'. Intuitively this means that the effectiveness of the cooling process diminishes as mining operations move away from the surface air cooling plant. In the extreme, the heat energy removed from the air in the bulk air cooler will eventually be re-absorbed as the air moves along the intake airways thus providing no relief to the working places.

Chilled water generated on surface is conveyed underground for use in secondary air coolers through thermally insulated pipelines to ensure that the water temperature remains as low as possible in order to maximize the heat absorption process at the air cooling site.

In open-ended pipe networks, the return water is pumped to surface, usually mixed with the mine's service water. This results in contamination of the chilled water which will now require treatment to protect the chiller evaporators from fouling and corrosion.

As an alternative to 'open' systems, the use of high pressure closed-circuit water chilling networks will reduce the pumping power demand considerably but will result in a higher initial capital expenditure. In addition, as the result of the higher levels of complexity and sophistication arising from very high hydrodynamic and hydrostatic system pressures, the system's risk profile will be elevated, therefore requiring high quality safety measures, and adequate levels of skilled maintenance for the network, machinery and equipment.

Underground refrigeration plants enjoy greater positional efficiencies and require considerably less energy for the circulation of chilled water. However, the coefficient of performance of these plants is considerably lower (around three as opposed to six for surface plants). This implies higher power consumption for the same plant cooling capacity. Larger plants require large excavations for the plants and for the underground heat rejection arrangements. Maintenance of and accessibility to the underground plants are more onerous. Furthermore, these plants use exhaust air for heat energy rejection, therefore limiting the cooling capacity generated underground and precluding the use of the air used for heat rejection further downstream.

If it is intended to implement controlled air recirculation as a strategy, with underground chillers providing the necessary cooling water, the capacity of the recirculating system must be optimized to ensure that enough reject air is available for the underground plant's condensers. It is clear that trade-off studies must be performed to establish the most cost-effective configuration for the provision of secondary cooling.

As discussed previously, mines operating below the 1 300 m horizon will require in-stope tertiary cooling to ensure that the reject air temperature objectives are achieved. Similar considerations to those presented above are required to establish the most energy- and cost-efficient refrigeration plant configuration.

The need to provide chilled water for secondary and tertiary cooling in quantities comparable to the service water requirements may favour the bulk cooling of all the water circulated through the mine. As an example, a mine producing 120 ktpm will consume 45ℓ/s of service water daily with a peak demand of 125ℓ/s. At these flow rates, the air cooling capacity of the chilled service water stream will be equivalent to 1 800 kW and 5 000 kW respectively. These relate to a cooling capacity of 15 kW/ktpm and 41.7 kW/ktpm respectively. Considering that the heat load for mines in the Western Limb at depths between 1 300 m and 1 800 m below surface varies between 100 kW/ktpm to 200 kW/ktpm, it is apparent that chilling of the bulk service water stream will not be sufficient to meet this load and that additional chilled water must be conveyed underground for secondary and particularly tertiary air cooling.

Refrigeration plant requirements

The planned expansion and deepening of mining operations within Anglo Platinum in the medium- to long-term requires the introduction of considerably more refrigeration and cooling power than has been the case up to now. More significantly, the electrical power demand for these operations is set to increase along a similar trend.

Chilled water distribution strategies

The introduction of chilled service water or bulk service water cooling is set to become the norm as operations extend beyond the 1 300 m horizon. As a result of this, it is expected that electrical power consumption will increase and therefore power-efficient water distribution strategies must be considered.

The use of high pressure piping for the distribution of chilled cooling water underground has been mentioned previously and possibly offers the most power-efficient solution. Retrofitting these high pressure pipes in working shafts is not deemed feasible.

The use of direct contact heat exchangers inevitably precludes the pressurized return of the cooling water to surface. This means that the water has to be pumped-out together with the service water. Again, retrofitting this technology in an existing plant may only be viable if spare pumping capacity and shaft infrastructure are available. The advantage of direct contact heat exchangers is that they are more efficient, less sophisticated, more robust, portable and relatively inexpensive. Logistically they are the obvious choice for tertiary cooling strategies where constant re-positioning of these units is required as, for example, in a stope.

Indirect contact heat exchangers, typically consisting of metal-finned tube assemblies are more delicate, heavier, more difficult to handle in limited spaces (particularly high pressure units) and susceptible to fouling, which will diminish the efficiency of the heat transfer processes and reduce the air cooling rating while increasing the overall power consumption for the installation.

Figure 6 outlines schematically the evolution of a generic air cooling system. Typically, the primary bulk air cooler will be the first component that will be commissioned and used for shaft sinking and initial development of the shaft. The unit is self-contained, with heat energy being transferred to the atmosphere through the condenser cooling tower (CCT). This plant will generate water at 5.0°C.

As the mine is extended and production increases the second phase will be introduced to generate water at 1.0°C. This will be used as chilled service or as cooling water distributed to secondary and tertiary air coolers. A pre-cooling tower (PCT) is used to handle the primary feed

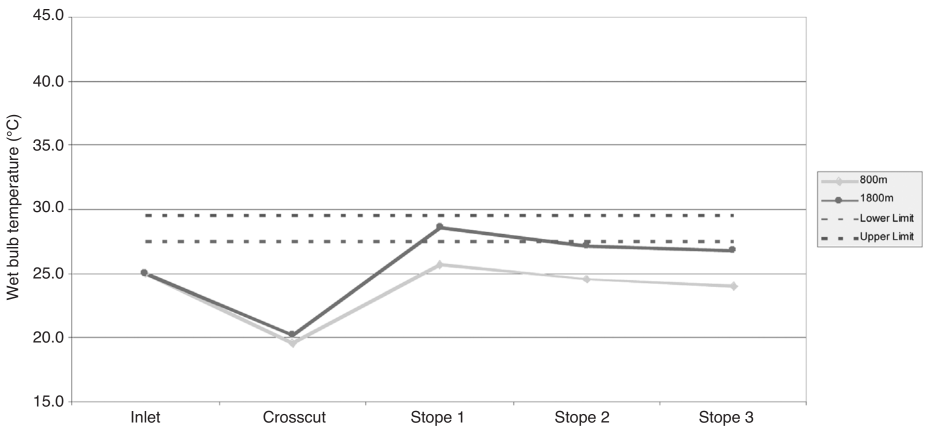

Figure 5. Effect of tertiary cooling and differentiated air speeds on wet bulb temperature variation

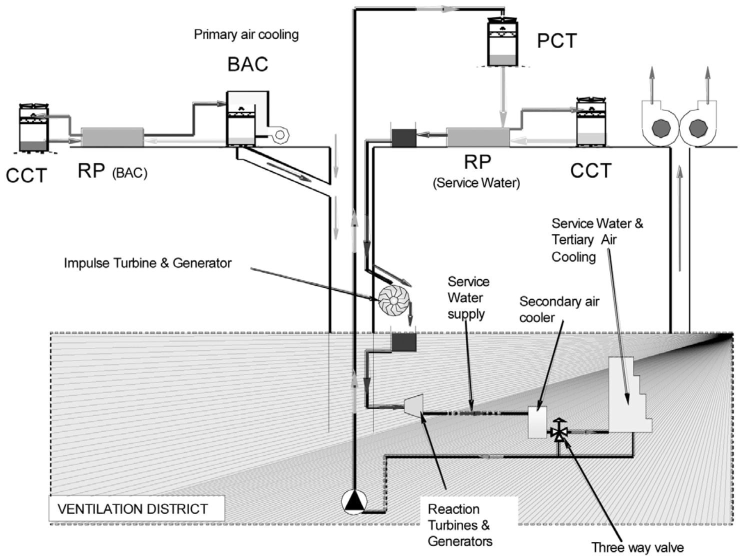

Figure 6. Schematic representation of a modern cooling system

(usually treated water returned from underground) in order to maximize the free cooling effect available from the atmosphere. The PCT reduces the water temperature from 28.0°C to about 24.0°C on a hot summer day.

As indicated in Figure 6, the water enters an underground section along an insulated pipe and is coursed directly into a secondary air cooler. The three-way valve downstream of the cooler will drive the demand for cooling through this heat exchanger. This means that during the working shift, the chilled water will be circulated to the secondary air cooler first and if any is required by mining operations in the stopes or development ends served by this line, then the three-way valve will allow through passage of the cooler return water to the face. When the service water consumption in the section downstream of the cooler is reduced or stopped, the excess water is released into a (dedicated) return line. If the return water is kept separate from the drain water, it may report directly to the clear water dam by means of a separate drain-hole system. At the end of the shift, the system may be shut down totally to limit power usage.

At the start of the following shift, the system is re-activated. The process may be automated to allow pre-cooling of the section prior to re-entry. Figure 6 also indicates the possibility of connecting tertiary coolers located in the stopes, effectively utilizing the service water rejected from the secondary cooler. If water is produced at 1.0°C on surface it is conceivable (see below) that it will reach the stope at about 18°C to 20°C, provided that pipes are insulated and the system is operated optimally. Water at this temperature may be used effectively for tertiary cooling either directly through a jet spray or indirectly in blast-hole drilling or water jetting (where this takes place).

Observations and considerations

An important aspect of this analysis is the transient nature of thermodynamic conditions encountered at depth. Cooling systems are designed to provide adequate conditions at steady state with surface BACs buffering the effect of varying surface atmospheric conditions. At the same time, underground cooling systems are usually designed to handle heat loads that have been 'smoothed' over the diurnal cycle.

In reality, particularly where rock temperatures exceed 40°C, re-entry into a blasted panel at the start of the cleaning shift can subject workers to high temperatures due to the lower ventilation regime (due to the reduced cross-sectional area) and the presence of a sizeable, fragmented and hot rock mass. The best line of intervention to correct these conditions rapidly is to 'boost' cooling by means of chilled water sprays cooling the air stream and that can be moved as the workers proceed with their activities. Alternatively, the use of water jets operated with high pressure chilled service water has shown to be effective to counter these conditions. It is therefore important that low temperature water reaches the face to provide this cooling boost capacity.

The optimal operation of such a system therefore requires:

- Good insulation of chilled water supply lines
- Low residence times in pipes (reduce the number of dams on the supply side of the system, maximize service water through-put in the off-shift period)
- Enhance the through-flow of chilled service water after off-shift periods for air cooling purposes (for example, automate the three-way valve to start-up the secondary cooler one hour prior to the start of the shift).

In general terms, as conditions become more severe with increasing depth, the demand for cooling should not be dictated by service water utilization but rather by the need for reducing the ambient temperature. The two are not always concurrent and the occurrence of 'temporal hot spots' requires that the cooling system is able to provide the necessary boosts when necessary.

In the foregoing sections it was stated that chilled water should be used optimally and that the chilled water should reach the working face at the lowest possible temperature. As a last comment it was said that the cooling plant should be able to provide 'boosting' capacity to manage hot spots. These performance requirements may be achieved by designing and operating these systems with the assistance of a number of components that have been shown in Figure 6.

Energy recovery

Energy recovery devices may reduce the electrical power necessary to pump service, cooling and fissure water to surface. Energy recovery devices may reduce the pumping power by up to 80% in the case of highly efficient systems such as the three chamber pump feeder (3CPF) system or hydro-transformer, in the absence of fissure water.

Devices such as the 3CPF and hydro-transformer are relatively simple units to operate. Essential to their operation is the timing of the valves that open and close the various water streams. The principal drawback of both these systems is that water must be sent underground so as to pump (in some cases even more) water out of the mine. This also implies that fully operational stand-by pump stations will be required. Considering that the pumping load is out of phase with the de-watering demand, these strategies require the use of large underground storage dams to buffer the two diverging demands.

The use of energy recovery turbines coupled to electric generators is also a tried and tested alternative for the generation of electrical power. This method is not as efficient as the 'u-tube' methods mentioned above and also will not cater for fissure pumping. Turbines prefer a steady base-load and therefore coupling these to bulk air coolers as shown in Figure 6 will be advantageous.

The primary turbine in Figure 6 is an impulse turbine (Pelton wheel) located at a strategic depth below surface. The unit will recover about 55% to 60% of the power required to return the same water quantity to surface. In order to maximize flexibility, it might be desirable to have a number of smaller-capacity turbines in parallel. This configuration will enable the handling of a range of flows over the daily production cycle. This implies that during the off-peak period, only one turbine will be operating while the others will be on stand-by. The turbine station must be located high-up in the shaft system to provide enough residual head to enable the use of the service water further downstream. In addition, the dam downstream of the station should not be too large to limit (chilled) water residence time and heat pick-up.

Modern operations make use of pressure-reducing stations to regulate the water pressure on different levels. Figure 6 shows that small reaction (Francis) turbines may be utilized to recover electrical energy while performing the same function and providing adequate residual line pressure.

Whereas Pelton wheel turbines are readily available and have been used within Anglo Platinum, an initial search of Francis turbines suitable for this application has so far failed to identify units feasible for the required operational regimes. Of importance here is the fact that where energy is recovered, as a bonus, the rise in water temperature due to the Joule-Thompson effect is reduced. It is stressed, however, that the reason behind choosing any of these energy recovery devices must remain the ability to recover energy available in the distribution network in a cost-effective manner.

Thermal storage

Positioning refrigeration plants on surface presents unique opportunities for the generation of large quantities of chilled water or ice during low demand periods (usually after 22:00) for use during high demand phases of the cycle (after 07:00). Thermal storage is a tactic that reduces power consumption during peak tariff periods and makes chilled water quantity available during the peak consumption period. This strategy is advantageous considering the current power tariff structure.

Considering that the peak demand for service water during the day coincides with the higher tariff bands, there is scope, if the refrigeration plants and associated thermal storage systems are large enough, to enable the stoppage of the refrigeration plants during the day and utilize a thermal storage strategy that will 'clip' the electrical power demand during tariff peaks.

Another advantage of this strategy is that the refrigeration cycle efficiency is higher at night as a result of the lower atmospheric temperatures.

Ice thermal storage is a refinement of this concept. The advantage of using ice in a thermal storage system lies in the use of the latent heat of fusion of the ice which reduces the physical size of the storage tanks. This advantage must be tempered against the higher capital costs of ice plants and lower coefficient of performance of these plants.

The use of thermal storage is feasible and must be selected based on individual performance, infrastructural merits and overall ownership costs.

Alternative power sources

The affinity between solar power and absorption refrigeration plants is well documented. Initial investigations indicate that this synergy is feasible in certain applications and at certain sites. This involves powering adsorption refrigerators by means of hot fluids (oil or metal salts) generated in solar collectors. These technologies are capital-intensive and have a low coefficient of performance (close to 1). The benefit is that solar power is freely available. In designing such systems it must be considered that stand-by capacity must be available to counter spells of poor solar power availability. In addition, plants must be over-sized and storage thermal capacity must be provided to enable energy or thermal storage during the day for utilization at night. The feasibility of using solar power will be determined by cost considerations and availability (shortage) of electrical power.

Operation on demand

Whereas the foregoing technologies are technically feasible and many have been proven in mining applications, the operation of ventilation and cooling 'on demand' does not enjoy the same degree of support in South African operations. The feasibility of this strategy is based on the need to reduce overall power consumption and to determine whether it is necessary to ventilate and cool the entire mine all of the time. If implemented properly, the ability to activate air movement in a section of the mine or cooling at will is deemed feasible for certain applications and might offer cost savings without compromising environmental conditions.

The reluctance of switching-off fans, particularly in mines where flammable gas may be liberated is well understood and it is advocated that continuous ventilation of such operations is essential.

The strategy of cooling on demand was investigated in detail for deep level gold mines where it was found that the 'thermodynamic inertia' of the rock mass would preclude the successful utilization of this strategy as the heat build-up over 'off' week-ends could not be off-set by the cooling capacity of existing systems. The reason for this was simply that the existing plant was sized to provide cooling capacity based on the 'average' demand and was not able to 'boost' its performance over a short period of time to offset the 'thermodynamic inertia' of the system.

It is postulated that the thermodynamic properties of platinum-bearing rocks are such that their combined 'thermodynamic inertia' will be lower than that of gold mines and that the effect can be more easily overcome by adequately-sized systems. The issue is to be able to establish the required 'boost' capacity, to ensure that it can be activated timely and whether it is reasonable to expect that the (higher) cost of the 'over-sized system' required for this purpose will justify the power savings. This is a strategy that could be considered even where sections of existing operations are being extended.

Conclusions

This paper illustrates concepts of mine ventilation and cooling that are deemed feasible for systems being planned in the medium- to long-term. These concepts are considered to be executable under given circumstances and, except for the Francis turbine application, have been tried and tested in the field.

In addition, the strategies illustrated in this paper offer a number of alternatives and synergies that can be exploited in order to provide fit-for-purpose systems against the backdrop of increasing capital and operational costs.

These new challenges can be met successfully as long as these systems are designed and operated adequately. The 'secret' to this is in the ability to adapt operational regimes to run at optimum efficiency over the life of the projects while taking into account short cyclical demands. Modern systems have to be adaptable and flexible to adjust quickly and accurately to changing conditions. This is a very important shift in emphasis, driven by the need to be energy-wise without compromising the output—in the interest of health and safety.

The most important aspect is ability to manage these systems so that they operate continuously in the intended manner and respond correctly to changing conditions. The level of sophistication of control systems, instrumentation and components governing these is relatively high. In addition, the environmentally-trying conditions encountered underground are well-known and must be countered with tough and reliable components and machinery.

Accurate assessment of conditions and the ability to change operational parameters in line with the information received is essential in achieving real-time control of systems.

The real challenge is in finding the right level of technical skills needed to install and operate these systems. The current skills shortage is affecting the operation of existing systems. The levels of technical complexity inherent in these systems are higher than is currently the norm but are well within the capability of locally available skills—if only these were to be found.

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