The application of refrigeration in mechanised mines

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INTRODUCTION

Australia has a long history of underground mining. Even with advances in open cut mining equipment, techniques and economics, many orebodies are still best mined by underground means. In addition, modern exploration tools are 'uncovering' orebodies that are at increasing depths. South African mines are currently producing from below 3 km, and developing down to 5 km depths – it is likely that Australian mines will also become much deeper over the next 20 years. One of the most significant technical challenges in deep mines is the problem of heat. Community expectations and legislated standards continue to drive operations towards improving the working conditions in mines. The hazards and costs associated with chronic hot working conditions (heat illness, poor safety, poor productivity, higher operating costs and poor morale) are also becoming increasingly recognised (Brake, Donoghue and Bates, 1998). The exposure of miners to many other occupational hazards has been reduced over the past 50 years. However, despite air-conditioned cabins greatly reducing the heat stress on mobile plant operators, there are still many Australian mine workers subject to levels of thermal stress that existed a century ago. There are several reasons for this, including a frequently-poor understanding of the physiology of working in heat by mine management, no agreed mining code of practice for working in heat, the lack of a robust, practical-sized instrument to measure heat stress, the cost pressures on the industry and, to some extent, deep-seated traditional management and worker practices. However significant progress has been made in many of these areas (Brake and Bates, in press), with the net result that there is likely to be a trend towards installation of refrigeration of some form in many Australian mines in the future. This will add directly to the cost of operation, but will also have direct and indirect benefits, including cost benefits. It should also be noted that Australia is not at the forefront of adopting practices to manage temperatures in the workplace: South African metal mines usually have refrigerated cooling, and Canadian mines spend large sums on heating, with heating costs (averaged over a full year) of up to $A1 per tonne mined (Bandopadhyay *et al*, 1997)

The history of mine refrigeration dates back to 1919 when the first plant was installed at Morro Velho, Brazil. By 1965, the total installed capacity (worldwide) reached about 100 MW(R)[i]. Since 1965 the growth in mine refrigeration capacity has been exponential, with a doubling every six or seven years (Howes and Nixon, 1997). South Africa is by far the largest user of mine refrigeration, with over 300 refrigeration machines installed.

This paper discusses the key design issues associated with the application of refrigeration in underground metal or coal mines. Whilst the emphasis is on large, surface plants, small, surface or underground refrigeration plants can also be very effective in the correct application and many of the principles of design and operation are the same.

CRITERIA FOR REFRIGERATION

Consider a hypothetical mine. There will be a spread of temperatures in the various workplaces at any point in time. A well-designed and well-maintained ventilation system has a standard deviation of workplace temperatures of (typically) about 2° C Wet Bulb[ii] (WB). Assuming the temperatures are normally distributed, this means about 66 per cent of workplaces lie within one standard deviation of the mean, 95 per cent of workplaces lie within two standard deviations (4° WB), and 99 per cent lie within three standard deviations (6° WB).

32° WB is widely considered as the *absolute upper limit* in which well-acclimatised, industrial workers should be expected to work, or even travel. Assuming this mine is to have workplaces with temperatures exceeding 32° WB only 'rarely' (<1 per cent probability), even on the hottest summer days, then the average workplace temperature in the mine should not be allowed to exceed 28° WB on these same days. Bear in mind that 28° WB is still a very hot and humid condition in itself. It exceeds the surface WB temperature during even the hottest periods of the hottest days in almost all locations in Australia (eg even Darwin only peaks at 28° WB). Moreover, workforce productivity and therefore costs are also known to be affected by high temperatures; therefore apart from the health, safety and morale issues, high workplace temperatures also directly affect the 'bottom line'.

As a sensible rule of thumb, if the *average* temperature of underground workings at a mine *exceeds* 28 degrees wet bulb (WB)) on the hottest days, or the temperature of *any* working area exceeds 32° C WB, then some sort of cooling system should be adopted, unless operations in these areas are suspended or curtailed during these hot periods.

A design value of 28° WB means that, *on the hottest days*, the distribution of temperatures in the active workplaces of a well-ventilated mine would look something like this:

24 - 26° WB	16 per cent
26 - 28° WB	33 per cent
28 - 30° WB	33 per cent
30 - 32° WB	16 per cent
>32° WB	<1 per cent

Note that even with this design criterion, one in six workplaces will have a temperature exceeding 30° WB.

The overall mine heat load is complex in nature and a function of many factors, (Pickering and Tuck, 1997; Brake and Fulker, 2000), including

- surface climate,
- autocompression[iii],
- machinery, especially diesel equipment,
- geothermal heat from strata,
- groundwater,
- oxidation,
- explosives,

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i MW(R) and kW(R) are abbreviations for MW or kW of refrigeration capacity respectively.

ii The wet bulb temperature is basically the temperature at which liquid water will evaporate into the air under steady state conditions and where there is no net addition or loss of heat in the air-water system, ie the sensible heat lost by the air in evaporating the water (seen as a reduction in DB temperature) is exactly offset by an increase in latent heat content of the air.

iii Autocompression denotes the heat added to air as it moves towards the centre of the earth, solely by virtue of conversion of its potential energy into heat. As air drops down an intake airway, it will heat up by between four and 6° WB per 1000 metres of vertical depth. This occurs even if no external heat (eg from rock walls or machinery) enters the air at all in the airway.

- broken rock,
- fill or cement heat of hydration, and
- miscellaneous sources, such as lighting and personnel.

Both the relative size of each heat source and the overall heat load can vary very significantly between mines, with the largest factor being the volume flow of intake air. The relative sizing of the heat loads at the Enterprise mine in NW Queensland is shown in Figure 1. The total heat load (excluding the climatic component due to the changing temperature of the intake air, which obviously varies throughout the year) is about 40 MW(R).

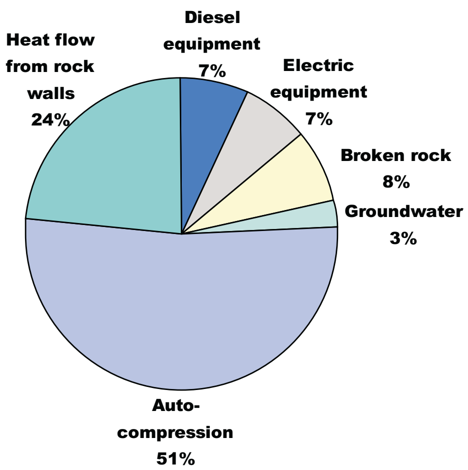

FIG 1 - Heat loads at Enterprise mine (N-W Queensland), excluding the impact of changing surface temperatures due to changing seasons (climatic load). Total non-climatic load is about 40 MW(R).

The actual impact of heat on an underground mine can be visualised as in Figure 2. This shows the same 'pie' diagram rolling up and down on the surface climate. The Mount Isa mid-summer surface WB limit is about 25° C with mid-winter minimum being about 3° WB. The 'target' value for the underground environment is 28° WB.

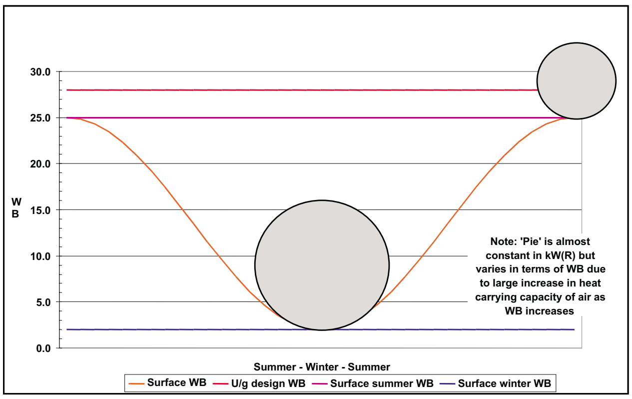

FIG 2 - The interaction between climatic and 'endogenous' (internal) heat loads in a mine. The peak summer surface temperature is 25° WB. The 28° WB line is the maximum 'target' average underground workplace limit. Clearly as the 'pie' rolls up the climatic slope as summer approaches, the 28° WB underground target will at some point be breached. This is when refrigeration should be considered.

In general, localised heat problems require local refrigeration solutions, whereas more widespread heat problems require some form of 'bulk'[iv] air cooling.

If refrigeration is required, the questions to be answered include the following.

- where should it be provided (surface or underground)?
- what form or combination of forms should it take (self-contained underground plants, underground air coolers fed with chilled water generated in a surface refrigeration plant, surface bulk air cooling, ice plants, etc)?
- how much of each form is required? (Brake and Fulker, 2000)
- how much will it cost (capital and operating)?

Mine cooling costs will vary significantly depending on the heat loads in the mine, the volume flow of intake air, and the 'target' WB temperature in the underground workplaces, but even in relatively severe Australian conditions, surface bulk air cooling is unlikely to exceed an operating cost of $1 per tonne for metal mines or $0.20 per tonne for coal mines[v]. This cost is significant, but the potential benefits are also significant. There is also potential for these direct costs to be reduced if controlled recirculation were to be successfully implemented, in much the same way that recirculation (of up to 80 per cent of total air requirements) provides a marked reduction in air-conditioning costs in large above-ground facilities. An alternative to recirculation is the controlled re-use of air ('series ventilation'). At present, this is generally considered to be poor ventilation practice, but in deep operations is likely to become commonplace and safe, with the application of suitable controls and safeguards.

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iv The term 'bulk' refers to an air cooler that chills the entire fresh air to the mine, or to a major part of the mine.

v Consider a notional mine producing 1 Mtpa (metal) or 5 Mtpa (coal) requiring 400 m^3/s of air of intake air, and a surface refrigeration plant that drops the WB temperature of the intake air by 4° C, with an overall year-average coefficient of performance of 4.0 (this is the ratio of kW of refrigeration produced for each kW of electrical power consumed). Assume a site power cost of eight cents per kWh and that the plant is 100 per cent capacity-utilised during the four summer months and not utilised at other times (in practice the spread over the year would be greater, but the capacity-utilisation in summer would average much less than 100 per cent as peak capacity is only required on peak hours of peak summer days). A generous maintenance and consumables allowance of 75 per cent of the power cost is also provided. Total refrigeration opex is $0.74 million per annum (metal: $0.74 per tonne; coal: $0.15 per tonne). Installed firm plant capacity would be 7 MW(R). However, there are also direct cost benefits of this 4° WB improvement to working conditions that will offset a portion of the additional opex. This refrigeration cost of $0.74 million per annum should also be compared to the actual cost just to move the 400 m^3/s through the mine. For a total pressure drop around the mine of 2.5 kPa, and a combined fan and motor efficiency of 75 per cent, this would be $934 000 per annum. Also note that, after refrigeration, most metal and some coal mines should be able to work with less than 400 m^3/s, which would further reduce both airflow and refrigeration costs. Ventilation costs are proportional to the cube of the airflow, so that a 25 per cent reduction in airflow due to refrigeration will lower ventilation costs by 60 per cent to $394 000. Refrigeration costs are also partly proportional to airflow, so that the refrigeration costs might fall (say) ten per cent to $665 000 for a total V and R cost of $1 059 000, compared to $930 000 without refrigeration. In this case, the installation of the refrigeration only adds to total V and R costs by about $130 000 pa. This is *before* accounting for any benefits to health, safety, morale or any benefits in productivity and overall operating costs as a result of cooler working conditions. This analysis ignores the capital cost of the plant or the associated electrical power and water supplies, but note that refrigeration, if it makes a lower primary airflow possible, will also have some capital cost offsets, in that ventilation shaft diameters and other main airway sizes can be reduced.

By way of cost comparison, the air-conditioning system in a large surface building is about 15 per cent of the total capital cost of the building, with the refrigeration plant contributing about 50 per cent of the total air-conditioning cost (ie 7.5 per cent of the total building cost) and the remainder being in the ventilation and refrigeration (V and R) distribution systems (ducting etc). Mount Isa Mines has recently installed a $25 million refrigeration plant as part of its $400 million upgrade for the Enterprise mine. The plant capital cost (excluding airways) is about six per cent of the total mine upgrade cost.

REFRIGERATION STRATEGY AND DIFFERENCES BETWEEN MECHANISED AND NON-MECHANISED MINING

In theory, the cheapest refrigeration strategy would be one that cools *only* the air immediately surrounding the worker (microclimate cooling). Such a system has high *positional efficiency.* In practice, such systems are not technically achievable due to the mobility of the workforce, the number of workplaces and the new workplaces that are constantly being developed in an operating mine. However, with the increasing trend to mechanisation, air-conditioned cabins are a simple solution to the needs of many workers underground. Unfortunately, there is still much manual work in Australian mining, and the combination of relatively heavy manual work (even if intermittent) along with high workplace temperatures may result in an unacceptable risk of heat illness, safety incidents and poor productivity. In metal mines, work that involves both high work rates and high thermal stress includes some types of ground support, some portions of the development mining cycle (especially charging the face), production blasting and hanging electrical cables. Roof support, tramming and maintenance in return airways can be equivalent activities in coal mines. This workplace heat stress, together with the fact that even workers in an air-conditioned cabin need to be able to walk out to safety if their vehicle breaks down, means it is essential that *all* places where workers are required to work *or enter* must have acceptable environmental conditions. This is also a sensible requirement imposed by most statutory regulators.

If the temperatures at the workplace are primarily generated by heat loads in the workplace, then the efficiency of the refrigeration system decreases as the cooling is moved progressively away from the workplace. This occurs for two reasons. Firstly, cooling is lost to unwanted heat sinks (eg rock strata or diesel units) en route to the workplace and secondly, to make up for these losses, the refrigeration plant needs to produce chilled air at *lower* temperatures than it otherwise would. As the cooling loss itself is proportional to the ΔT(or 'driving force') between the chilled air and the heat sinks, the rate of cooling loss increases as the plant is moved away from the workplace.

However, in most underground Australian mines, a large portion of the heat loads are generated well before the air reaches the workplace. For example, with the very hot surface temperatures experienced in much of Australia, (a function of Australia's latitude and low mean altitude above sea level), the *surface climate* is a major determinant of the overall underground load. With deep Australian mines, the surface climate and *autocompression* can together make up two thirds of the overall refrigeration requirement. Compare this to the South Africa Witswatersrand (Table 1) where the elevation above sea level (1500 m to 2000 m, ie higher even than Denver, Colorado) results in peak summer wet bulb temperatures of about 18° compared to about 25° at Mount Isa, 28° C at Port Hedland, or even 23° in Sydney. Moreover the average surface rock temperature (the starting point for the geothermal gradient) is 28° C at Mount Isa compared to about 18° C on the Central Witswatersrand. South African mines are much deeper and the workings are more laterally spread out, being largely flat, tabular deposits. This results in a long transit time for the intake air to a South African mine, compared to an Australian mine. Long transit times mean more opportunity for heat pick up. This high surface rock temperature, together with the high geothermal gradient (20° per km at Mount Isa, compared to about half this on the Witswatersrand) frequently leads to high virgin rock temperatures (VRTs) at relatively low depths in many Australian mines.

TABLE 1

Critical differences between deep South African and Australian mining regions, in terms of heat loads and implications on cooling strategies.

	Witswatersrand	Mount Isa/ N-W Qld
Surface elevation (m above sea level)	1700 m	300 m
Average yearly surface DB	18° C	28° C
Peak summer surface WB	18° C	26° C
Average surface rock temperature	18° C	28° C
Geothermal gradient	10° C per km	20° C per km
Average virgin rock temperature at 2 km depth	36° C	68° C
Diesel plant usage underground	Little/none	Extensive
Mechanisation of mining activities	Low	High
Mobility of workforce underground	Low	High
Intake air transit time to workplaces	Lengthy	Short
Thermal flywheel (damping) effect in intake airways	High	Low
Exogenous to endogenous heat loads (climatic to other heat loads)	Low	High
Summer to winter turndown ratio	Low	High

In addition, South African mines are labour-intensive and make extensive use of hand-held, compressed air operated rock drills, which use copious quantities of water to cool the drill bits and for dust suppression. Miners work at the same location all shift. Contrast this to Australian mines, which are heavily mechanised and use more 'massive' mining methods. Most hot, manual work done in Australian mines does not require the simultaneous use of service water, and Australian miners are very geographically mobile within the mine[vi].

These major differences between the heat load and mining methods in South Africa and Australia mean that care needs to be taken in adopting South African practices in Australia without a clear understanding of the differences in climate, mining practices, and depth of operations (Brake and Fulker, 2000).

Cooling of the air on the surface of a South African mine is therefore relatively inefficient due to the low climatic heat load, and the long transit times in the intake airways prior to arriving at the work place. It is for this reason that South African mines tend to make extensive use of localised underground air cooling close

vi South African experience is that at least 1 kL of service water must be consumed per kt of ore produced to make chilled service water effective. Australian experience at Mount Isa also indicates that chilled service water is not effective in highly mechanised operations, compared to the highly labour-intensive operations in South Africa. Most Australian mines only use service water intermittently (eg to water down a recently blasted development muckpile). The water has been sitting in the delivery pipe to this face for some time and will have warmed to the DB temperature of the air in the heading. The face is watered down for 20 minutes (say); it is typically just starting to get cool by the time the job is completed.

to the workplaces, and also make extensive use of chilled service water to the hand-held drilling machines, as this has been found to be very effective in providing cooling directly to the workplaces. In practice, this means South African refrigeration plants, even when located on the surface, generate most of their refrigeration output as very cold water (typically 0.5° to 1.0° C) to be sent underground. The water is generated as cold as possible so as to carry the greatest amount of cooling underground in the least amount of water, as pumping costs back to the surface in these very deep mines are very high. When surface bulk air cooling is installed, it usually has a secondary or supplementary role to chilled service water, and South African surface bulk air coolers are therefore designed for inlet water temperatures of 0.5° to 1.0° C. Due to the low surface ambient WB temperatures, the 'return' water from such a bulk air cooler to the refrigeration plant is also relatively cool.

In contrast, most of the heat load in Australian mines is due to the extreme surface summer climate. This, combined with the very rapid intake transit times, makes surface 'bulk' chilling of the air technically more effective and attractive. In addition, it is *much* cheaper to install and operate refrigeration on the surface, and *much* easier to maintain a surface plant than an underground plant or a surface plant with an extensive network of underground piping, cooling devices and return water pumps to the surface. Finally, because Australian mines are highly mechanised, chilling of the service water does not significantly improve conditions where manual work is being carried out because these jobs do not use much service water or do so for only relatively short periods of time. The exception to this would be underground coal mining, where both continuous miners and longwalls make extensive use of service water on a continual basis, and chilled service water could be an effective cooling strategy.

A further advantage of surface plants is that they do not deteriorate as quickly as underground plants. This makes them more amenable to leasing, or even hiring, as the residual values are much higher. Leasing or dry hire is a particularly attractive option for mines with short lives, or with only short-term heat problems.

It can therefore be shown that for most *deep* Australian mines, surface bulk air cooling is usually the cheapest and most effective option. For mines that have a combination of shallow and deep production areas and a common intake airway, underground cooling is probably the best option, because provision of refrigerated air to the shallow areas is expensive and unnecessary. Local areas that have high heat loads but low/modest airflow requirements (eg major underground electrical installations such as ore handling, or workshops) may also be best served by local cooling, as bulk air cooling is indiscriminate and may result in over-cooling other areas just to meet the requirements of a limited region of the mine.

A detailed study including simulation of underground heat and moisture loads and average annual climatic changes is warranted to establish the most cost effective refrigeration arrangements.

In terms of when to adopt refrigeration, as a very general rule of thumb if any workplace in the mine is below the *critical depth*, then some form of external cooling will be required. The critical depth is the depth below surface at which air will exceed the underground target WB temperature solely through autocompression without taking into account any other heat loads at all. For example, consider a mine in which the worst summer days result in surface WB temperatures of 25° C[vii]. Intake air in this mine will increase by about 4° WB per 1000 m[viii] of vertical depth solely due to autocompression. If the 'target' underground WB is 28° C, then any workplace deeper than 750 m will have a temperature exceeding 28° C before any allowance is made for strata or diesel or any other source of heat. For workplaces above the critical depth, the cheapest method of cooling is flooding the workplace with air. This has two benefits: it removes the heat with only a smaller increase in air temperature, and secondly, it results in higher wind speeds across the skin surface of exposed personnel, and higher wind speeds have beneficial effects on evaporative cooling off the human body. However, if the workplace is below the critical depth, then the addition of more air merely adds to the heat load in the workplace, as the air itself (and by itself) results in unacceptable temperatures.

The situation is illustrated in Figure 3, which shows that as the heat problem in a mine increases, the appropriate response is to increase the fresh airflow to the workplaces. As a working place becomes hotter (eg with depth or more equipment), the correct initial response is to 'flood' the workplace with a higher proportion of fresh air. This will 'dilute' the contaminant (in this case—heat). However, the dilution strategy becomes progressively less effective as the heat problem becomes more substantial, as the air itself starts to become a major heat source. At some point (generally at about the critical depth[ix]), refrigeration is required. Given the cost to produce refrigerated air, it is generally much cheaper to reduce the refrigerated airflow to the minimum practical value (typically 0.5 m/s or the

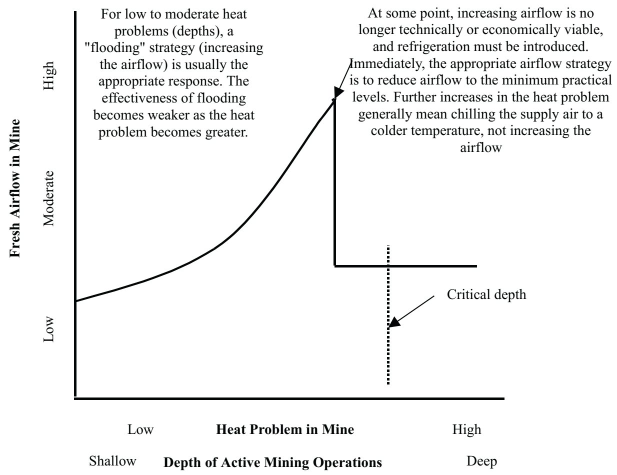

FIG 3 - Appropriate airflow strategy as a function of heat problem in mine.

vii This is not the very worst short-term period on the very hottest day, which might typically be about 2° WB above this value. The extreme value of 27° WB is not used because it is attenuated due to damping in the intake airways, and for other reasons.

viii 4° WB per km depth during summer. During winter, the typical increase in >6° WB per km depth. This is solely due to the fact that heat added to 'hot, humid' air results in a lower increase in WB than heat added to cold, dry air.

ix The actual depth at which refrigeration is required will rarely be at exactly the critical depth but will depend on how much 'damping' occurs in the intake airways, what value is used for the surface WB design limit (ie how conservative this value is compared to the extreme values actually seen in summer), the diesel intensity in the deeper workplaces and whether the deeper workings are 'active' or not. Active workings (those exposing fresh rock surfaces) generate much more heat than inactive workings. Therefore, for example, local 'spot' refrigeration may be required when a new, deep, ore handling system is being developed and constructed, but may not be required (say) a year later when the rocks surfaces have aged and the diesel intensity is lower.

minimum required to dilute other contaminants, such as diesel fumes[x]). Even if the heat problem increases further (eg the mine goes deeper), the appropriate strategy is to chill the air even further, rather than to increase the airflow.

In an existing mine, one simple means of obtaining a *rough* estimate of the desirable amount of refrigeration is to estimate, from experience, how far into spring or summer the mine can progress before underground conditions become unsatisfactory. The heat content of the air at this point is then compared to the heat content during the more extreme summer periods and an estimate of refrigeration requirements can be made. For example, if a mine starts to have substantial problems from the middle of October onwards and the long-term average surface WB at this time of the year is 18° C (heat content 50 kJ/kg air), and the maximum summer surface WB is 26° C (heat content 79 kJ/kg air) and the airflow through the mine is 500 m^3/s at standard density (1.2 kg/m^3), then a rough estimate (ie a starting point) of the refrigeration required would be 500 m^3/s × (79 - 50) kJ/kg × 1.2 kg/m^3 = 17.1 MW(R) *before* any allowance is made for load matching or spare capacity.

Computer programs that calculate the full thermodynamic heat and moisture characteristics of the mine ventilation system (particularly the air intakes and delivery systems to the workplaces) are now available and should generally be used before any serious expenditure is contemplated. However, considerable care and experience is required in the assumptions and constants used in these programs.

As discussed earlier, for mines with a localised heat problem, such as developing a new, rapid-advance heading at the bottom of the mine, small underground refrigeration plants ('spot coolers') located strategically, or even sled mounted and relocatable, can be a cost effective option. For example, a 'hot' development end being ventilated by twin 180 kW contra-rotating fans feeding twin ducts to service a truck and loader at the face could have a 500 kW(R) spot cooler installed at the fan. This would reduce the temperature in the heading by about 2° WB using only about 130 kW of electrical power, ie substantially less than the 360 kW of fan power. However, care must be taken in the selection of any underground refrigerant to ensure it does not add to the hazards already present in the underground environment. On this basis, ammonia is unacceptable for underground plants. But even halon refrigerants such as R22 (eg 'Freon 22') need to be used carefully. By itself, R22 is relatively safe, but if it is ingested by a diesel engine, it is converted to the toxic phosgene gas. Likewise R134A can be converted into the highly toxic and corrosive gas, hydrogen fluoride, at very high temperatures. Moreover, because underground plants need to reject their heat into the return air, they must be sited adjacent to a return air circuit. In practice, because they are to chill fresh air, this means they must be located near both fresh and return air circuits. This limits the range of locations where these plants can be installed. Furthermore, the relatively small amount of air circulating in a mine, along with its high temperature in the return airways, makes heat rejection underground relatively inefficient and seriously restricts the size of underground plants. Off-setting this, spot coolers have very high positional efficiency.

x Even apart from the issue of the minimum airflow to dilute contaminants, there remains a minimum practical airflow solely related to heat and temperature. This is because to provide a lower airflow and still remove the necessary heat, the supply air must be chilled even further than it otherwise would. This colder supply air increases the rate of heat flow from the strata, ultimately becoming partly self-limiting. In addition, as the airflow decreases, *even if the strata heat flow were to stay constant*, the temperature increase (ΔT) for a lower airflow will be larger than that it would be at a higher airflow. Therefore, to maintain adequate workplace and return temperatures, the airflow cannot be reduced below a minimum practical and economic value.

It is also important to recognise that it is the capital and operating cost and effectiveness of the *total* refrigeration *system* (including the 'load' or underground environment) that must be optimised in a refrigeration plant design. It does not matter how cost effective the refrigeration plant itself is, if the overall system has been poorly designed. The discounted lowest life cycle cost (DLLCC) concept should be used in evaluating the various options.

Irrespective of whether the plant is installed on the surface or underground, and whether it produces chilled water for bulk air cooling or as service water, many principles of mine refrigeration plant design and operation are common. As surface plants are generally preferable to underground plants for deep mines, this paper focuses primarily on surface refrigeration plants.

RE-USE OF FRESH AIR

Most mining jurisdictions require or encourage air to be taken to the workplace and then 'by the most direct practicable means' into the return airways. Somewhat curiously, there seems little concern by regulators about the use of very long intakes such as surface ramps, with major heat and potential fire sources (such as diesel units) operating in them.

One of the features of modern mechanised mining is the very substantial increase in fresh air requirements in the mine. From 1967 to 1977 (the early years when diesel equipment was introduced into underground mines), the total volume of fresh air in Ontario mines doubled for no change in mine production. The introduction in the 1980s and 1990s of even larger diesel units (an AD55 underground truck currently under trial in Australia has a 485 kW diesel engine) is pushing mine operators towards ever-increasing airflow requirements, based on the typical 0.04 or 0.05 m^3/s per rated engine kW. These big diesels need large amounts of air, but only where and when they are working. If the big diesel is very mobile (as is frequently the case), then many areas in the mine may be 'over-ventilated' on average (but clearly not when the big diesel is in that area).

It is therefore useful to introduce a concept called the diesel *airflow efficiency* of a mine, defined as:

$$\text{Diesel Airflow Efficiency} = \Sigma\,(\text{air required for large diesels}) / \Sigma\,(\text{total intake airflow in mine})$$

'Large diesels' is usually taken to refer to development or production vehicles, ie those with engines greater than about 100 kW.

Clearly, an ideal operation would provide 'just' sufficient air through the underground workings to meet the statutory requirement (assuming this is the most difficult contaminant requirement to meet, which it may not be). As mines become larger and/or older and therefore more spread out, or more mechanised, the diesel airflow efficiency can fall dramatically. In these circumstances, the possibility exists to examine series ventilation of some of the workplaces. This is based on the notion that much of the 'fresh' air has only been poorly utilised and can 'do more work' prior to being expelled from the mine. This has the potential to significantly lower the fresh air requirement in a mine, and with underground ventilation costs typically amounting to 40 per cent of the total underground power cost in a mine, the potential benefits are substantial.

It is critical to recognise, however, that series ventilation has the same potential problems as recirculation of air: an increase in contaminants to hazardous levels. Therefore, series ventilation must only be adopted after careful studies, including well-documented risk analyses, and with proper controls introduced. In many mines, the most difficult contaminant to control in a series ventilation circuit is the heat. In this circumstance, refrigeration could be employed and the cost of refrigeration can be offset against the reduced airflows required when a series or semi-series ventilation circuit is implemented. Note also that where cooling is via a direct-contact air-water air cooler (the usual case), the cooling device acts as a 'scrubber' and therefore has some re-conditioning effect on the air.

TRANSIT TIMES IN INTAKE AIRWAYS

Air can comfortably travel at 15 m/s down a vertical intake shaft. Therefore, for a workplace 1000 m below surface and adjacent to a vertical intake, the transit time of the intake air travelling at 15 m/s is just over one minute. However, wind speed in *travelways* must be restricted to about 5 m/s to avoid excessive dust problems. Therefore, if the intake to the same workplace is a one in ten ramp from surface, then the intake air transit time would be over 30 minutes. This vastly increased transit time (from one minute to 30 minutes) provides substantially more opportunity for the air to pick up heat, fumes, diesel particulates, gases and dust from strata, diesel engines, etc.

Network analysis programs such as Ventsim™ have two useful features that help evaluate transit times and the quality of the intake air to a mine workplace.

Firstly, by simulating a 'contaminant' at the surface intake, Ventsim™ will provide the earliest time at which the 'contaminant' will reach any particular point in the network. If the 'contaminant' is 'fresh air', then the transit time for fresh air to reach any particular workplace in the mine can be established.

In addition, if a mine has two fresh air intakes of very different quality, such as a vertical shaft and a lengthy haulage ramp, then simulating a contaminant with an arbitrary value of 100 units at (say) the mine portal will provide the 'concentration' of the contaminant (in this case, the hotter and dirtier ramp air) at any particular point in the mine.

Any ventilation design, or proposed changes in ventilation strategy, can be easily evaluated, in terms of transit time and quality of intake feed to the workplace, using these two features.

PLANT CAPACITY

Historically, very few mine refrigeration plants ever achieve their design capacity. One of the principal reasons for this is the lack of a design code for mine plants, similar to those that have been developed over many years for most other engineering applications. In addition, few mining or mechanical engineers on mine sites have sufficient experience with refrigeration to be able to adequately specify a mine refrigeration plant (Brake, in press).

One key problem is that the size of the plant varies so dramatically with the amount of air to be cooled[xi] and the selected 'design' temperatures into and out of the bulk air cooler. Figure 4 shows how the plant capacity requirement can vary by in excess of 100 per cent for various changes in airflow and surface design temperatures. It is therefore important to critically challenge each assumption, to assess the plant capacity under all credible scenarios and to develop a strategy for each. This may mean a modest sized plant 'up front' with the option to add additional chilling modules, or with the option to install underground air coolers fed from a surface chiller, or an underground refrigeration plant. Sensitivity analysis and a formal decision analysis process should be used, to avoid bias and subjective assessments.

Mine refrigeration plants are required to operate over a wide range of ambient conditions. Actual plant capacity at any point in time is very dependent on what these conditions are. It is normal to quote a 'nameplate' or nominal plant capacity at a nominated reference or design condition, which by convention in other air-conditioning applications is often the one per cent, 2.5 per cent or five per cent condition. The 2.5 per cent condition, for example, is the surface wet bulb temperature that is only exceeded for 2.5 per cent of the year (219 hours per annum). Sizing a mine plant to meet the 2.5 per cent condition and no more, based on typical criteria used for office buildings, is generally an unsatisfactory approach for the following reasons:

- There is usually no 'hard physical labour' occurring inside most office buildings! Therefore temperature excursions above the 'design' are not as serious as in a mine where a significant proportion of work requires high metabolic rates.
- The temperature 'set point' in an office is for 'comfort conditions', usually between 20 and 25° C with a relative humidity of about 50 per cent (ie WB between 14 and 18°). There is a substantial buffer between these temperatures and an unsafe condition (WB>32°). Moreover, the spread of temperatures in a mine is much greater than in an office building. An office has ducts and outlets carefully positioned and fitted with dampers to direct cool air evenly to all working places in the building. The dynamic nature of a mine and the very large mobile diesel heat loads in it results in a much higher spread in temperatures as discussed earlier. This wide spread means that any excursion will impact more severely on a mine than an office.
- If a developer is building a new multi-story office building, *capital cost* is very important because the developer is paying for this. However, the tenants will pay for the *operating cost* of the plant. This includes both maintenance on the refrigeration plant and the power costs to run it. Therefore, a small (low capex) plant with high operating costs produces the best return for the developer. This is certainly *not* true for mine owners, where the true overall 'ownership' cost of the plant must be established and optimised. Because mine refrigeration plants are an insignificant fraction of the overall market for refrigeration systems, most 'packaged' refrigeration plants are not suited for mining applications. They are not robust enough and result in high operating and power costs. Power and maintenance costs are often very different between 'city and the bush'. This bias towards low capex/high opex solutions from refrigeration plant suppliers affects not only compressor selection, but also most of the other components of the plant, particularly the condensers.
- Office buildings typically recirculate 80 per cent of the air within the building. If the refrigeration system fails, the air being recirculated is already at the 'design' temperature and therefore the temperature increase over time is moderate.

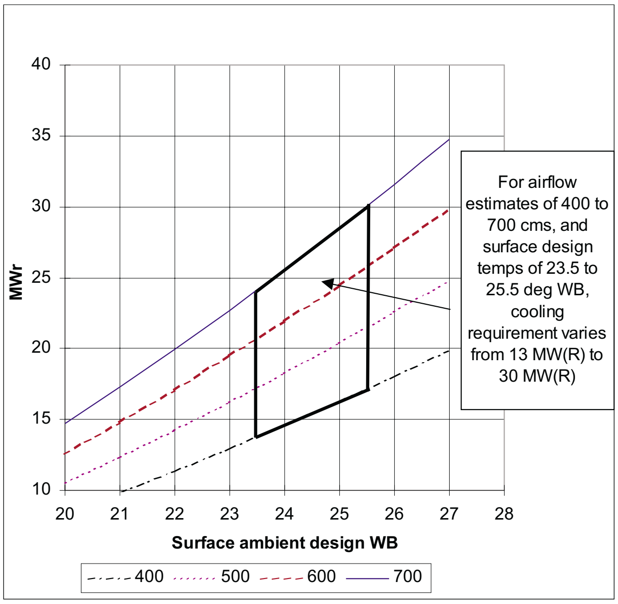

FIG 4 - Variation in overall cooling requirement with airflow and surface WB temperature.

xi It is important to specify what air density is used in the various calculations. For example, a mine which is 1500 m below surface and which needs 500 m^3/s of chilled air underground, will need about 15 per cent more air than this (by volume, not mass) to be chilled on the surface due to the increased density underground. This may impact on the sizing of the fans and bulk air cooler, although the refrigeration capacity should be unaffected.

Most mining legislatures ban recirculation. Therefore if the refrigeration system fails in a mine in mid summer, the entire thermal impact of the hot surface air rapidly impacts on workplace temperatures.

- Due to the high recirculating flow in office buildings, an inefficient refrigeration plant results in a much lower cost impact than it does on a mine where the 'once through' nature of the ventilation means that the cost to generate the cooling must be kept as low as possible.
- The ventilation and refrigeration system is as integral to a hot mine as is the ore handling system. In fact, the ventilation system is more critical. If the ore handling system is not operational, ore passes and bins often provide some buffer before production ceases entirely, and even if production stops, many other activities can continue and most mine workers can be gainfully employed. If the ventilation/refrigeration system in a hot mine fails or partially fails during summer, then many activities can no longer be conducted safely and workers may need to be withdrawn. This is especially so if the maintenance of satisfactory airflow and temperatures are essential for safe egress.
- Furthermore, an underground refrigeration 'load' (eg a system of air coolers distributed throughout the workings) can never be perfectly matched in capacity to its surface plant. This is especially true as the number of underground cooling devices increases. In practice, even with the buffer provided by cold-water dams, a load match (coupling) of about 70 per cent to 80 per cent is the best that can be achieved when the number of underground refrigeration loads exceeds four or five devices. This is similar to the 'diversification factor' in power stations. In other words, whilst cost effectiveness and capital cost optimisation are important in selecting plant capacity, an 'optimised' design is unsatisfactory if it simply can't cope with the near-maximum temperatures being experienced in summer.

Once the heat loads and 'firm' plant capacity (including diversification factor) have been estimated it is then critical to allow a de-rating factor before arriving at the required 'nominal' plant capacity. A figure of about 20 per cent should be allowed here. This allows for component suppliers who inevitably over-estimate their component capability, for thermal losses (eg from the insulated pipes or dams to the environment) and also for the heat added to the circulating water through the chilled water pumps (in the evaporator circuit), which can consume as much as ten per cent of the compressor capacity. The heat to be rejected through the condenser circuit can also increase by up to a *further* ten per cent due to the heat gain in the condenser circuit water pumps.

Fouling is another factor that has a substantial effect on plant capacity. Fouling is a process in which a heat exchanger becomes dirty and the heat transfer mechanism less efficient. Realistic estimates of fouling factors with clean and dirty heat exchangers must be made (Brake in press, 2001).

The nett impact of these considerations is the need to specify a higher refrigeration plant capacity than is required merely to match the theoretical mine load. Provision must therefore be made in the sizing of the overall plant, and of individual components, for suitable design margins. However, it is not satisfactory to simply increase the required overall sizing of each component by a set 'margin' (eg 20 per cent) because this 'margin' may be built into the plant design in the wrong places, or in the wrong way.

It is also important to recognise that any calculation of a refrigeration load, particularly in a dynamic entity such as a mine, will only be an estimate. As for other performance specifications, such as for main fans, a 'duty envelope' should be considered which reflects the estimation errors in the major components of the load calculation, and the refrigeration plant must be capable of operating over the bulk of this duty envelope. The incremental capital cost of additional refrigeration capacity is generally small compared to the cost of an upgrade after the plant is operational.

SURFACE REFRIGERATION PLANTS

There are two broad strategies for using surface refrigeration plants to provide cooling to the underground work place (Figure 5). The first is to chill water, which is then pumped underground and used in direct-contact, water-air air coolers located strategically within the workings, and perhaps also to use this water as chilled service water. The second is to chill water as before, but to use it to chill the intake air *before* it is sent underground. Because both methods require the production of chilled water, the principles of operation are similar, although there are some differences and these are highlighted where applicable. It is therefore useful to provide some further general details on surface refrigeration plants, although a more comprehensive description of the actual engineering aspects of refrigeration plants is given in Brake (in press).

SURFACE BULK AIR COOLING

Surface bulk air cooling consists of two components: a refrigeration plant producing cold water with a heat rejection facility (usually a cooling tower, Figure 6), and a direct-contact, water-air, air cooler (itself a type of cooling tower) to chill all or part of the intake air (Figure 7).

The capital cost of any cooling tower is related to its size, which in turn is proportional to the flow rate of air through the tower (and hence also the amount of water that must be circulated through the tower to achieve effective water-air ratios). It is therefore often cost-effective to *over*-chill only a portion of the total downcast air, and then mix this after the air cooler with uncooled air to achieve the design intake air temperatures.

The economic proportion of chilled versus unchilled air depends on the trade-off between capital and operating costs of the installation.

Off-setting this capital cost of over-chilling air is the fact that if all the intake air goes through the air cooler, then if the refrigerant is toxic but water soluble (such as ammonia) and leaks from the plant room as a cold, dense cloud moving towards the intake shaft, then the air cooler will absorb a significant portion of the refrigerant cloud before it enters the mine. In addition, it requires more electrical power to produce colder water, so that over-chilling the air requires more refrigeration capacity.

OBSCURE PROBLEMS IN MINE REFRIGERATION

There are many subtle issues that can occur when refrigerating a portion of the mine air. These need careful and systematic review, via well-formulated risk assessment, to avoid unnecessary cost and production-related problems subsequent to installation.

One simple problem is that when air is chilled below its dew point temperature (which is usually the case in mine refrigeration applications), then any subsequent contact with unchilled air will result in moisture vapour in the unchilled air condensing at the interface with the chilled air, creating 'fog'. Depending on the proportions of the mix, the fog may extend well beyond the interface. Fog is clearly undesirable in an underground mine and re-design work can be difficult and expensive.

Another example is a mine that was chilling air on the surface and then directing it down the main hoisting shaft and into the workings. During the summer following commissioning of the refrigeration plant, the balanced skips on the Koepe friction hoist slipped catastrophically on the drum and were driven under gravity into the shaft bottom (and headframe). Part of the problem was that the cold air at the top of the shaft was chilling the hoisting ropes as they moved in and out of this cold zone. When the ropes then entered a very hot zone at the ore loading station at the bottom of the shaft (the chilled air was removed from the shaft above the ore loading station to avoid contamination), water from the hot, humid air at the ore loading station was condensing on the cold ropes (which were below the dew point temperature of the hot air). The rope surfaces became saturated over a period of time. This saturated surface combined

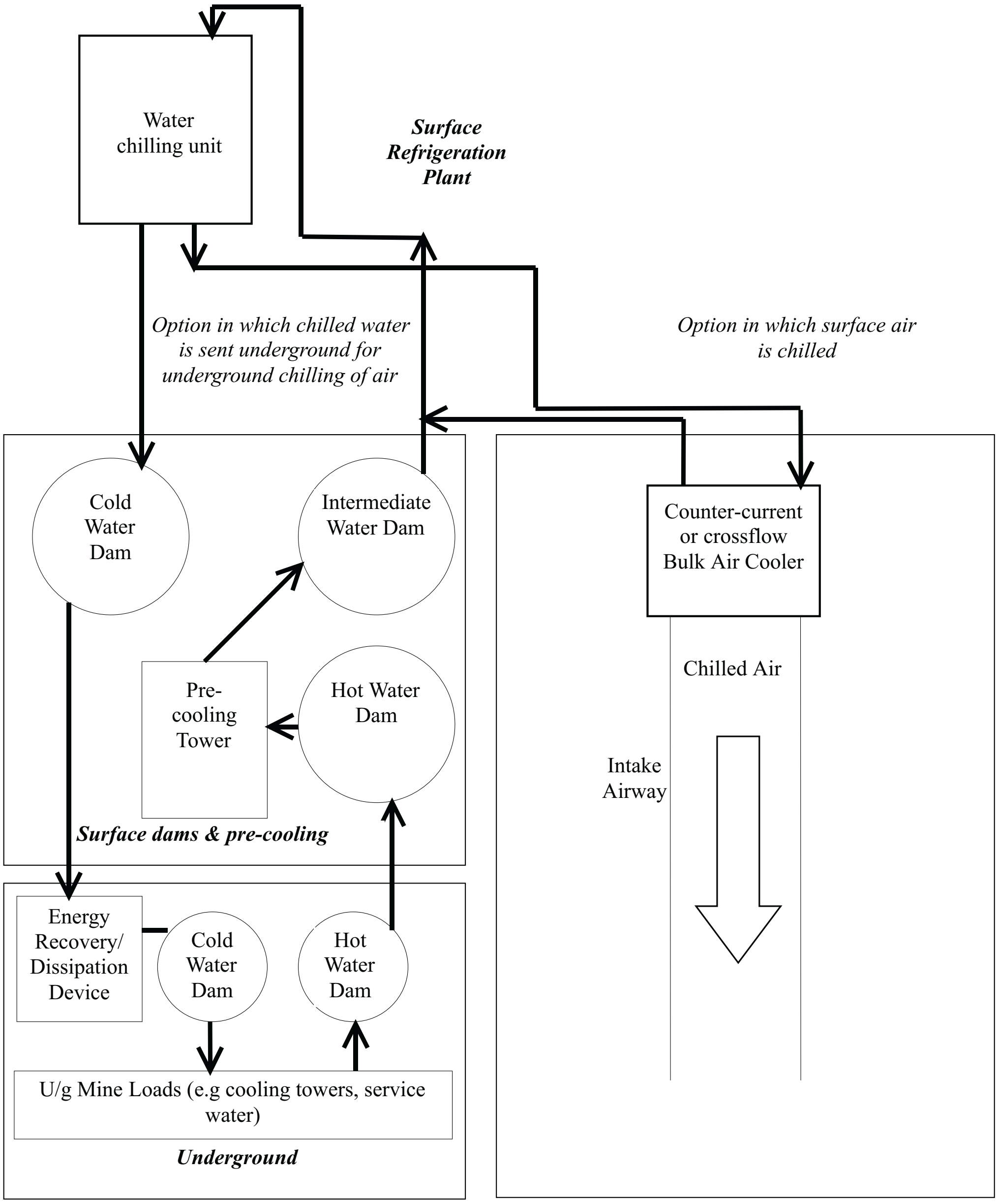

FIG 5 - Surface refrigeration plant with surface or underground cooling. Surface cooling is a bulk air cooler; Underground cooling can be a bulk air cooler, series of distributed smaller air coolers or spray chambers, chilled service water or combination of each.

FIG 6 - Surface refrigeration plant and condenser cooling tower (photo courtesy of *Mount Isa Mines Limited*). The refrigeration plant is to the left with the condenser cooling tower to the right. Plant capacity is 25 MW(R).

FIG 7 - Surface bulk air cooler (photo courtesy of *Mount Isa Mines Limited*). BAC is 22 m high × 16 m deep × 24 m wide, and is capable of cooling 750 kg/s of intake air from 25° C WB/43° DB to 14.1° C WB/DB.

with dusty air at the fully-enclosed top of the shaft (previously open, but now closed to capture the cold air) to form mud and slimes, which accumulated on the friction drum finally resulting in slippage.

SUMMARY

Underground mining in Australia will continue as more productive and cost effective methods and equipment are developed, and as modern exploration tools uncover deeper high-quality orebodies.

The thermal environment in which Australian miners work is likely to come under further scrutiny in the future and improved methods of cooling are likely to be required.

Refrigeration does have application in most hot mines and the operating cost can often be partly off-set by reduced airflows and therefore reduced ventilation power costs, in addition to the benefits to health, safety and morale, or the benefits of operational improvements in productivity or operating costs.

Where adopted, refrigeration has major impacts on many facets of the ventilation system and the operation of mobile plant. In particular, the airflow strategy must change from ‘flooding’ to ‘minimum’ use of air.

Surface bulk air cooling is usually the most economic and practical mine refrigeration option in situations where the mine layouts can be adjusted so that chilled air can be delivered to only those regions needing it. Where surface bulk air cooling is not practical, other options including surface-chilled service water, surface-chilled water feeding underground air coolers, and underground refrigeration plants can be investigated.

‘Series’ ventilation is likely to become more frequent, especially in refrigerated mines, due to the increasing size and high mobility of diesel equipment. No guidelines for series ventilation currently exist, and these will need to be carefully developed using a risk assessment approach.

‘Off the shelf’ packaged commercial water chilling plants are usually not suitable for mine applications, particularly for underground applications. This is because of the significant differences between mine requirements and those of most commercial buyers of refrigeration plants.

It is essential that the overall plant capacity meet all credible operating requirements. Individual components must be sized accordingly. Design criteria and the trade-off between capital and operating costs must be specified for the tenderers to properly design the plant. Careful tender evaluations are required.

All safety issues, including the more obscure problems of introducing chilled air and the issues of refrigerant toxicity and heat rejection, need to be considered when designing a refrigerated mine, or retro-fitting a portion of an existing mine with chilled air.

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