THE SYNERGISTIC BENEFITS AND LIMITATIONS OF HYDRO-POWER FOR MINE COOLING

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The financial benefits of hydro-power are dominated by its superiority as a power source in the underground workings of deep level mines when compared to an inefficient compressed air system. These benefits are even greater in hot mines that enjoy the synergy of a combined source of cooling and energy in the production zone. From a qualitative point of view, the benefits of hydro-power are the excellent positional and time-of-use cooling efficiencies. In some cases, the use of hydro-power may reduce or even eliminate the need for supplementary in-stope cooling.

Contrary to expectation, recent work has shown that the macro cooling strategy for deep mines is insensitive to the use of hydro-power. In other words, the feasibility of hydro-power is not influenced by cooling considerations, nor vice versa.

The choice of system pressure will not have a significant impact on the design of the mine cooling system as the quantity of water required for hydro-power is unlikely to exceed that required for cooling purposes and must be justified by the hydraulic energy efficiencies, even at lower pressures.

This paper discusses the realities and myths of hydro-power as a mine cooling medium, especially in deep hot mines.

1. INTRODUCTION AND METHODOLOGY

Although hydro-power is still not in widespread use, there are several mining sections that have been supplying their underground mining operations with only hydro-power, electricity for many years. Indeed one entire mine (Northam Platinum) was designed from the outset to maximise the use of hydro-power and has been doing so for over 15 years. Compressed air was only reticulated for the ventilation of refuge bays. However, the uptake of hydro-power throughout the industry has been restricted by the difficulty of retro-fitting into existing operating shaft structures. Hence hydro-power is usually only considered for new shaft installations. Fortunately hydro-power need no longer be considered a new technology and can be adopted with confidence.

The custodians of the underground environment have long been keen observers and supporters for the development of hydro-power, as the mechanical and logistical challenges have been overcome. They were eager to apply and enjoy the benefits of:-

- improved face advance rates (due to faster drilling), therefore fewer stopes and less heat per ton of rock mined;
- cooling being supplied where and when it is required;

- minimising the number of formal in-stope air coolers
- reducing the number of dams (and therefore heat pick up) in the circuit;
- converting pressure head of service water into useful work thus reducing the Joules-Thomson effect;
- using high pressure cooling coils which allow coolth to be extracted from the water whilst at its coldest, before release of any pressure energy;
- quieter rock drills and better visibility

Numerous studies over the years have confirmed that the high capital costs are soon recovered from the enormous energy savings. Many of the mine specific studies relating to the cooling benefits have been conducted in-house and not formally published. Bluhm Burton Engineering is fortunate enough to have been involved in a number of studies embracing a variety of shaft and infrastructure configurations. This paper focuses on a review of the mine cooling aspects of hydro-power which were most thoroughly investigated during the DeepMine research programme.

2 DEFINITION OF 'CONVENTIONAL' MODEL MINE

As described above, the findings of this work have evolved from a number of studies. In each of these studies, it was important to establish a very rigid base case mine, with variables kept to a minimum so as to focus on the specific impact of hydro-power, and to avoid introducing variables that were not sensitive to the selection of either hydro-power or conventional systems. One example considered an existing mine to a depth of 3,500 m with a new tertiary shaft down to 5,000 m. The required cooling system was then optimised for both conventional and hydro-powered mining options. The typical layout of the cooling system for such a deep level mine is shown in Figure 1.

As a base case, the conventional mine has a nominal total air cooling load of 100 MW of which auto-compression is 42%, tunnels and stations 30%, stopes 16%, developments 8% and other 4%. When losses are included, the total refrigeration requirement is of the order of 115 MW. Underground refrigeration is maximised up to the combined heat rejection capacity of upcast air and return water, and provides about 36% of the mine refrigeration needs. The majority of the refrigeration, typically about 64%, must be provided on surface and this refrigeration plant comprises pre-cooling towers, water chillers and ice plants. The cooling is distributed to surface bulk air coolers 10%, underground bulk air coolers 30%, secondary cooling up to the stope entrance 32%, service water 6%, in-stope coolers 3%, losses to ventilation (useful) 9% and other losses 10%. A pie-chart summary of the cooling system is given in Figure 2.

As a reference, the order-of-magnitude cost of the capital infrastructure for the ventilation, refrigeration and cooling equipment is about R1,500 m. These costs include refrigeration plant, energy recovery turbines, multi-stage pumps, air coolers, pipes, dams, main fans, booster fans and air compressors. The total power consumption is 70 MW with a life-of-mine power operating cost of about R1,000 m.

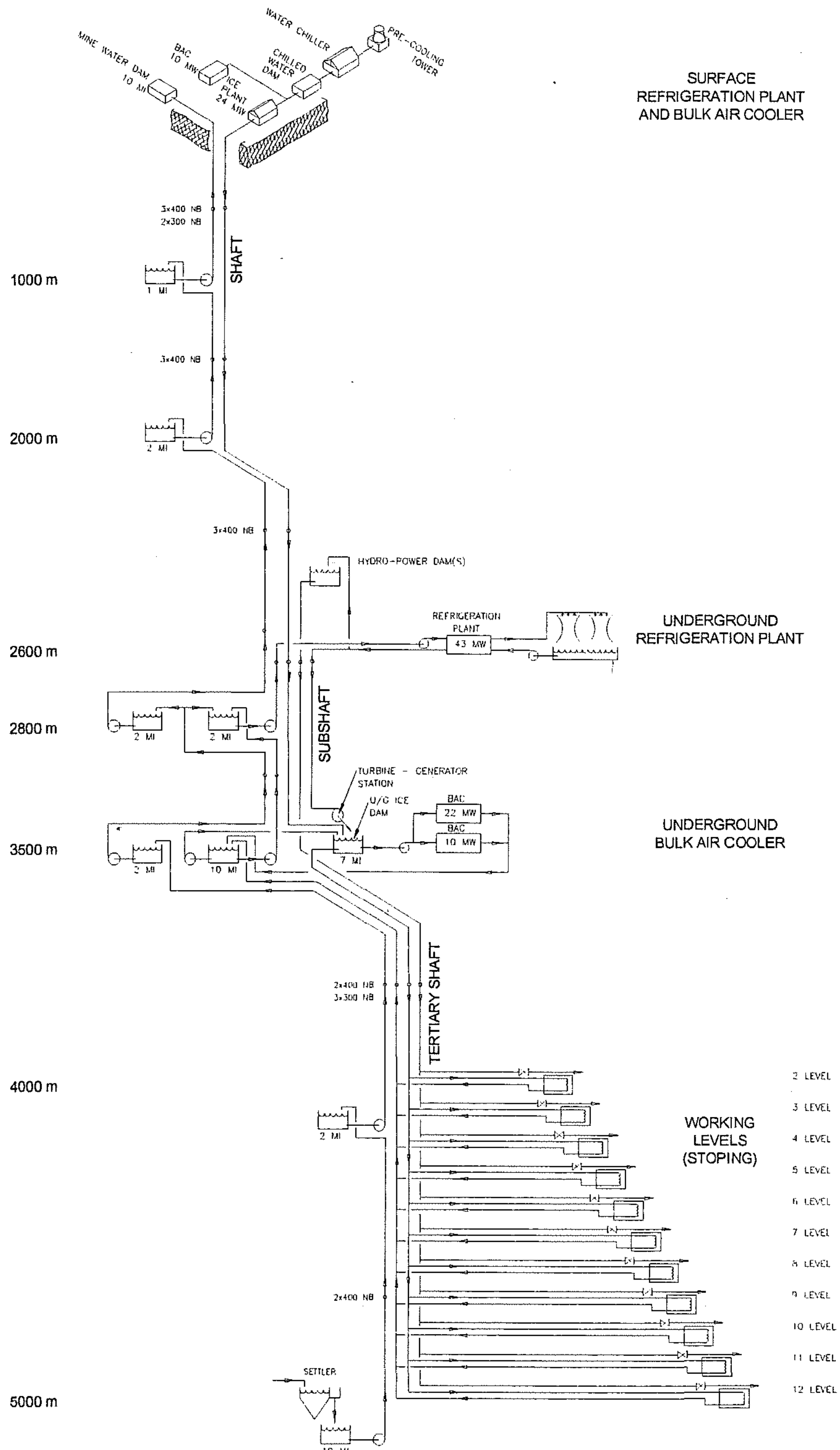

Figure 1: Typical layout of cooling system for deep mine

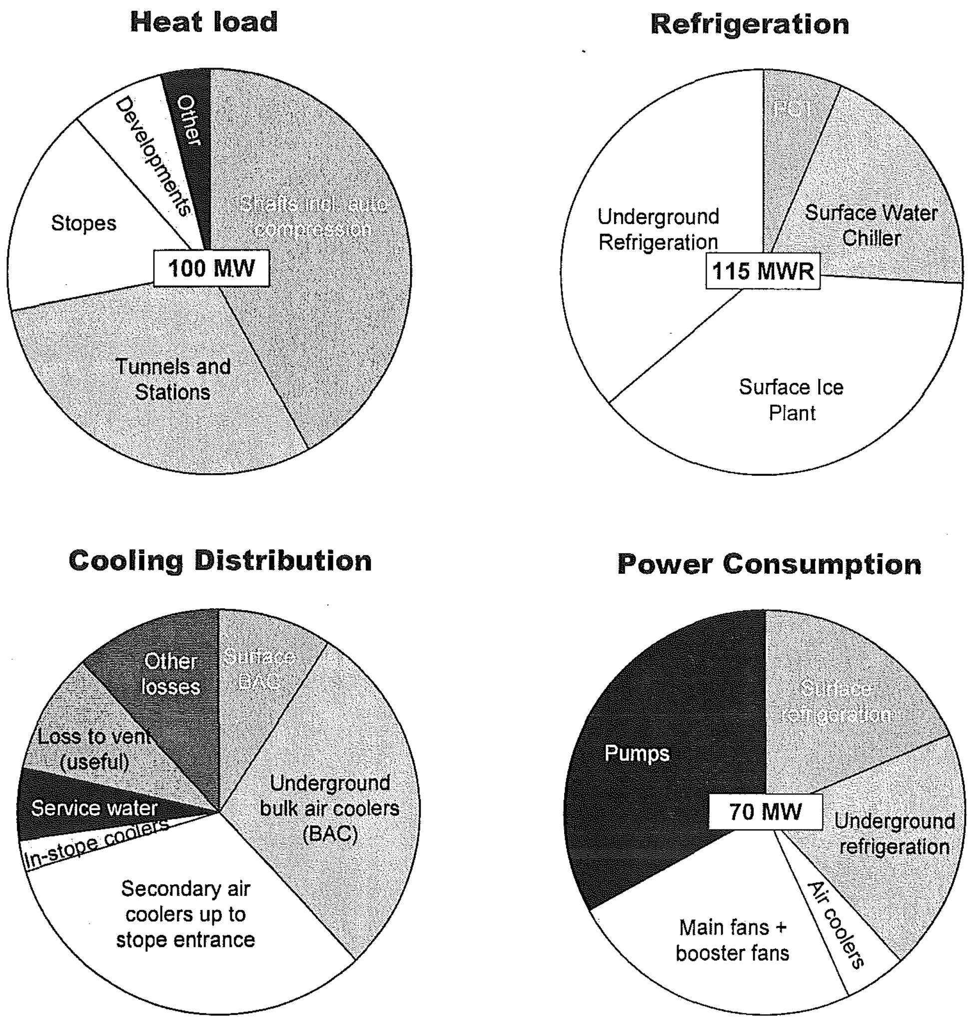

Figure 2: Pie-chart summary of cooling system components for typical deep mine

3 DESCRIPTION OF 'HYDRO-POWER' SYSTEM

Thus far hydro-power has only been implemented on a few mines. Hydro-power is simply high pressure water that is available for powering mining equipment. The principal users of hydro-power water, which dominate the consumption, are rock drills and water jetting guns used for cleaning rock from the face zone. Secondary uses are for prop-setting intensifiers and blasthole cleaners. Figure 3 shows a typical layout of hydro-power equipment in a stope. For deep mines, the system pressure for hydro-power is typically about 14 MPa in the stopes. At these pressures, the accepted norm for in-stope water consumption for mining equipment is 1.6 t/t (ton of water consumed per ton of rock mined). Greater quantities of water are required for lower system pressures.

Especially in deep mines, the choice of system pressure will not have a significant impact on the design of the cooling system as the quantity of water required for in-stope hydro-power equipment is unlikely to exceed that required for cooling purposes and must be justified by the hydraulic energy efficiencies. For this situation, in-stope coolers are required to supplement the cooling.

Two fundamental choices exist for the vertical distribution of hydro-power; either a single distribution system from a single dam, with a multitude of pressure-reducing valves, or a number of dams each supplying a group of levels over a narrow pressure band. The multiple dam system is generally simpler and requires fewer and cheaper valves. Although turbines can be used for energy recovery in a multiple dam system, this potential benefit is counter-balanced by the additional thermal losses in the dam excavations. Therefore, from an overall cooling perspective, there is no significant difference between these two distribution systems and the final selection will primarily be dictated by site-specific constraints.

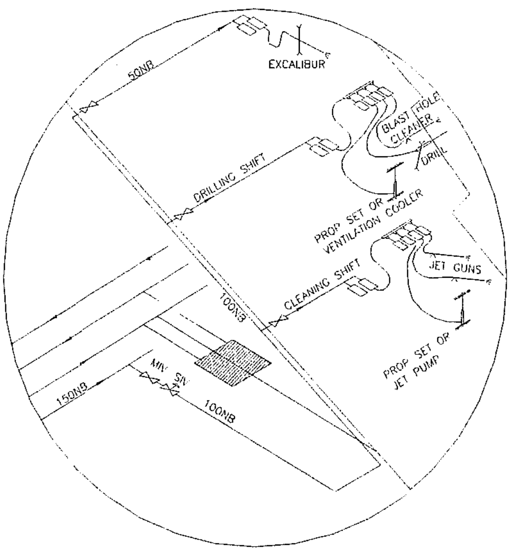

Figure 3: In-stope hydro-power equipment

4 MODELLING PROCEDURE

The analysis of a mine cooling system is complex due to the interaction between ventilation, refrigeration and cooling distribution. Therefore, it is not surprising that the optimisation procedure is highly iterative, as depicted in Figure 4. A suite of simulation tools was used to model each component of the cooling system in detail. These simulation tools enabled various systems and combinations of systems to be compared under different circumstances. Commercially available network simulation software was used for the thermodynamic modelling of the ventilation system and this tool was used to determined heat loads, air flow distribution, and duties of air coolers. Ventilation leakage was accounted for using resistance factors, deduced from an industry survey, so that leakage quantities responded dynamically to changes in system pressures. The analysis of the cooling distribution network considered all heat transfer in the pipe network arising from friction, losses to the ventilation air and heat transfer between the ventilation air and drain water. The design of the refrigeration system was optimised using a custom-built simulation program that evaluated surface water chillers, ice plants, underground water chillers, dams and energy recovery devices. The integrated model considered the effect of ventilation leakage, backfill and cooling behaviour of the various in-stope water consumers, such as service water, surplus free-discharge water usage and in-stope cooling water. In this regard there is a trend towards diminishing cooling benefits when using large quantities of free discharge service water.

By definition, free discharge water is service water that is used in mining equipment. In addition to this water, extra water may be introduced for cooling effect and may be applied in a formal air cooler or could also be free discharge water. Recent studies have shown that the overall air cooling effect of using free discharge water is relatively small in comparison with the total heat gain to this water (induced from exposed rock surfaces). This implies highly ineffective use of chilled service water since the air cooling effect is inadequate and also since excessive refrigeration duty would be required to recondition the service water. The analysis uses algorithms that relate the cooling efficiency to the quantity of water used in a stope. These algorithms were adjusted to reflect the different profile of the hydro-power water usage.

The starting point for the analysis was to introduce hydro-power into the stopes in its role as a powering system and then to investigate its possible use for elements of the cooling system, starting from the stopes and working back towards the shaft. For an optimum cooling system in a deep mine, the appropriate design philosophy is to maximise surface bulk air cooling, secondary cooling on the levels was kept to a minimum and pre-stope cooling was maximised, thus minimising in-stope cooling requirements. A similar procedure was followed for the conventional mine system.

The modelling procedure allowed the total ownership and operating cost for the entire ventilation, refrigeration and cooling distribution system to be determined in a consistent manner for each of the scenarios considered.

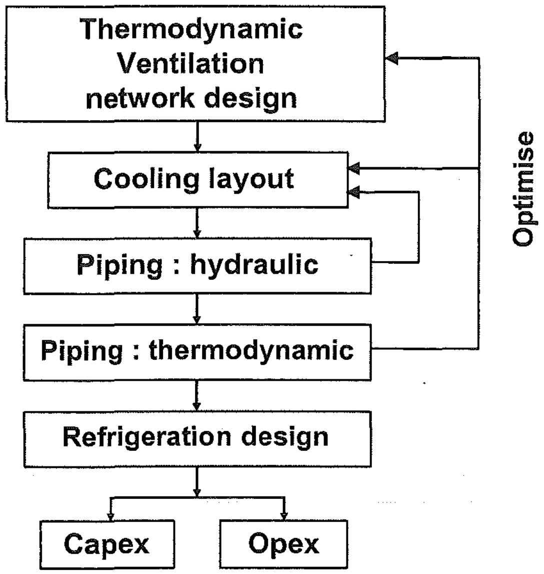

Figure 4: Modelling procedure for optimised cooling system

5 KEY DIFFERENCES BETWEEN ALTERNATIVE SYSTEMS

In general, stopes using hydro-power will, on average, require more chilled water than equivalent stopes using compressed air. The apparent better performance of the conventional mining method can be attributed to the role played by the compressed air as an additional source of in-stope cooling and the effect of water arriving at a lower temperature. These cooling effects are compared below.

5.1 Effect of compressed air

According to thermodynamic principles, the use of compressed air in stopes provides a potential cooling effect of 1.3 kJ per kton mined. The industry average compressed air consumption is 0.25 kg/s per ktpm of which half is assumed to do useful cooling. As a reference, this equates to 1.2 MW useful cooling duty for a production of 180 ktpm. Therefore, the hydro-power system will require more chilled water to compensate for the apparent increased stope heat load.

5.2 Effect of water arriving at an elevated temperature

Studies have shown that there are important differences in the temperature of chilled water supplied to stopes. The arrival temperature of service water to hydro-power stopes, still under pressure, will be marginally warmer because of the longer reticulation from the elevated dam. However, a more significant difference is observed in the discharge temperature from the hydro-powered equipment, after the Joule-Thomson effect has converted the residual pressure (after any useful work done) into heat. Even when assuming a relatively high mechanical efficiency for the hydro-power equipment, the free discharge water temperature will still be higher than conventional service water. Therefore, the hydro-power system will require more chilled water to compensate for the loss of cooling capacity at the slightly elevated temperature.

5.3 Effect of service water utilisation

Based on historic findings as well as recent research done in hydro-power mines, conventional mining methods only requires an average face water usage of 1.0 ton water per ton of rock mined, while the corresponding figure for hydro-power mining is 1.6 t/t. The greater throughput of chilled service water for hydro-power results in a lower requirement for supplementary in-stope cooling. From a cooling perspective, this is considered one of the main advantages of hydro-power.

5.4 Positional and time-of-use efficiency

Hydro-power has excellent positional and time-of-use efficiencies and provides a direct localised cooling effect to operators of drills and water jetting equipment. However, on a broader scale the cooling effect of free-discharge water becomes severely diluted by heat induced from exposed rock surfaces and recent studies [5, 6] have confirmed that formal in-stope air coolers are more effective in distributing coolth.

6 DISCUSSION OF RESULTS

Recent studies for deep mines have shown that the macro cooling strategy is insensitive to the use of hydro-power. In other words, the feasibility of hydro-power is not influenced by cooling considerations, nor vice versa. These specific findings for the deep mine example given in Figure 1 are discussed below.

6.1 Refrigeration and cooling system

The main difference of hydro-power is an increase in total refrigeration and cooling duty (about 1.6%) to replace that provided by compressed air. There are generally only slight differences in duties and layout of the cooling system. For deep mines, secondary cooling on the levels is of sufficient magnitude to justify a separate, medium pressure, closed circuit, distribution system, right up to, and including, the pre-stope coolers. Fewer in-stope coolers are required for hydro-power since the greater throughput of service water (1.0 t/t vs 1.6 t/t) already provides increased cooling duty, albeit less efficient compared to formal in-stope air coolers.

A general observation, which recurred in a number of investigations, was that the water reticulation design should favour the needs of the dominant consumer in that area, but also that if there was sufficient demand for a specific need, then a separate optimised supply could be justified. This applies to the selection of water supply into the stopes. Hydro-power accounted for over 75% of the minimum in-stope water requirements and a second, low pressure, supply for the balance of the cooling was not justified, nor is it practised in mines currently implementing hydro-power. In-stope coolers must therefore be selected to operate off the hydro-power supply.

The total owning and operating costs was shown to be R120 m cheaper for the hydro-power system, equivalent to 5% overall cost saving. This was totally dominated by the power saving of R150 m for the air compressors but offset to a lesser extent by the reduced energy recovery of R17 m. Capital costs for both systems were similar, but slightly more (R30 m) for hydro-power.

6.2 In-stope cooling system

Surplus free-discharge water has been shown to be an expensive and relatively inefficient cooling method [5]. Therefore, any cooling water required in excess of normal mining service water should preferably be applied in a controlled manner in high efficiency air coolers to maximise the cooling efficiency (maximum direct air cooling effect and minimum heat induced from rock). This is particularly true with hydro-power where the high pressure is both expensive to generate (additional pumping power) and is released as heat (Joule-Thompson effect) if not used for powering purposes.

6.3 Impact of higher face advance rates

Hydro-power has the potential to dramatically increase face advance rates in mines. Sensitivity studies have been carried out to investigate the effects of higher face advance rates on the provision of ventilation and cooling when using hydro-power. One sensitivity study considered a face advance rate of 25 m per month. The production scheduling was completely re-worked to generate the new positions for stoping and development. As expected, the number of stoping lines reduced proportionally, but in many respects the layouts remained very similar compared to the original 15 m per month scenario. The downcast airflow only reduced by 6% - a smaller reduction than was expected due to minimum velocity requirements on the levels and development needs. The combined reduction in stope heat load and auto-compression effect provided an overall heat load reduction of 4.2% with refrigeration needs proportionally reduced. This analysis confirms the potential benefit of achieving higher face advance rates.

It should be noted that the higher face advance rate causes several changes to the pre-stope and in-stope cooler population. The cooling provided by the hydro-power (linked to tonnage) was the same for both advance rates. However, with fewer stoping lines, there was less air to be pre-cooled in the stope cross cuts, which then had to be cooled more often with in-stope coolers. The net result was that in-stope coolers more than doubled, while secondary coolers reduced by 11%.

7 CONCLUSIONS

The financial benefits of hydro-power are dominated by its superiority as a power source in the underground workings of deep level mines (more than 15% system efficiency) when compared to an inefficient compressed air system (less than 4% system efficiency). In other words, the feasibility of hydro-power is not influenced by cooling considerations, nor vice versa. However in hot mines, use of hydro-power enjoys the synergy of a combined source of cooling and energy in the production zone. As a reference, a recent case study in a deep mine has shown that the use of hydro-power could realise a modest cost saving of 5% in terms of the total owning and operating costs of the mine cooling system (the cost saving is mainly attributed to the lower power cost without air compressors). Hydro-power has the potential to dramatically increase face advance rates in mines and this feature could generate further cost savings of 4%. It is clear that the many synergistic benefits (productivity, economic and cooling) of hydro-power will ensure that this technology remains a strong contender for future mining operations, especially new deep-level mines.

It is a myth that hydro-power itself is a superior cooling system. In reality the hydro-power system actually requires more refrigeration in order to compensate for the 'missing' cooling effect of compressed air and the effect of water arriving at a slightly elevated temperature. Consequently, stopes using hydro-power will generally require more chilled water than equivalent stopes using compressed air. In hydro-power stopes, the greater throughput of chilled service water for mining equipment may help reduce or even eliminate the need for formal in-stope air coolers which could be a major advantage. However, caution against using excessive free-discharge water because it becomes contaminated with unnecessary additional heat induced from exposed rock surfaces and only provides a localised direct air cooling effect.

8 ACKNOWLEDGEMENTS

This paper has included results from the DeepMine collaborative research programme and this is clearly acknowledged. The paper however also includes observations from other independent studies and expresses the authors' opinion and not necessarily that of DeepMine management. The interested reader may wish to reference the following relevant DeepMine projects: Task 6.4.1 [Cooling generation systems], Task 6.5.3 [Chilled water distribution systems], Tasks 6.6.1 & 6.6.2 [In-stope cooling appliances], Task 6.5.1 [Optimisation of mine cooling system] and Task 13.3.2 [Optimisation of hydro-power mine cooling system].

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