Numerical modelling of heat flow in mines

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ABSTRACT

For deep mines with excavations situated in areas of high virgin rock temperature, the majority of heat entering the excavations is via conduction through rock. The fundamental equations describing heat transfer within the rock and the transfer of this heat from the surface of the excavation to air flowing in the excavation are complex. For example, boundary conditions are not uniform and heat flow into the excavation is not symmetrical; rock surfaces may be partially wet with convection, evaporation and radiation taking place simultaneously at the rock surface; in stopes, mining activities take place cyclically with varying amounts of service water used at different periods in the mining cycle. Thus numerical approximations are required to model heat flow in mines. This paper describes recent developments in the simulation of heat flow into mine excavations. In particular, models developed for underground dams and stopes are described in detail.

INTRODUCTION

In order to design optimum mine cooling systems that ensure a safe working environment and achieve maximum productivity combined with cost effective operation, it is essential to be able to predict the various heat loads and cooling effects in a mine accurately.

The majority of heat entering deep mine excavations is via conduction through rock. The fundamental equations describing heat transfer within the rock and the transfer of this heat from the surface of the excavation to air flowing in the excavation are complex. For example, boundary conditions are not uniform and heat flow into the excavation is not symmetrical; rock surfaces may be partially wet with convection, evaporation and radiation taking place simultaneously at the rock surface; in stopes, mining activities take place cyclically with varying amounts of service water used at different periods in the mining cycle. Thus a number of numerical approximations have been developed. The problem has previously either been reduced to one of radial symmetry by using a uniformly damp airway to represent one that is in reality partly wet and partly dry, or a large set of partly wet cross-section problems has been solved numerically from which a general solution based on interpolation has been developed[1,2,3]. These solutions have been successfully applied in software used for predicting heat loads in mines, for example, Tunnel[4], Vuma[5], Environ[6] and the quasi-steady method[7].

This paper discusses recent developments in the simulation of heat flow into mine excavations. In particular, models developed for underground stopes and dams are discussed in detail.

HEAT FLOW IN UNDERGROUND STOPES

The stoping zone is one of the major contributors to the overall mine heat load and the use of large quantities of chilled service is being considered to combat this heat load in deep mines. Since the 1970's many mines have adopted chilled service water as an inexpensive means of distributing cooling as service water is an inherent part of many mining activities. Exposed chilled service water in the working zones cools the ventilation air directly and also, as the water flows over the hot rock surfaces, it cools the rock. This cooling effect is obtained at the correct time, coinciding with the working shift since this is the period of peak water usage.

An alternative powering system to ‘conventional’ compressed air, the use of hydropower (i.e. high pressure service water) has been introduced in a number of South African mines. Although on an overall mine-wide heat load basis there is insignificant difference between hydropower and conventional systems, there are differences in the cyclic use of service water in production zones. Recent studies, mainly in respect of hydropower mines, indicate that at higher water consumption rates, the service water can leave the stope at a temperature significantly lower than the wet-bulb temperature of the ventilation air and therefore is not used as effectively as at lower flow rates[8].

Therefore, it is becoming increasingly more important to determine the efficiency of chilled water usage in stopes in order to optimise future ultra-deep mine cooling systems, especially considering the high capital and operating costs associated with a mine cooling system.

Recent underground field trials

Underground field trails were carried out to examine the transient cooling effects of chilled service water usage in stopes[9]. The test site was a stope situated in norite with known thermal properties and with a measured virgin rock temperature of 60°C.

Various tests were conducted to simulate the different cooling effects that may occur during a mining cycle with chilled water being used for activities such as drilling, watering down and water-jetting. For each of these tests, the transient thermal response in the surrounding rock mass was monitored using temperature probes installed to various depths within the rock. The typical stope geometry and rock temperature probe positions for a measuring station are shown in Figure 1. Three similar measuring stations were located along the length of the 25 m test site. Instrumentation was also installed at the entrance and exit positions of the test site to monitor the temperature change of ventilation air and service water. The supply water and air flow rates were also monitored.

An important observation is that chilled service water, applied to the exposed rock surface, rapidly cools the surface layer of rock, as shown in Figure 2. For this example, chilled water at 15°C was allowed to flow freely on the rock floor for a period of 4 hours. The high heat transfer rate from rock to water can be explained as a change in the dominant thermal mechanism from convection heat transfer (air-side limited) to conduction heat transfer (rock-side limited) and was observed for both a fully wet surface (running water) and for a damp surface. This change in mechanism also explains why rock heat transfer is only a weak function of water flow rate.

Figure 2 also shows that recovery of rock temperatures at the end of the wetting period is more gradual than the rise during the wetting phase and there is evidence that a residual damp rock surface moderates this process.

Analytical model

A new procedure has been developed for quantifying the transient cooling effects of chilled service water usage in stopes. This procedure is applicable to the advancing face zone of a stope where most of the service water usage takes place and also where acceptable local ambient temperature conditions are most critical. This procedure incorporates two types of heat models: a rock heat model and a general stope model. The rock heat model considers transient heat conduction effects within the rock mass surrounding a stope and is used to predict the boundary heat flux induced by rock wetting and stope. The general stope model sums all stope heat components and is used to predict local air temperature conditions within the stope as well as the temperature of service water leaving the stope. A brief description of these models is presented below.

Rock heat model

A rock heat model has been developed which calculates the boundary heat flux induced by rock wetting and stope ventilation. The model is based on a 2-dimensional unsteady-state finite-difference analysis of the stope advancing face zone with surrounding rock mass and cyclical boundary conditions corresponding to various mining activities. Boundary conditions include an air convection coefficient for dry surfaces and an infinite convection coefficient for wet and damp surfaces. A quasi-steady-state solution is obtained once the results for successive mining cycles do not differ significantly.

The basic procedure applied in the rock heat model is as follows:

- Define mining activity cycle and associated rock-wetting pattern, as shown in Figure 3.
- Calculate rock boundary heat flux profile using finite-difference unsteady-state numerical analysis. Numerous runs are required in order to cover the full practical range of boundary conditions for water temperature, air temperature and air speed.
- Formulate general interpolation tool for calculating rock heat flux for any particular boundary condition. One simplification that is applied is to scale the heat flux for a wet rock surface in proportion to the temperature differential that exists between rock and water. This scaling method is valid since the air cooling effect [convection] is insignificant in relation to the water cooling effect [conduction] on the rock surface.

The finite-difference numerical analyses were carried out on a 300 MHz PC using a commercial CFD package. The 2-D solution mesh was optimised at 16.5 m × 21.5 m using a fine 0.1 m × 0.1 m grid size immediately around the 1.5 m × 3.5 m stope section and a coarser grid size at further distance from the stope. Functionality was programmed into the model to advance the face zone by 1 m and apply backfill in worked-out area after each mining cycle. Typically, the solution required about eight complete 2-day mining cycles before a quasi-steady-state solution was obtained. The overall solution time was less than one hour using a time-step of 6 minutes and involving a total of 1920 time increments.

Results of these detailed analyses are in the form of boundary heat flux plots. An example of predicted rock temperature isotherms surrounding a stope is shown in Figure 4.

General stope model

This thermodynamic simulation is performed in a spreadsheet type model. The model sums the major heat sources, comprising exposed rock heat, broken rock heat, fissure water heat, backfill material heat and machine heat.

Next, the model calculates the heat gain to the ventilation air and chilled service water, accounting for the thermal interaction between the air and water. In order to determine the change in air and water temperatures it is necessary to integrate the heat loads over the length of a stope. The spreadsheet model performs this integration by dividing the stope into small sections and summating the heat loads for each incremental section. This procedure is iterative since the ventilation air and service water flow counter-current to each other.

Inevitably the analysis must be based on a number of simplifications, as follows:

- All service water is introduced at the top of the stope face zone and leaves at the bottom.
- Ventilation air flows counter-current to the service water flow.
- Air and water leakage from the stope face zone is negligible due to high backfill cover.

- All water streams are fully mixed; therefore water temperature is uniform at each section.
- Size and location of wetted areas remains static for each mining activity; therefore an average wetting profile is applied in the model.
- The model also makes allowance for the effect of extended surface area due to waviness of water surface, formation of water droplets and also mass transfer effects.

Conclusions

A new model has been developed for calculating the transient heat load in a stope over a mining cycle. The model has been validated using data obtained in recent underground field trials. In general, predicted rock temperatures showed acceptable agreement with measured field data and this confirms that the model can be confidently applied to other mining scenarios.

The model has also been applied to a 'deep mine' case study to determine the optimum stope cooling strategy: whether it is best to use chilled water in formal air coolers (air-water heat exchangers) at strategic locations in a stope or simply continue with the current practice of using chilled water in mining equipment, such as rock drills and water-jetting guns[10]. The appropriate water quantities for air coolers and mining equipment were also obtained.

HEAT FLOW INTO UNDERGROUND DAMS

Deep mines making extensive use of chilled water underground, whether for mine service water or for air cooling purposes, or both, often use chilled water dams, both on surface and underground. The use of dams makes it possible to size refrigeration equipment to handle average cooling requirements while enabling the chilled water system to cope with varying demands, and also to provide continued cooling for a period should cooling equipment failure occur.

However dams do incur cooling losses, and it is important to be able to quantify these losses. As underground dams are often situated in rock in an area of high virgin rock temperature, and have to be ventilated for safety reasons, the water in dams is subjected to an undesirable heat load, and it is important to be able to predict this heat load.

Water in dams receives heat from the submerged rock surfaces, and on its surface by convection and condensation from the ventilating air and by radiation from the exposed rock surfaces, as illustrated in Figure 5.

Rock heat exchange comprises both conduction from the submerged rock surfaces, and thermal radiation from exposed rock surfaces. Exposed rock surfaces can also result in heat transfer to the air - some of this heat can subsequently be transferred to the dam water.

Heat exchange between the air and the water surface comprises both sensible heat transfer and latent heat transfer, due to condensation on the cold water surface.

If a chilled water storage dam is to perform its function the water level will change with time. Generally the dam will be full, or approaching full in the early morning. Water required during the main morning shift will result in a lowering of the water level, with a minimum water level occurring around 15h00. After this time the dam water level will start to rise, the dam becoming full again early the next morning. Obviously the details of these dam level changes depend on the specific circumstances in the mine.

In a dam there are rock surfaces in the 'tidal' zone, where the rock is submerged when the dam water level is high and exposed when the water level is low. When this rock is submerged it is exposed to cold water, and will be cooled. When it is exposed it is initially cold, and will be heated by both sensible and latent heat transfer from the air. Rock in this tidal zone thus forms part of a regenerative heat transfer process, whereby heat is transferred from the air to the water via the rock.

Theoretical model

The heat transfer processes occurring in an underground chilled water dam were analysed for what was considered to be a reasonably representative dam.

The dam was taken to have a capacity of 5 Ml. Initially it was assumed to be situated in a nominal 5 m wide by 4 m high excavation with a total length of 300 m. In later work, which is not described here, the width (and consequently the length) was varied to obtain a range of rock surface areas in the tidal zone.

The dam water content was assumed to vary from full down to 25% full. The incoming water entered at a constant flow rate of 170 l/s, and a constant temperature of 5ºC. Figure 6 shows the variation in dam water content.

Heat transfer from the rock constituted the main computational problem. The large difference in rock surface temperature between submerged and exposed rock surfaces, and the complication of the heat transfer processes taking place to and from the tidal rock surfaces meant that conventional methods for estimating heat flow into underground excavations were unlikely to be reliable. The use of a finite difference equation approach was felt to be necessary.

In addition the large differences between exposed rock surface temperatures and the water temperature indicated that thermal radiation heat transfer processes should be included in the analysis.

With the assumed water consumption pattern, and the dam size, the tidal zone was 2.5 m high. A mesh size of 5% of this, or 125 mm, was selected for the finite difference equation analysis.

Excessively long computing times would be required if the finite difference equation analysis were to cover the full age of the dam excavation. Computing times would be long both because of the age, which could be many years, and because it would be necessary to extend the mesh for large distances into the rock, as cooling would extend into the rock for many tens of metres.

Instead the finite difference equation analysis was designed to solve the short-term heat flow problem resulting from the daily changes in water level in the dam. Thus the analysis established, using trial and error procedures, that initial rock temperature which resulted in a zero net heat flow from the rock into the dam excavation. One of the results of the analysis was a value for the mean rock surface temperature.

According to the superposition principle the long term rock heat flow, the heat flow resulting from the difference between the virgin rock temperature and the mean rock surface temperature of the excavation, could be calculated separately and added to the short term heat flow results. The calculation of the long-term heat flow is easily done using well-established methods.

The only problem with this approach is that while the short term analysis gives clear information on the heat flow to the dam water and the heat flow to the air, the long term heat flow figure is the total into the excavation, with no simple way of arriving at separate values for the heat flow into the dam water and into the air. However, this issue becomes relatively unimportant for certain optimum cooling strategies. For example, one of the conclusions of this work is that heat gains are significantly reduced if heat transfer between the air and the water is reduced, by reducing either the air flow rate or the air temperature, or both. When this is done the air cannot receive a large amount of heat from the exposed rock surfaces, and thus knowledge of the long-term rock heat becomes relatively unimportant.

The finite difference equation analysis handled both heat conduction within the rock and heat transfer at the rock surface.

The stability criteria which apply when using the finite difference equation approach to transient two-dimensional heat flow problems require that the space and time increments are chosen so that

- $Fo \leq 1/4$
- $Fo \leq 1/[2(2+Bi)]$
- $Fo \leq 1/[4(1+Bi)]$

Where Fo and Bi are the Fourier and Biot numbers respectively.

As mentioned earlier the space increment was chosen as 125 mm. The time increment was thus selected so that the above inequalities were satisfied. An additional requirement, so that the data on dam water level variations could be easily used, was that there should be an integral number of time increments per hour.

It was assumed that the rock was homogeneous and isotropic, and values for the thermal conductivity and the thermal diffusivity that were typical of Witwatersrand quartzite were used (5.74 W/m.K and 0.00000255 m^2/s respectively). Some calculations were also done using the thermal properties of norite (2.63 W/m.K and 0.00000116 m^2/s respectively).

Surface heat transfer was handled as follows: -

- Submerged surfaces - Rock surface temperature equal to the dam water temperature
- Exposed surfaces :-

Convection - The air mass flow rate was an item of input data. The following equation was used to calculate values of the convective heat transfer coefficient, based on the open area above the surface of the water in the dam.

$$hc = 3.4 \text{ (mass velocity)}^{0.8} / \text{(equivalent diameter)}^{0.2}$$

Condensation - When the rock surface temperature is below the dew-point temperature of the air condensation will take place. When this occurs an equivalent heat transfer coefficient and air temperature is calculated. This is done by calculating a series of values of total heat flux to the surface for different assumed surface temperatures. The surface temperature resulting in zero heat flux is the equivalent air temperature, and the rate of change of heat flux with surface temperature is the equivalent heat transfer coefficient.

Thermal radiation - Thermal radiation was considered separately for each exposed surface element. Each element was assumed to receive thermal radiation from the dam water surface, each element in the tidal zone of the sidewall, the sidewall above the tidal zone and the hangingwall.

For each exposed surface element a value of the thermal radiation view factor was determined for each of the above sources, on the assumption that the source extended indefinitely in the horizontal direction.

While, as mentioned above, the air mass flow rate was specified, the calculation procedure did not take into account changes in the air temperature. This was because this would have necessitated setting up either a full three-dimensional set of finite difference equations or several sets of the two-dimensional equations. Both approaches would have resulted in a huge increase in computing time.

The results of the calculations thus do not provide a complete picture of heat flow into the dam excavation, but they do provide the basis for establishing this complete picture.

Results

Before discussing the results in detail it is necessary to deal with some further aspects of the finite difference equation approach. These concern the extent of the finite difference mesh and the time period to be used for the simulation.

It is important that the finite difference mesh should extend sufficiently far into the rock so that the temperature changes resulting from the changing dam water level should not propagate as far as the boundaries. It is also important that the selected boundaries should not be too far into the rock, because this would adversely affect computing times.

Some initial trial and error work established that the finite difference mesh should extend about ten metres into the rock.

As mentioned earlier the finite difference equation approach was aimed at establishing the short-term heat flow values. If the dam water level variations are repeated every day it takes some time to establish the temperature distributions in the rock, and hence the heat flow values to reach a steady recurring state. Some trial runs showed that temperatures were still changing, although only very slightly, after more than a hundred days.

In practice dam water levels do not repeat exactly each day, and weekends cause a further disruption. It was felt that there was little point in using a time period that was sufficiently long for a theoretically correct recurring state to be established when no underground chilled water dam would ever operate in this way. Somewhat arbitrarily a time period of seven days was selected, and all results refer to conditions on the seventh day.

The results are best illustrated graphically. Figure 7 shows how the various rock heat flows vary over a day. The submerged rock can only transfer heat to the dam water, and the pattern of this heat transfer follows the dam water level. The exposed rock gains heat by convection and condensation from the air, and loses heat by thermal radiation to the cold water surface. The mean value of the total heat flow to the exposed rock is equal to the mean value of the heat flow from the submerged rock to the water. As mentioned earlier this is necessary if the finite difference equation approach is to model only the short-term heat flow component. The equality between these two values is achieved by trial and error during the computing process.

Figure 8 shows how the various heat flows to the dam water vary over a day. The major heat flow component is from the air, and it can be seen that this varies significantly during the day. This heat flow component depends on the convective heat transfer coefficient, and upon the dam water temperature (and upon the air temperatures, which remain constant over the 24 hour period). While heat flow directly from the air is the major component, the other two components (regenerative heat flow from the tidal rock surfaces, and thermal radiation from exposed rock surfaces) are also significant.

Figure 9 shows how the dam water temperature varies as a result of the heat flows shown in Figure 8. The results shown in Figures 7, 8 and 9 all apply to one dam size and shape, and to one air flow rate and temperature.

Simulations have shown that the magnitudes of the cooling losses for typical dam scenarios can vary from about 500 kW to 1500 kW depending on the dam ventilation circumstances, dam size, dam shape and temperatures.

Conclusions

Procedures and methods have been developed for predicting the heat gains to the water from both the air and surrounding rock for underground chilled water dams. Field measurements were made at an underground chilled water dam and the predictive methods were then applied to this dam for comparison with the measurements. The agreement was reasonable although the predictive approach appears to underestimate by possibly 20-30%.

The main conclusion is that heat transfer from the ventilation should be reduced to a minimum by limiting the air flow rate (this will also reduce the regenerative and radiation heat components) and this should take priority over any other way of reducing losses.

The only way of reducing the long-term heat flow from the surrounding rock is to install insulation on the rock surface. This insulation will reduce the long-term heat as well as the regenerative and radiation heat components. Direct heat transfer from the air to the water surface can be reduced by use of an insulation blanket on the water surface (but such insulation, without rock surface insulation, would not reduce the regenerative heat transfer).

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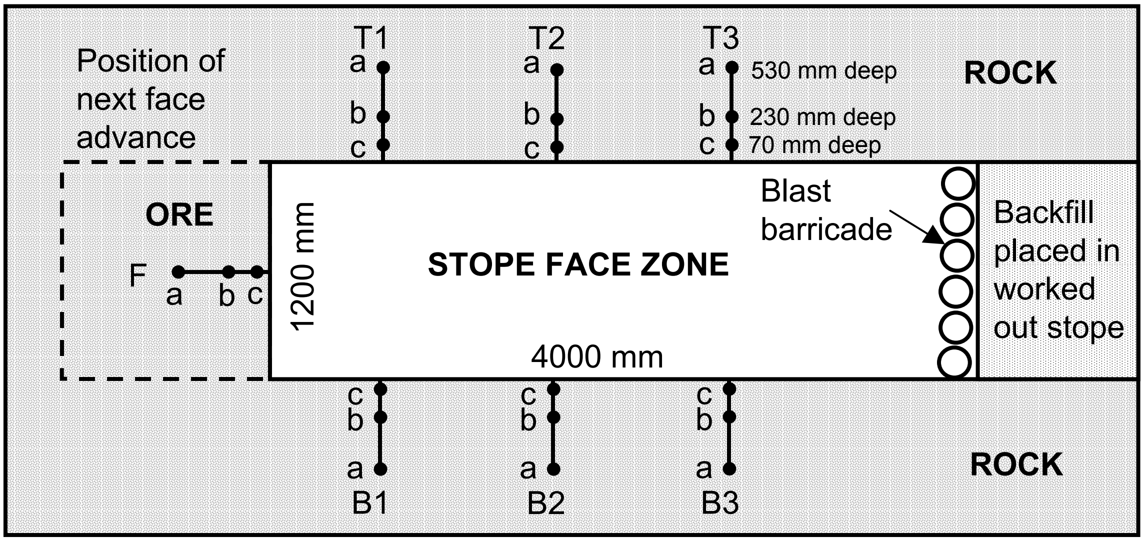

Figure 1 Typical section through stope used for underground field trials[9]

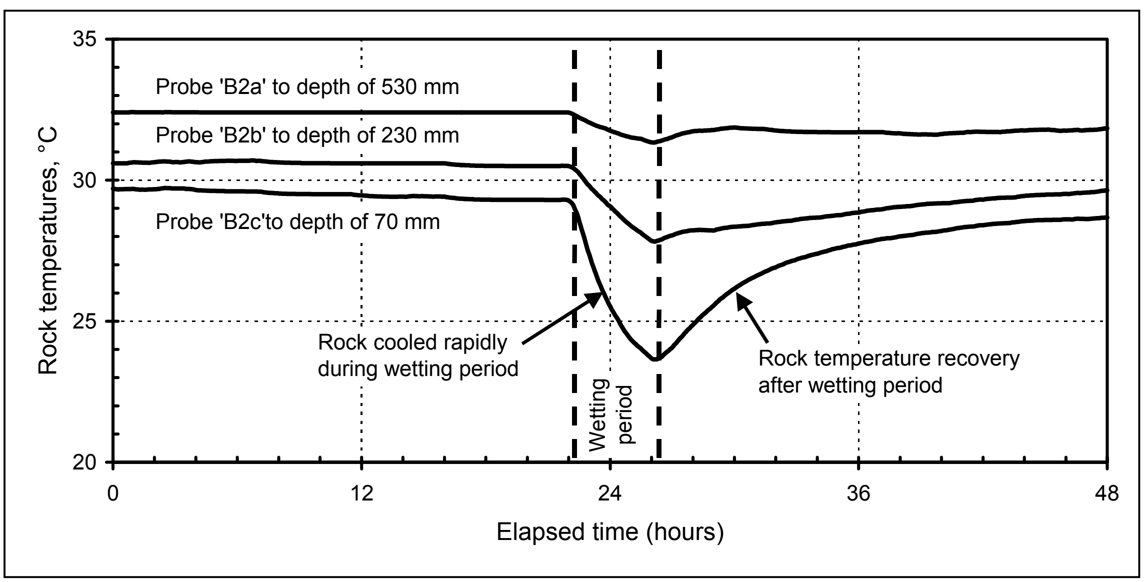

Figure 2 Underground rock temperature measurements[9]

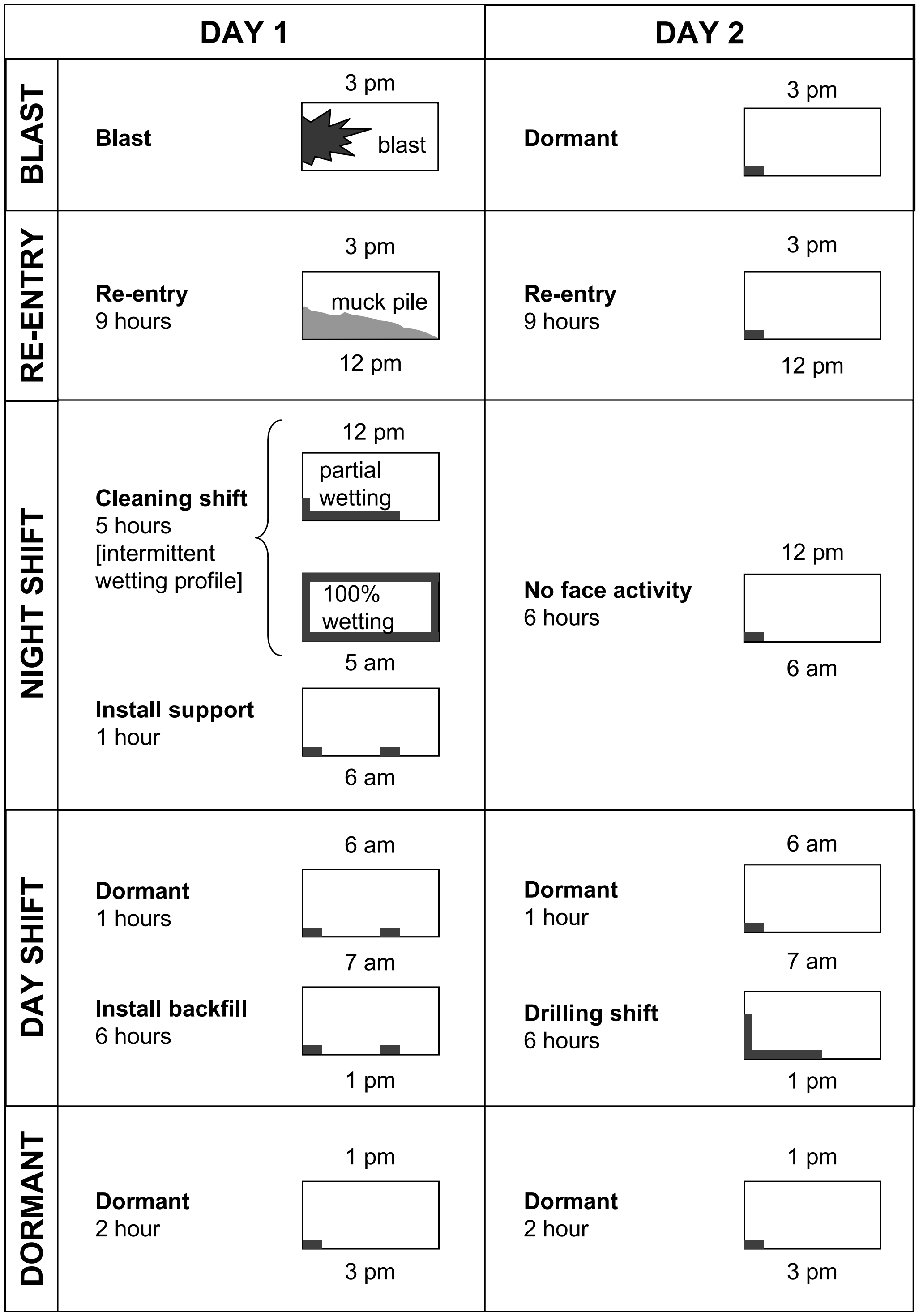

Figure 3 Typical stope mining cycle and associated wetting profile

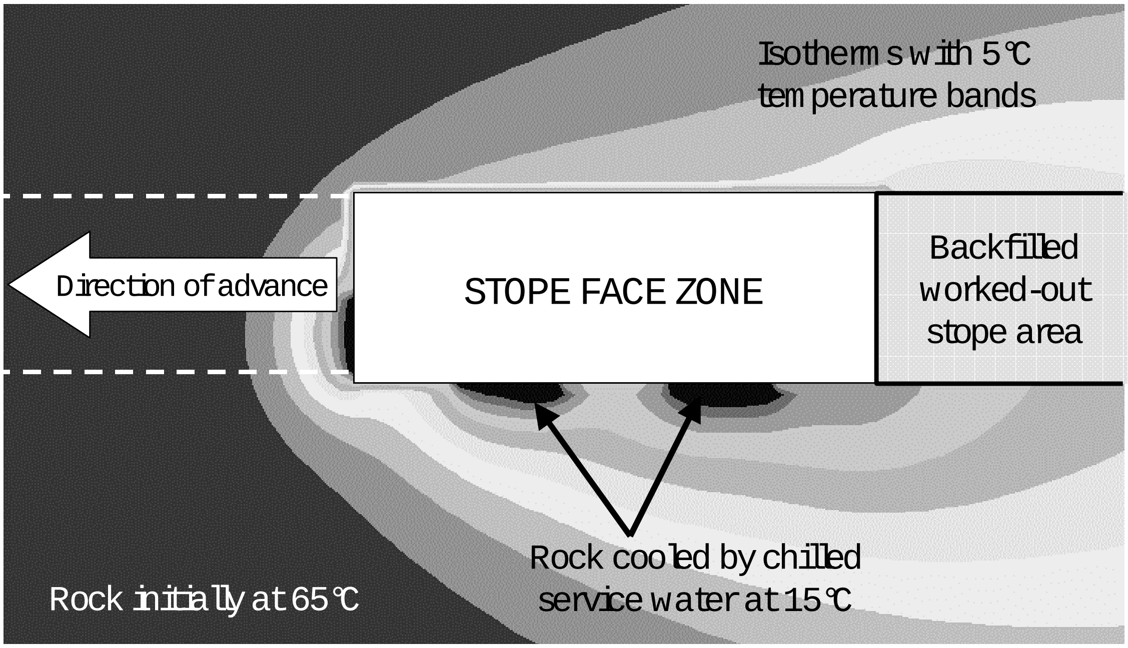

Figure 4 Example of rock temperature isotherms as predicted by model[10]

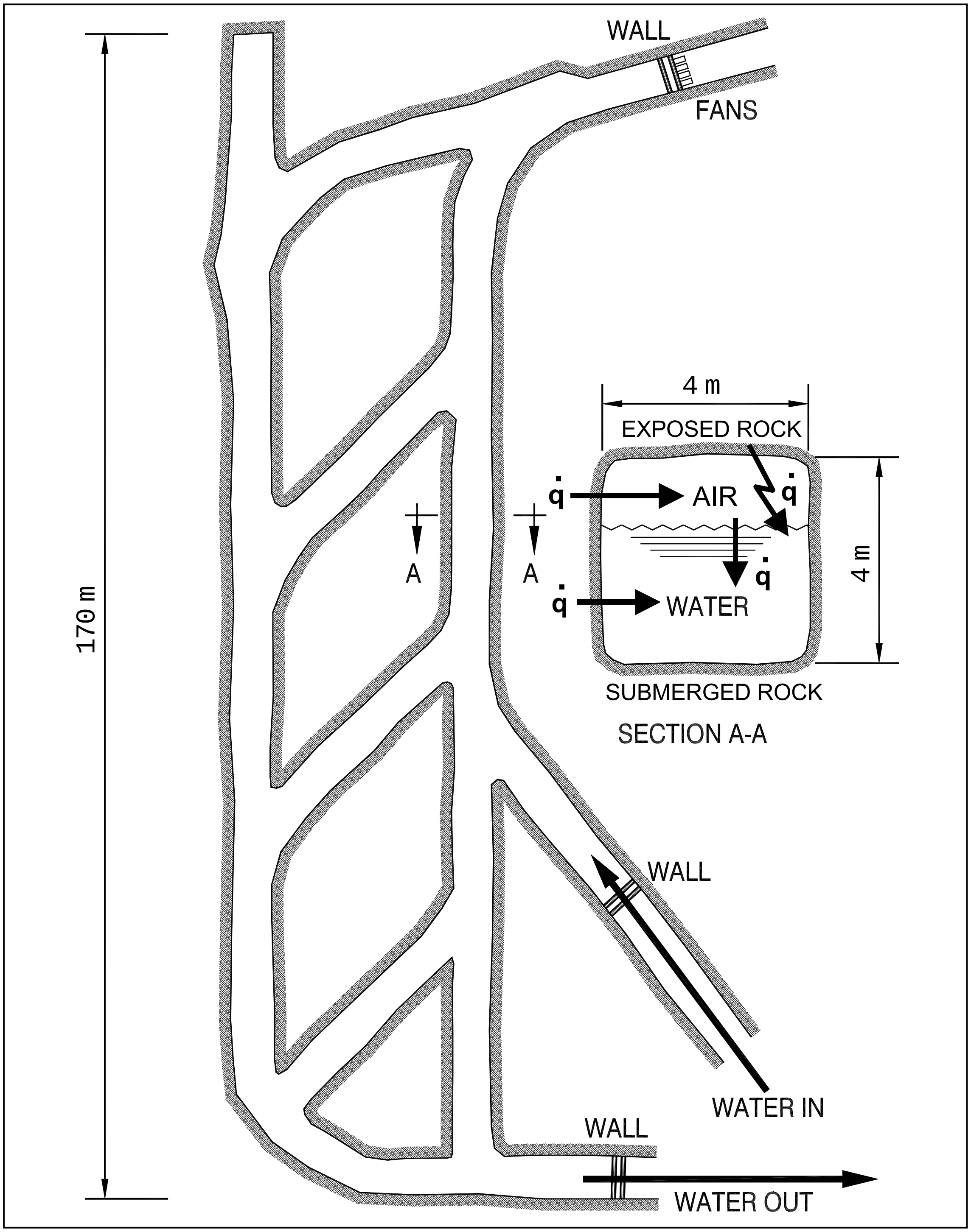

Figure 5 Typical layout of underground chilled water dam

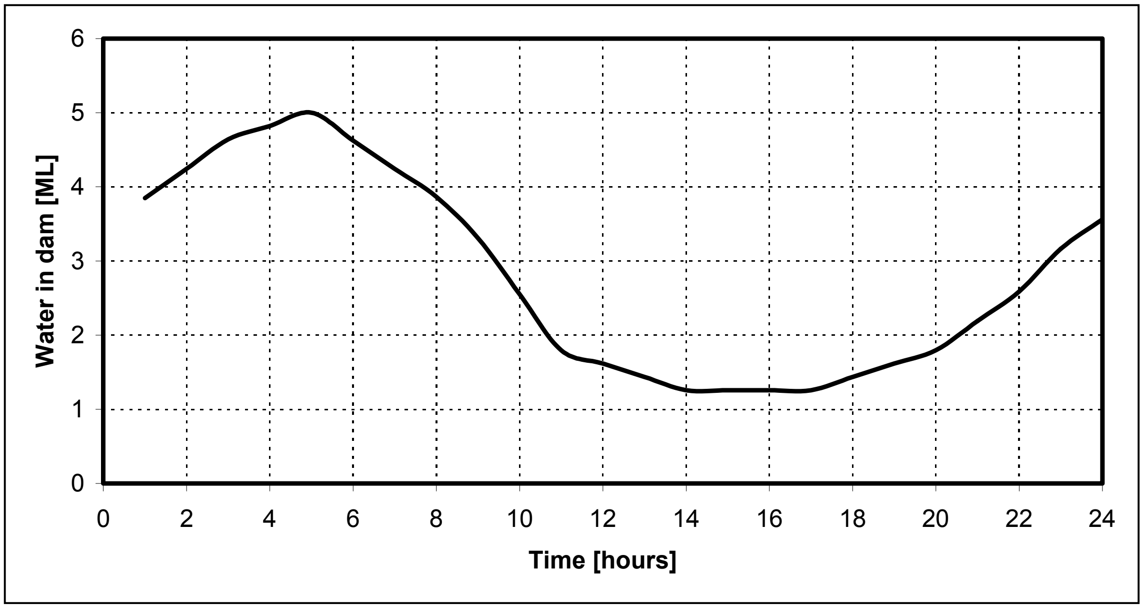

Figure 6 Water level in underground chilled water dam

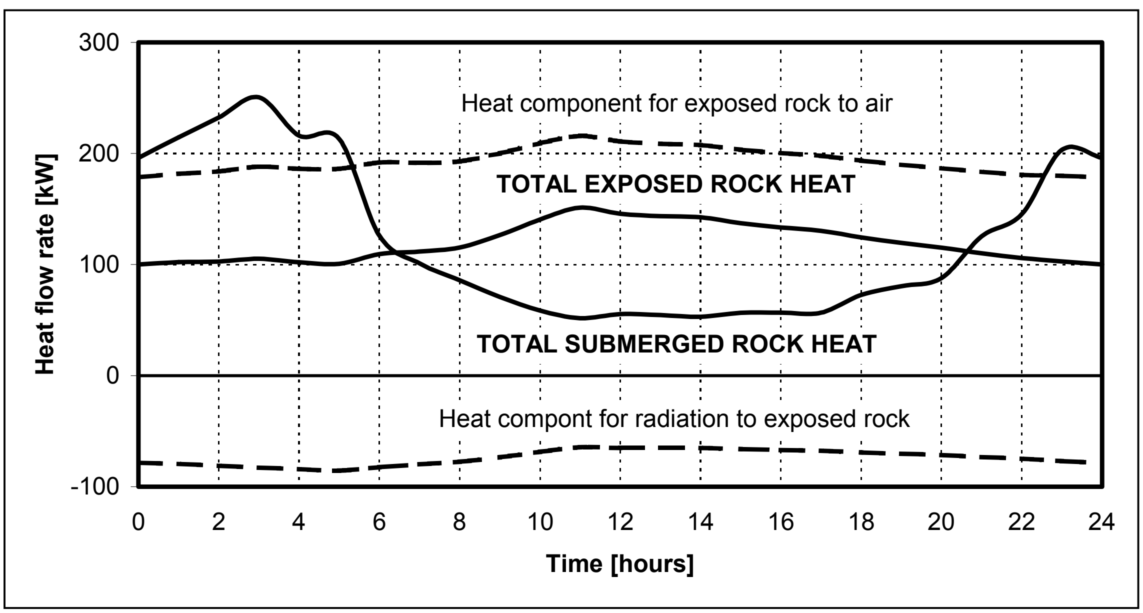

Figure 7 Rock heat flow into underground chilled water dam excavation

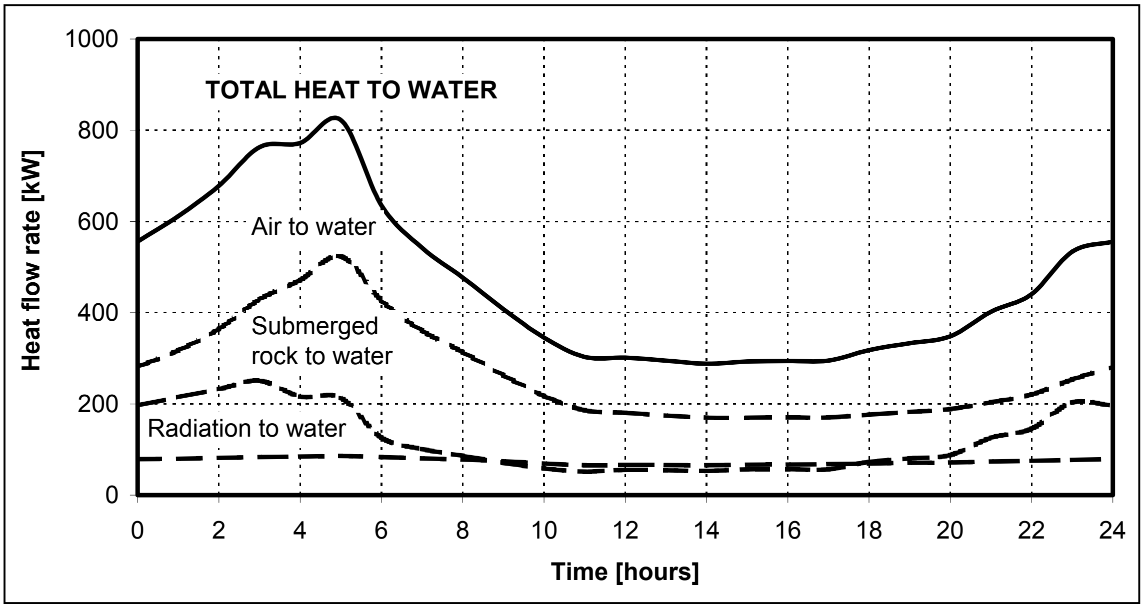

Figure 8 Heat flow to chilled water in underground dam

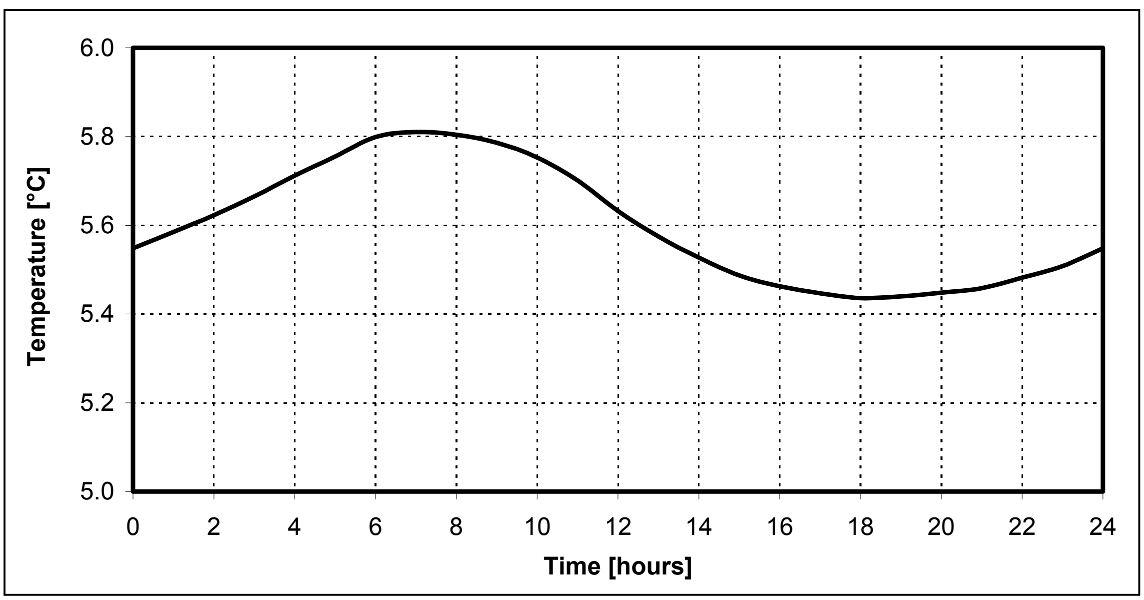

Figure 9 Predicted temperature of chilled water in underground dam