The Ventilation and Refrigeration Design for Australia's Deepest and Hottest Underground Operation – the Enterprise Mine

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Introduction

The Enterprise mine (EM) is located at Mount Isa and is wholly owned by Mount Isa Mines Limited (MIM). This high grade copper mine extends from about 1000 m below surface to almost 2000 m below surface. A recent $400 million upgrade has taken the operation from a production rate of 1.3 Mtpa to a capacity of 3.5 Mtpa. The effects of high surface ambient temperatures in summer, combined with the depth of the mine and high virgin rock temperatures results in heat stress in the working place that, without intervention, would exceed the levels that human physiology can withstand. It would also result in significant decreases in productivity and high accident rates even where work is possible. Moreover, with a very hot and deep mine, the needs of "egress" and entrapment of workers during a mine emergency must be carefully considered.

Enterprise Mine has taken a "systems approach" to the issue of working productively, healthily and safely in heat. This involves setting limits of thermal stress for workers, understanding productivity decrements when working in heat, establishing productive and healthy environmental targets, developing engineering solutions to meet these targets, creating a well-educated workforce with respect to working in heat and then developing health protocols to ensure workers' health is protected.

Refrigeration must be added to the mine to provide acceptable and productive conditions underground. By the time the mine is commissioned in 2000, Enterprise mine will have an installed refrigeration capacity of in excess of 40 MW(R).

The ventilation engineering principles proven over many years at the other Isa underground mines are tailored to "flooding" the mine with air to remove the heat, which is the main contaminant. This principle will not work at the Enterprise mine, for reasons discussed below. With the underlying ventilation principle no longer satisfactory, a complete review of the entire ventilation principles and engineering solutions was required for the Enterprise mine.

Hazards, Risks and a System to Manage the Risks

The control of hazards related to in working in heat were reviewed under three categories:

- *Engineering*: what engineering solutions can be put in place to reduce and maintain the risks at acceptable levels?
- *Procedures*: what procedures are required to ensure the risks can be managed at acceptable levels?
- *Competency*: what level of education, training and competence is required by all persons in the system to ensure the risks are sustained at an acceptably low level?

Hazard management was reviewed in three respects:

- *Prevention*: removing or reducing the risks from heat hazards
- *Monitoring*: monitoring the level of risk created by the hazards
- *Contingency*: developing contingency plans that minimise harm if the risk from the hazard rises to a dangerous level. In other words, if Plan A fails, what is Plan B?

These are shown diagrammatically in Figure 1.

Enterprise Mine then developed a series of statements (Figure 2) that embodies this philosophy in terms that management and the workforce could relate to.

All the elements of this system are required to be in place and working effectively if the system as a whole is to operate properly (see Figure 3)

The Engineering Requirements of the System

Certain minimum amounts (volumes) of air are required to dilute noxious and nuisance gases and particulates to acceptable levels. A major pollutant in the underground air in the Enterprise mine is heat. In general, it is the heat in the mine workplace at EM that is the determining factor in the amount of air and refrigeration required. The management of heat in the Enterprise mine is expected to be the single most significant success factor in the on-going operation of the mine, although there are other innovations being introduced to the operation, especially in the area of paste fill. Special protocols have been developed to ensure all levels of heat can be handled safely and without damage to health (Brake, Donoghue and Bates, 1998).

In the final analysis, there are three key issues to be resolved:

- What quality of air is required in each area of the mine, over time?
- How much (quantity of) air is required in each area of the mine, over time?
- What is the "best" way of delivering the required quantity and quality of air to each area of the mine, over time?

A key concept is that optimising the ventilation cannot be done simply for a single "snap shot" of the mine's life: it must be done "over time". The ventilation consequences of the normal "ebb and flow" of a mine operation over its life, from construction through to remnant mining, must be considered.

Ventilation design is an iterative process even when the mine is not considering refrigeration – it requires optimising airflows and airway sizes and fan duties. In a refrigerated mine, there are several more design parameters to be optimised. It is therefore essential to treat the engineering of the environment as a system, and to use a systems approach. Taking a narrow view means that one problem may be optimised, but at the expense of producing an unsatisfactory or sub-optimal system as a whole.

Quality of air required

Local statutory regulations, codes of practice and other standards (such as Australian and International standards) can either set mandatory requirements or provide technical guidance as to the quality of air required in the mine. In general, because people must be able to traverse most areas of the mine (to fix equipment, to inspect ground conditions, to muck out shaft spillage), the relevant limits are those that apply to people rather than equipment. However, where the requirements for equipment are more onerous, then these would apply.

Statutory and codified requirements are usually of two types:

- maximum concentrations of harmful substances, e.g. carbon monoxide, aldehydes, dust, NO and NO_2 etc, and
- minimum airflow requirements, either in terms of volume (m^3/sec) or velocity (m/s).

By estimating the production of harmful substances in the mining process, the required dilution rates with fresh air can be calculated in a relatively straightforward manner, although care needs to be taken; for example, not every item of diesel equipment in the mine is operating all the time, nor is it operating at full engine power.

Obviously, it is rare for the design *quality* of air to change over the life of the mine.

The particular case of heat

Heat is a particular case of an unwanted air-borne contaminant. There are three almost "unique" features of heat:

- With other contaminants, usually the only practical control mechanisms are to dilute the air so that the contaminant is reduced to a safe level, or to prevent the contaminant entering the air. With heat, it is also possible to "re-condition" the air, i.e. remove some of the heat by refrigerative air-conditioning. It is also possible to make the cooling impact of the air more effective, at least for humans, by increasing its velocity over the human skin, i.e. without removing any heat at all. These factors are not true of other contaminants.
- With most airborne contaminants, use of a respirator can ensure the inspired air is safe for the lungs; however, a respirator will not remove "heat".

- Higher levels of heat result in significant decrements in productivity, in addition to impacts on health and safety. Generally, there is a critical threshold below which health and safety is not affected, although productivity is. This is because there is a crucial nexus or "link" between heat stress and health and safety problems. This link is the state of hydration, acclimatisation and health of the individual. Workers *can* work safely in hotter conditions, up to limiting values, *providing* more regular and longer breaks are taken and *providing* they are healthy, acclimatised, well hydrated and self-paced. Work can be done safely, but it can be very unproductive, with very high rest components in the work/rest cycle.

Measurement of Heat

In terms of the impact on humans, many indices have been developed to measure heat stress. However, most of these require measurement of some or all of the following parameters:

- Dry bulb (DB): is the temperature in common use and referred to in weather reports.
- Meant radiant temperature (MRT): is the heat load due to radiation from a hotter body (e.g. the Sun) to a cooler body (e.g. a person). In an underground mine, radiant loads come from rock surfaces (especially fresh rock), diesel engines and the dry bulb temperature of the air (which, itself, is a "hot body"). It is usually measured with a thermometer inside a blackened copper globe, with suitable corrections made for DB and wind speed over the globe.
- Wet Bulb (WB): is the temperature at which water evaporates into the air (at a particular dry bulb temperature) once equilibrium between the water and air has occurred. It is very much more important than the dry bulb temperature to physiologists as the evaporation of sweat is related to the partial pressure of water vapour in the air (in effect, the humidity). Knowing any two of dry bulb temperature, wet bulb temperature or humidity (along with barometric pressure) will allow calculation of the third.
- Wind speed: as discussed earlier, the wind speed over the skin is a key issue in the rate of evaporation of sweat and therefore of body cooling.

In an underground mine, it is common to assume the radiant temperature is the same as the dry bulb temperature. This is not always true, especially for operators of hot diesel equipment if not in air-conditioned cabins; however, equipment to measure radiant loads was not, in the past, suited to the underground environment. With new technology, better heat stress measurement devices are now becoming available (Bates and Matthew, 1996).

Sources of Heat

Heat is both an input to and a "by-product" of mining. Heat is produced or derived from a number of sources in any mine (Pickering and Tuck, 1997). These include:

- autocompression[1],
- machinery: plant and equipment,
- geothermal heat from strata (i.e. influenced by virgin rock temperature (VRT) and other factors)[2],
- fissure water,
- oxidation,
- explosives,
- broken rock,
- miscellaneous sources, such as lighting, personnel, service water.

A further, and major, issue on heat is the heat contained in the air even before it enters the mine. This is a function of the surface climate.

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1 Autocompression is a term which denotes the fact that the air going underground heats up merely by virtue of the conversion of the "potential" energy of the air at surface into heat when the air moves closer to the centre of the earth. At EM, autocompression will increase the wet and dry bulb temperatures by about 6.5^0 and 8^0 respectively at the average depth of the mine, which adds about 22 MWr to the required refrigeration loads.

2 At EM, the geothermal gradient is 20^0/1000 m from a surface rock temperature of 28^0.

The Mount Isa climate is shown in Figure 4. At Mount Isa, the maximum (or *limiting*) summer surface condition is 26.5^0 WB[3]. The reference surface condition (exceeded about 220 hours or 2.5% per year) is 25^0, the *average* summer (December to March inclusive) condition is 21^0 WB.

Heat loads can be estimated with reasonable accuracy using well-established procedures (Hemp, 1989). The approximate proportions of heat from the various sources at the EM are shown in Figure 5. The size of the "pie" is about 40 MWr.

Note that these values *exclude* the impact of the Isa climate, which is very substantial.

At the summer reference condition of 25/35, and assuming a "design" temperature at the workplace of 28/36, the surface air contributes 13 MW of cooling (i.e. the surface air is still cooler than the required air temperature in the workplace). At the mid-winter temperature of 10/15, the surface air contributes 61 MW of cooling, totally changing both the size of the "pie" and the relative proportions of each component. As expected, with climatic heat load swings of this size, the surface bulk air coolers can be turned off completely for about 20% of the year.

Heat is also a special case when it comes to optimising airflows. This is because of an effect known as the *critical depth*. Critical depth is the depth below surface at which air at the underground workplace will exceed the *maximum* (design) condition solely through autocompression without *any* other heat gains. Critical depth is a function of surface temperatures and the depth of the mine *only*. Critical depth is therefore deeper in winter (because surface air is colder) and shallower in summer. The point about critical depth is that if the workings are above the critical depth, then the cheapest control measure on heat is usually to "flood" the workings with air. However, if the workings are below the critical depth, then the air itself adds to the heat load; in this latter case, the primary airflow should be kept to the minimum practical and the heat controlled via refrigeration.

It is normal to design the refrigeration requirements for a notional "average" workplace at the "average" depth of the operation. Local refrigeration arrangements are then used to ensure that the deeper (and hotter) areas are not under-cooled.

The average depth of the Enterprise mine in its first six years is 26A sub or 1350 m below surface. The critical depth at a surface temperature of 25^0 C WB is 1150 m below surface or 23C sub.

Human Physiology and Heat

Heat illness in underground, Australian miners has been recently described (Donoghue, Sinclair and Bates, 2000). This paper is the first to document the clinical features, haematological and biochemical profiles and thermal stress on these workers.

The ability of the body to dissipate heat is a function of many factors. The key ones are:

Cardiovascular fitness: a strong, fit, heart (the pump, including provision of essential oxygen from the lungs to operate the pump) and good circulation are essential.

Obesity: this effectively insulates the body and lowers the surface area/body mass ratio, reducing heat loss.

Acclimatisation: this is the sum total of all the adaptations the body has to extended exposure to heat.

Hydration levels: the body has to remain well-hydrated when working in heat. Even small degrees of dehydration cause significant decrements in the ability to work in heat.

Clothing and Personal Protective Equipment (PPE) requirements: the more clothing and PPE that is worn, the greater the insulation effect, the lower the water vapour permeation through the clothing and PPE, and the more difficult it is to stay cool. In an underground mine, there is no direct exposure to radiant heat (except at newly blasted rock faces), so there is nothing to be gained from using clothing to reduce radiant heat loads.

Environmental conditions: evaporation is affected by several environmental factors. However, the two most significant in an underground mine are humidity and air speed over the skin. Obviously, at zero humidity it is very easy for water (sweat) to evaporate from the skin into the air. When the air is saturated

[3] In future, wet bulb/dry bulb temperature combinations will be written as 25/35: the wet bulb always preceding the dry bulb. All conditions are at 97.5 kPa. Note that the wet bulb temperature can never exceed the dry bulb temperature, so there is no such thing as 35 WB/25 DB.

(100% humidity), it is much more difficult for evaporation to occur[4]. At intermediate points, the difficulty in evaporation increases as humidity increases, which is why "hot, humid" air is much more stressful than "hot, dry" air at the same temperature. Air speed over the skin improves the rate of evaporation under all circumstances (except at 100% humidity or very high wet bulb temperatures) and therefore facilitates work in heat.

Of equal significance is the amount of heat that the body needs to reject. Clearly, this is primarily a function of the work rate. The maximum efficiency of the human body is about 20%, but it is rare to be this high. The harder the body works, the greater is the metabolic rate. To ensure conservative designs, it is usual to ignore any "real" (i.e. useful mechanical work done) and assume the entire metabolic rate (energy expenditure) must be released as heat.

The relationship between *Thermal Work Limit* (Brake and Bates, in press), (called *Air Cooling Power* (ACP) at Enterprise Mine), and air velocity for the higher wet bulb temperatures typical of thermally stressful situations underground is shown in Figure 6. The units of TWL are watts per square meter of body surface. A 70 kg person has a surface area of about 1.8 m^2, so that a metabolic rate (energy expenditure) of 200 W/m^2 is equivalent to 360 W.

Note the significant increase in TWL up to about 0.5 to 0.7 m/s. Beyond this point, although TWL continues to increase, it does so almost linearly rather than exponentially. Therefore most of the benefit of higher airflows is harnessed by a minimum velocity of about 0.5 to 0.7 m/s.

Note also from Figure 6 that if an average cooling power of the underground workplace was set at 180 W/m^2 (say), which would "cover" work up to a metabolic rate of 180 W/m^2, then this could only be achieved by WB temperatures of about 27 to 28 degrees. Higher temperatures than this become asymptotic to the required cooling rate, or require unrealistic or impractical wind speeds.

From inspection of Figure 6, it can be seen that whether the mine is above or below the critical depth, and whether it is relying on refrigeration or "flooding" as the heat control mechanism, there is a lower limit on airflow that must be achieved. However, this can be achieved by:

- stronger primary ventilation, i.e. more fresh air, or
- less primary ventilation but augmented by increased velocity of air over the skin, e.g. using an "airmover"[5].

Using an airmover to increase the velocity of air over the body does not constitute "recirculation" of air, which is effectively banned in most jurisdictions.

Because TWL is measured in W/m^2, it can easily be compared to watts of refrigeration "coolth". The impact of localised cooling using refrigeration or an airmover can therefore be measured directly. For example, consider a workplace being ventilated with 10 m^3/s of air at 30^0 WB, 40^0 DB, 40^0 Globe, 100 kPa barometric pressure and a wind speed of 0.2 m/s. The initial TWL is 105 W/m^2. Local refrigeration of 100 kWr [kilowatts of refrigeration effect[6]] is installed. Standard psychrometric equations can be used to calculate that temperatures will drop to 28. 0^0 WB and 31.4^0 DB, which results in an increase in TWL to 150 W/m^2. The capital and operating costs of this engineering intervention (refrigeration) can be directly evaluated against the cost benefit of improved productivity Using the above example, the TWL could have been increased to the same 150 W/m^2 by increasing the wind speed over the skin to 0.8 m/s without any addition of refrigeration This is achieved almost cost-free.

On the other hand, the introduction of refrigerated air has had a noticeable effect, as predicted, on required air volumes at the working place. Typical comments such as "we can now get away with half the air we used to require" are borne out by Figure 7, which shows the volume of air to a typical 40m^2 cross-section

4 Evaporation is still possible while the skin temperature exceeds the dew point temperature. However, once the dew point temperature exceeds skin temperature, then moisture will condense from the air onto the skin, i.e. the reverse of evaporation, and the latent heat of condensation will be added to the skin, resulting in rapid hyperthermia.

5 An "airmover" is a compressed air-operated, venturi device with no moving parts.

6 The unit of refrigeration output is a megawatt of "coolth" or refrigeration, written MW(R). The amount of electrical power required to generate a MW(R) varies according to several factors. As a general rule of thumb, for a large, industrial, purpose-designed plant, an *overall* "coefficient of performance" of about 3 is typical and means that a 20 MW(R) plant requires about 6.7 MW(E) (megawatts of electrical energy) to operate.

underground workshop going from 50 m^3/s before refrigeration, to *half* this amount by only reducing the wet bulb temperature a little over 1^0.

Productivity

When humans work in heat, their deep body core temperature will not rise to dangerous levels while the cooling power of the environment is greater than the metabolic heat generated as they work.

Once the cooling power is exceeded by their metabolic rate, the heat can only be stored in the body, which can quickly rise to dangerous internal "core" temperatures.

Productivity is also seriously affected by excessive thermal stress. For example, if the metabolic rate (work rate) for a particular type of work in an environment of low thermal stress is 180 $W.m^{-2}$, and assuming a "resting" metabolic rate of 60 $W.m^{-2}$, then the productivity when working in an environment with a TWL of 120 $W.m^{-2}$ is given by:

Productivity = (120 - 60) / (180 - 60) = 50%, where (120-60) is the actual residual work capacity (the working rate less the resting rate) in this environment and (180-60) is the required residual work rate for full productivity. This then allows simple calculations of the cost of lost production and other economic impacts of environmental conditions

A sound upper design criteria, in terms of WB, for a typical workplace is considered to be 28^0 WB, as this should allow a metabolic rate of at least 180 W/m^2 with realistic airflows. This metabolic rate is above the average work rate in both metal and non-metal mines (Van Rensburg et al, 1991; Tranter, 1998). Good practice in terms of the "spread" of temperatures around this design maximum is considered to be 2^0 C WB (refer to Figure 8).

With the estimate of heat loads underground, the climatic profile and a "typical" spread of underground temperatures, the average and actual distribution of temperatures in the workplaces can be established for any given refrigeration scenario.

By then putting a cost on the lost productivity (direct wages plus production [revenue]) and a cost (capital and operating) on provision of more refrigeration, an "optimum" or design maximum wet bulb temperature at the working place underground can be established. For the EM operation (and most other mines), the optimum (maximum design) temperature at the work place is 28^0 WB @ 0.5 m/s airflow (170 W/m^2 TWL at 36^0 DB). Hence 66% of jobs should lie between 26 and 30^0 C WB; 95% of jobs should lie between 24 and 32^0 C and 99 % of jobs should lie between 22 and 34^0 C

From Figure 8, if the *average* workplace temperature is reduced, the percentage of shifts spent working in more extreme conditions (WB>30^0) is also reduced, but there are still some. But reducing the average requires much higher refrigeration capacity and operating costs.

If the *spread* (standard deviation) is reduced, with the average left unchanged, the percentage of short shifts is reduced and productivity improved *without* any extra capital or operating cost.

Note that even if there is a "normal" distribution of temperatures within the workplaces, the burden of "hot" shifts through the mine will not fall "evenly" but will be biased against the jobs that are deeper (more autocompression, higher VRTs, etc) and/or more difficult to ventilate (forced versus flowthrough, etc).

Methods of Control of Heat in Underground Mines

Methods of control of heat in mines is a substantial issue. As mentioned previously, there are two major control mechanisms:

- Higher airflows: either by way of more primary airflow through the mine, or by achieving higher local airflows using airmovers or other such devices, or both, and
- Refrigeration.

Many types of refrigeration have been proposed and trialed in underground mines. The relative advantage of these depends on such factors as: depth of the mine, local power costs and mining method. However, at EM, along with many other major new operations today, refrigeration is achieved by a mix of the following:

- Surface Bulk Air Cooling. Enterprise Mine uses an 8 MWr existing surface refrigeration plant generating cold water at about 3^0 C, in combination with a new 24 MWr plant generating cold water at

7^0 C, to feed separate cooling towers at the collar of two major intake shafts. Surface cooling has the advantage of easy maintenance on the plants, keeping the ammonia refrigerant out of the mine, lower condensing temperatures than underground, "free" refrigeration due to the difference between low wet bulb temperatures on surface and the condensing temperature, and high plant Coefficient of Performance[7].

- Underground Bulk Air Cooling. This uses a 10 MWr dedicated surface refrigeration plant to generate cold water (10 C), which then drops underground into an energy recovery device (at EM this is a Pelton Wheel[8]) and then feeds underground Cooling towers and Spray chambers. Some underground bulk air cooling is essential to provide the flexibility the ventilation engineer needs to overcome the impact of higher heat loads on the deeper areas of the mine. Achieving this solely by surface bulk air cooling would result in some areas of the mine being over-cooled, an expensive solution. This is particularly the case if the fresh air intakes are shared with a separate mine, which is the case with EM, where intakes are also shared with the existing Isa Lead mine.
- Chilled service water. Chilled service water is widely used in South Africa. However, it is been found to be of low practical benefit at Enterprise Mine. This is because of the low usage of service water in areas where workers are exposed to heat. Very little "hand held" mining is now done in Australia, and many drilling machines (which are the largest users of service water) now have air-conditioned cabins.
- Spot coolers: these are electrically-powered conventional split refrigeration systems installed underground, with the evaporator in fresh air and the condenser in return air. These can be used effectively for small heat loads (e.g. underground offices or cribrooms) up to about 300 kWr, where condenser heat can be rejected directly and locally into the return air (exhaust) circuit. Where close access to the exhaust circuit is not possible (most locations), conventional split systems cannot be used. Because of the cold temperatures at the evaporators (resulting in condensation of air with dust on evaporator surfaces), these units are best suited to good quality intake air or the installation of an easily maintained dust filter, to ensure effective operation of the evaporator over time. A refrigerant that is safe for underground use must be employed.

Estimating quantities of air: the primary ventilation requirements

The most crucial steps in estimating the quantity of air required for the mine are:

- Determining the activities that will need to be ventilated: development, drilling, ground support, blasting, hauling, etc. This must be a complete listing and include allowances for fixed plant, plus areas where persons need to visit or travel.
- Creating a design ventilation "standard" for each activity. This standard must, having considered the required quality of air and the noxious substances produced in this working place, include a required volume of fresh air. Note that a good ventilation standard will include at least the following items:
    - type of activity
    - method of secondary or auxiliary ventilation (forced duct, flowthrough, overlap, single or twin duct, etc)
    - development sizes
    - limiting distances (note that this may not just be such the obvious ones as distance to the face, but also distances to truck re-muck bays)
    - amount of diesel or other equipment in the workplace: types, kW, air-conditioned cabins (or not), etc
    - personal protective equipment (PPE) requirements of men in the work place

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7 COP of a surface refrigeration process is about 5 to 6. The pre-cooling tower before the plant has a COP of between 20 and 50. After taking pump and other power consumers into account, typical surface plants have an *overall* COP of about 3.

8 The Pelton wheel at EM recovers about 1 MW of electrical energy. It also reduces the effects of autocompression on the water itself. Without an energy recovering device, water will increase in temperature by 2.33^0 per 1 000 m. With energy recovery, the temperature increase would be typically 0.8^0 or less.

- metabolic work rates of men in the work place (W/m^2)
- leakage and losses of air: this is important as, even under good practice, these are real and relevant. In fact, in some cases, limited leakage from a ventilation duct may be desirable or even essential to ensure temperatures in the "outbye" side of each workplace do not exceed the maximums allowed.
- a separate standard may need to be produced for some activities which have very different ventilation requirements in their "cycle" (for example, a development face during boring versus during mucking)
- optimum volume and velocity of air (m^3/s and m/s) in each workplace. This is a large topic in itself. However, for practical purposes, the following guidelines hold:
    - where the mining operation is above the critical depth for all of the year, refrigeration is not required, and the optimum airflow is the minimum required to achieve acceptable air quality, or that required to provide acceptable air temperatures in the return airways during the summer period, whichever is the higher,
    - where the mining operation is below the critical depth during summer, refrigeration is required, and the optimum airflow will be the minimum required to achieve acceptable air quality, or about 0.5 to 0.7 m/s, whichever is the higher[9].
- Note that, even where diesel equipment is not operating but men are expected to work, it is considered essential to provide for some airflow. In many instances this will be related to the need to provide for cooling of any persons working in the area.
- After developing ventilation standards, a summary of ventilation requirements can be produced.

- Examine the mine development and production schedule over the life of the mine. This allows a schedule to be put together, based on the ventilation standards for each activity, showing ventilation requirements over the life of the mine. It is crucial to recognise that the volume requirement is a function of the number of workplaces to be ventilated and the standards at each workplace, *not the number of persons working in the mine*. An additional allowance should then be made. This merely recognises that:
    - There are inefficiencies: a development crew may be allocated six ventilated workplaces, but sets up duct and fans for ten workplaces. In theory, only six fans should be on at any one time; in practice, double or more working places may need to be ventilated at any one time for this crew.
    - A contingency must be provided to allow for estimation errors in the mine characteristic curve and/or the required air volumes: no-one designs a concentrator or hoisting facility to "just" achieve the required tonnage. Some contingency is prudent and accepted as good practice to ensure the typical "peaks and troughs" of production can be accommodated. Contingency also reflects the fact that the design is based on imperfect knowledge and that some change will always occur from the original assumptions or design criteria. These changes almost always impact negatively on ventilation requirements (i.e. need more not less). However, contingency only comes at a cost. A good and prudent design will allow for modest contingency that adds value, but not so large that it reduces the project value. It is a "balance of probabilities and consequences" issue - a matter of managing risks. Large contingencies reflect either insufficient information being available or insufficient detail design having been completed.
- It is also crucial that the construction and pre-production phase of the project be fully taken into account. It is well recognised that the construction workforce in a project usually exceeds the on-going operating workforce. This results in there being more workplaces to ventilate during construction than during subsequent production. Sometimes the ventilation requirements during construction are more onerous than during production, and this is aggravated by the fact that a key part of the construction program is putting in the very ventilation system required to construct or operate the mine. Moreover, any delays during the critical and cash-consuming construction phase are likely to seriously impact on

[9] Note that at low refrigerated air temperatures, "losses" start to increase significantly as these are related to the "driving force", or ΔT, between the air and other surfaces, such as the rock and mobile equipment.

the construction cost, and hence project return. Any construction program for a new underground mine needs to be built around the four key obstacles to be overcome during the construction period itself: ventilation, mullock disposal, emergency egress, and logistics (getting men and materials in and out of the mine). The most *logical* construction program, from an engineer's point of view, will rarely be the most effective or cheapest once these four key factors are taken into account.

In addition to the impact of the construction workforce, it is also vital to recognise that a project in its construction phase has three other adverse impacts on ventilation:

- many of the rock surfaces are "new" and therefore much hotter than they will be as they "age". Old airways are cooler than new airways, disadvantaging a mine in its construction phase;
- after the ventilation circuits are completed, the mine can operate more on flowthrough air, rather than ducted air. Flowthrough air is more reliable and effective than ducted air, again disadvantaging a construction project;
- during construction, the ore handling system is not operational (crushers, hoisting shaft, etc). Therefore waste and ore must often be trucked in diesel equipment. This large diesel loading is not required after the ore handling system is commissioned (if a hoist is being installed). Therefore diesel loads are usually higher and more concentrated in construction than during production.

Note that various "rules of thumb" also exist to estimate airflow requirements in mines. In the Australian context, with large-scale, highly mechanised mines and relatively large orebodies, a figure of 180 m^3/s per Mtpa (plus 150 m^3/s), or 3 to 3.5 m/s per kt per month is typical. Figures at the lower end of this range apply to cooler climates where heat is not a major contaminant OR to hotter climates or deep mines where refrigeration is required; figures at the higher end of the range tend to apply to moderate climates and depths where the main mechanism for controlling heat in the mine is by "flooding" the workings with air.

It is also important to recognise, particularly on deeper mines, that the density of air at the working place underground will be different to the density on the surface. Therefore volume requirements underground (which is where the requirements are set) will differ to those at the surface (which is where the air intakes are located), and affects the fan duties and the mine resistance curves (more dense air results in higher frictional pressure drops for any given airway).

Optimum Airway Sizes

Most development sizes will be dictated by the size of equipment required to operate in the area. However, major fresh and return airways may need to be larger than this, to accommodate the necessary airflows. The trend to using larger equipment has generally been beneficial for ventilation personnel, as the larger development has had a major reduction on mine airway resistance.

It is desirable, and in some cases due to statutory requirements, essential to have at least two fresh air intakes into the mine[10], and at least one exhaust to the surface. In most mines, it is convenient and most effective to bring fresh air into the mine on the same side of the orebodies as the major service accesses (usually the footwall), and to use the other side of the orebody (usually the hangingwall) to collect the return air and exhaust it to the surface. The basic design of the ventilation circuits must be matched to the mine production plans, stoping methods and the like. Linear programming or simulation exercises can be used to optimise the trade-off between surface refrigeration, airflows and airway sizes. However, the elaborate assumptions used in some refined optimisation exercises have a habit of coming undone in practice, after the mining operation has started and data has come to light that was unforeseen at the feasibility study stage. The danger with sophisticated optimisation protocols is that they are only as good, and as accurate and reliable, as the underlying data. It must be remembered that a mine is an extractive operation inside a "natural" (i.e. not man-made) system (the geology of the mine) and therefore is both constantly changing (a dynamic process) and never perfectly understood in advance.

Once a concept for the major airways has been established and the location and number of airways established, the optimum airway size can be established in a straightforward fashion by:

10 Most mining jurisdictions require two means of egress. This is best achieved using two fresh air intakes, as using an exhaust airway as the second egress could result in compromised escape or entrapment in the event of a fire.

- using a network analysis to simulate volumes, velocities, pressure drops and fan duty requirements for various airway sizes,
- estimating capital and operating costs of airways and fans and solving for the lowest net present cost,
- for horizontal intake airways, setting a maximum velocity of 6 m/s, which is the practical limit before airborne dust becomes a serious problem. Horizontal exhaust airways, where dust is not an issue, can accept economic velocities up to 10 to 12 m/s.
- for vertical airways, a maximum velocity of 13 to 16 m/s is accepted as a good working limit, although with deep mines (and hence expensive shafts), velocities of up to 20 m/s are not uncommon. The "critical velocity" range of 7 to 12 m/s should be avoided in wet shafts or where condensation could occur, as this is the point at which water droplets will remain suspended in the airstream, increasing shaft resistance and adding extra stress on the fan installation. Auto decompression must be taken into account in very deep mines.
- Towards the latter half of the mine's life, major parts of the exhaust circuit may be closed off (for example, where stopes have been extracted and taken exhaust airways with them). Therefore the sufficiency of the ventilation system must be assessed in these latter years as well as in the early years.

Fan and Refrigeration Plant Design

The issues of fan and refrigeration design (sizing, type of installation etc) are adequately covered in other sources (De La Harpe, 1989; Howes, 1983).

Key Issues For Ventilation & Refrigeration Design at Enterprise Mine

Good ventilation practice is at least in part dependent on the particular mining operation. However, some of the issues to be considered at the Enterprise mine include.

Keeping Heat Sources out of the Fresh (Intake) Airways to the working places

- No Surface Intake ("Push") Fans: all electrical power input to these fans manifests as an increase in air temperature
- Keep Circuit fans in intakes to the minimum
- Do not allow trucks to "idle" in fresh air; set up park bays in return airways
- Do not idle trucks or loaders under ventilation lines (all of which carry refrigerated air)
- Controlling Numbers of Diesel Equipment:

  Diesel Motors are about 30% efficient. Hence One Elphinstone AD40 truck @ 367 kW at full load[11] generates 1 MW in heat. Taking losses into account, the refrigeration system actually needs to generate more than 1 MWr of "coolth" on the surface to service each AD40 at full load. Because these are such large heat loads, which will impact on environmental conditions underground, AND on capital requirements for refrigeration plant and operating costs, large heat loads must only be introduced after careful consideration of the knock-on effects on the local and overall ventilation and refrigeration plan, and on personnel.

  Mobile diesel plant also create significant humidity problems. Each litre of fuel burned produces about 1 litre of water vapour, but taking other factors into account, it is not uncommon for a diesel vehicle to produce 7 litres of water vapour for each litre of fuel burned. It is therefore desirable to avoid wet scrubbers, due to the moisture they put into the air. Catalytic converters are the required standard at EM.

  A "Catch 22" therefore potentially exists: if development rates fall behind, a tendency is to bring in more crews and equipment which results in more heat which results in lower productivity which results in development rates falling even further behind.

  One key issue for diesel equipment is how long it operates in a particular area. For example, a large truck that only enters a development end every twenty minutes has a much less profound impact on the airflow and refrigeration requirements in that development end than a truck working constantly.

11 "Average" engine loading is about 70% of full load

This is not only related to the time the truck is on location, but also due to the "thermal flywheel" effect of the rock walls, which absorb a portion of heat when the truck is on site and then expel it into the ventilation air when the truck leaves. This allows a less substantial refrigeration and, possibly, airflow requirement, than if the truck is continuously in the end.

- Use electrical equipment where possible: electric motors are much more energy efficient than diesel motors resulting in less heat and no noxious gases[12].
- Keep transformers and other heat sources out of the fresh air feeding the workings, wherever practicable. A modest 1 MVA transformer with an impedance loss of 5% will generate 50 kW of heat constantly. Larger transformers will give off much more heat.

Keeping humidity out of the intake airways

It is crucial that the intake airways be kept as dry as possible as wet or damp shaft or airway walls result in much higher heat flows from the strata into the air. Therefore nuisance water, particularly in the intakes, must be avoided. Wherever possible, it should be collected and pumped away.

Maximise air velocity on the job

Use Air Movers to ensure velocity over the body is at least 1 m/s.

Direct feed from fresh air raises to the working place

Where duct must be used to ventilate a workplace, air is fed directly from the fresh air raise (FAR) to each job. This avoids the situation where air blows out of the FAR and is then picked up somewhere else and ducted to the job. In this latter case, the air will be hotter than when ducted directly from the FAR. 20 m^3/s of air in a 1.2 m diameter duct will reach the face of a 6 m x 6 m drive 400 m away in 23 seconds. The same airflow travelling through the drive itself would take 720 seconds. Clearly the heat picked up by air travelling in the duct will be inconsequential compared to that picked up in the drive.

Economical use of refrigerated air

Because the total amount of air into the EM must be kept to the minimum practical (to minimise the heat load from autocompression and the hot surface temperatures), the air must be used to maximum advantage. Leakage and other losses must be kept to a minimum otherwise recirculation will occur and environmental conditions will deteriorate.

Maintaining "concentrated" workings

As the workings "spread out", the heat load from the rock surfaces themselves can become the major internal heat load in the mine. It is vital that mining activities remain concentrated in the smallest practical geographical area.

Ventilation Duct

The weakest link in system is the ventilation duct. In the EM, air is ducted directly from each fresh air raise to the working place[13], so the EM is heavily dependent on ventilation duct. Installation standards and on-going maintenance of ventilation duct are critical. There should have no more than 30% leakage for a well installed and well maintained duct.

Air Conditioned Cabins

Maximise use of air-conditioned cabins: this improves productivity, safety and morale and reduces fatigue.

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12 However, even electric motors have their limits. At EM, motor failures on the Kiruna electric trolley assisted trucks have been traced to high dry bulb temperatures, which are now restricted to 35^0 DB

13 This is to ensure the air into the ventilation duct is as chilled as possible, thereby reducing temperatures at the working place, compared to other possible systems of auxiliary ventilation.

Microclimate cooling

When the circumstances are suitable, EM uses “cold vests” for limited duration work in very hot conditions.

Judicious use of insulation

Major chilled water lines (e.g. to bulk air coolers) are insulated. This is particularly important when these lines are located in return airways, as any “coolth” lost from the pipes is totally wasted.

De-rating production & other schedules

Production schedules (and all ancillary schedules) must be de-rated over summer for the EM, in accordance with the expected productivity loss on jobs that require high work rates.

The fact that the burden of hot work will not fall evenly should be built into the schedules.

Effective maintenance and operation of the ventilation systems

A properly planned and executed maintenance program for ventilation and refrigeration equipment is essential. The ventilation/refrigeration system is unique in that it doesn’t need the same output and performance all year round. However, it *must* achieve very high reliability and efficiency in summer; therefore as much maintenance as possible should be done in winter.

Ventilation and refrigeration equipment must be operated so as to achieve maximum *system* effectiveness. It must not be operated to achieve the lowest running cost of the refrigeration plants themselves. The point is to optimise the efficiency of the *system as a whole* and in particular, to obtain optimum efficiency from the underground workforce.

Controlling changes to the ventilation/refrigeration systems

There is no real difference between the ventilation and refrigeration systems and any other item of critical fixed “plant”. Any major changes to the design or operation of the system should be subject to the same standard as any other Plant Modification.

These would include not only changes to “mine design” but also to schedules (e.g. if ventilation raises are deferred)

Choice of clothing and personal protective equipment (PPE)

Clothing has a significant impact on the ability of the body to cool itself via sweating as the following shows, based on a temperature of 28^0 C WB, 36^0 DB, air speed of 0.5 m/s and with safety hat, safety boots, socks and underwear:

TWL for shorts only .... 201 W/m^2

TWL for trousers and short-sleeved shirt .... 193 W/m^2

TWL for trousers and long-sleeved shirt .... 184 W/m^2

Note that PPE requirements are a part of the ventilation standard for each workplace. Therefore the choice of PPE impacts on airflow and refrigeration requirements, and should not be changed without examining the knock-on effects to productivity and ventilation costs.

Key issues for PPE are: fabric vapour permeability and conductivity, clothing design (“bagginess”) and amount of clothing and type of PPE. For example, leather boots are much cooler than rubber “gumboots”.

Dust explosions

Dust explosions can be a potential risk in all coal mines and many operations mining fine-grained sulphide ores. Special precautions are required to manage the risks of dust explosions.

Condensation and Dew Point

Mixing cold and hot humid air in a mine can create unexpected problems. These range from relatively minor matters such as the dripping of condensation from chilled water lines onto major road haulages creating road maintenance problems, to major issues such as the head ropes on the U62 hoisting shaft (a Koepe winder) slipping due to condensation on the ropes, resulting in a full skip of ore crashing to the bottom of the shaft. Wet metal surfaces due to condensation also increases the likelihood of corrosion due to rusting, and results in the build-up of more dust and grime than otherwise. In some areas, high humidity can result in deterioration of the rock strength (ingress of moisture into cracks) or shortened working lives of ground support due to corrosion.

Instrumentation

Over the past 20 years, most mines have heavily instrumented their fixed plant and mobile equipment. This has improved performance, increased availability and reduced maintenance and operating costs. Sadly, few mines have properly instrumented the ventilation system [except perhaps the surface fans]. At the EM, the ventilation and refrigeration (VAR) system, being as crucial as it is to safety, health, productivity and costs, will be significantly instrumented. Some of these instruments are as follows:

- The top of important fresh air raises (FARs) will be monitored at Mine Control continuously for wet bulb (WB), dry bulb (DB) and CO (carbon monoxide), and at the bottom for WB and DB.
- All Circuit fans will be monitored continuously for motor amps. This provides a “surrogate” for airflow and also indicates on/off.
- All underground Cooling Towers will be monitored at Mine Control continuously for WB, DB and CO. The Cooling Towers will also be monitored at Mine Control continuously for Chilled supply water flow rate and fault (on/off) indication.

This will allow rapid fault-finding of any problems in the system, which will impact beneficially on productivity, costs, mine output and morale. It will also allow assessment of quality of air in the fresh air raises in the event of a fire, and provide a much better understanding in future years as to how the underground system responds to changes in surface conditions, refrigeration output, etc.

Fault-finding and training of personnel: supervisors, managers and workers in ventilation circuits

This has already been mentioned. However, instrumentation alone will not result in the highest realistic standards of up-time from the ventilation system components or the best practical environmental conditions. Supervisors, especially, need to be trained as to the location of fans and other controls and how to make simple adjustment to underground cooling towers, etc. Plus controls on who and when plant is adjusted or maintained need to be established and enforced.

Systems to audit the ventilation system

The importance of measuring the effectiveness of the ventilation system cannot be overemphasised.

The elements of an effective audit process are:

- Identifying the customers and other stakeholders and understanding their needs: at the end of the day, the ventilation system has “customers” who have views on what “fitness for purpose” and “value for money” mean in their context. The customers and their needs must be identified.
- KPIs: key performance indicators are the means of “keeping score” and ensure the customers are getting a product that is both fit for purpose and value for money.
- Ventilation and Refrigeration standards: these are essential to ensure the customer gets what he is after. Many defects in the ventilation system are caused by the customer himself, so this requires careful but firm handling.
- PFDs: process flow diagrams are the essential pre-cursor to providing an adequate means to determine instrumentation requirements of the system, scope and regularity of audits, and an effective, timely, fault-finding response.
- Communication: it is vital that a process be set up and followed by all parties to ensure that defects are identified early and fixed promptly and that future mine design *and schedules* are compatible with future ventilation design (or vice-versa).

With a well designed ventilation and implemented system, the key role of the ventilation staff becomes one of advising on necessary changes to the ventilation circuits and operating strategy as the mine develops, and auditing the effectiveness of individual components and the system as a whole. At EM, an audit process has been developed that encompasses, among other matters:

- Daily checks of key ventilation components and conditions and monitoring of KPIs.

- Follow-up within 24 hours with written reports on all serious ventilation defects and failures, especially on "dust reports" and "hot jobs" or heat illnesses.
- Issue of non-compliance reports for serious breaches of ventilation standards.
- Issue of bi-weekly and end of month KPI reports.

Escape (egress) and entrapment

When the ventilation system fails at EM during summer, temperatures will increase rapidly and the airflow throughout the mine will fall almost immediately. Natural ventilation pressure is at its lowest in summer, and the elaborate ventilation networks and non-return dampers installed on most underground fans will mean that airflows through the orebody will rapidly diminish. Experiments in the mine (Brake, 1997) have shown that the WB increased from 28^0 to 33^0 within about 90 minutes and to 33^0 to 36^0 WB (depending on the location) within 2 hours, with temperatures continuing to increase after two hours (albeit more slowly). These conditions have major ramifications on egress and entrapment, and consideration work has been undertaken to ensure mine workers can be kept in a safe condition, or escape safely, in the event of power failures or mine fires (Brake and Bates, 2000; Brake, 1999).

Conclusion

The Enterprise Mine will be Australia's deepest underground mining operation and will be among the hottest underground mines in the world. It will be the working environment for several hundred workers, technical and support staff and visitors for at least fifteen years. During construction, a workforce of almost 700 persons needed to be ventilated and kept cool. With high virgin rock temperatures and the adverse Mount Isa surface summer conditions, the workforce will be exposed on a continual basis to adverse thermal conditions. Mount Isa Mines has developed a comprehensive system of engineering and other solutions to managing the risks associated with working in heat.

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Figure 1 The Elements Of A System To Control Risk

	Equipment/ Engineering	Procedures	Competency
Prevent			
Monitor			
Contingency			

Figure 2 The EM Philosophy on Working In Heat

Engineering the Environment
We choose airflows, the amount of refrigeration and other engineering solutions to bring the heat to acceptable levels
Job Design
We use air-conditioned cabins, air movers, labor-saving devices and other ways to improve the local environment or reduce the physical effort required for work
Ventilation & Refrigeration Standards
We develop standards for the way we install and operate equipment, or go about our work, so that our engineering solutions will be effective
Health & Safety Medical Protocols
We provide health procedures and medical tests to ensure that heat illness is avoided or picked up at a very early stage and treated
Education
We educate our workforce so they understand what happens when they work in heat and can do so safely and without damaging their health
Emergency Response
We provide a means of ensuring that anyone who develops a heat illness can get effective, immediate treatment.

Figure 3 How the System Fits Together

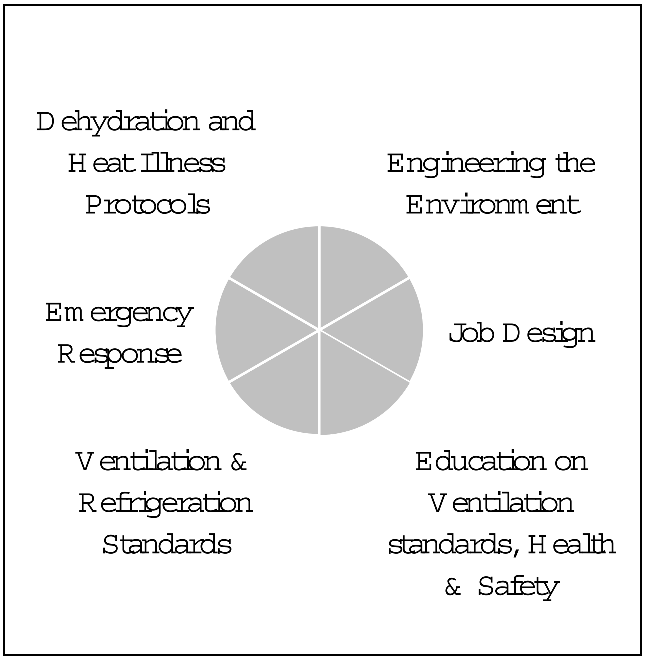

Figure 4 Surface Climatic Data for Mount Isa

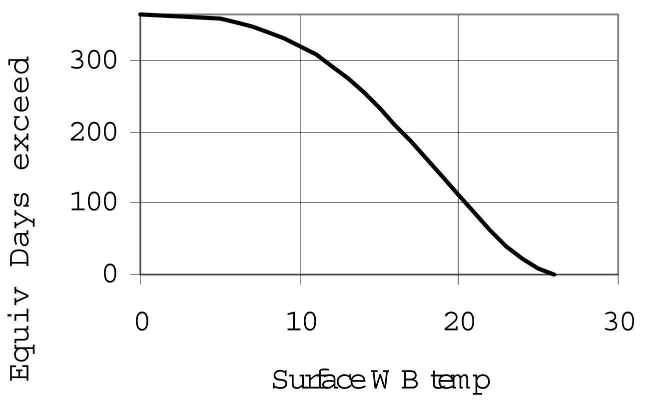

Figure 5 Heat Loads at EM (excl surface climate)

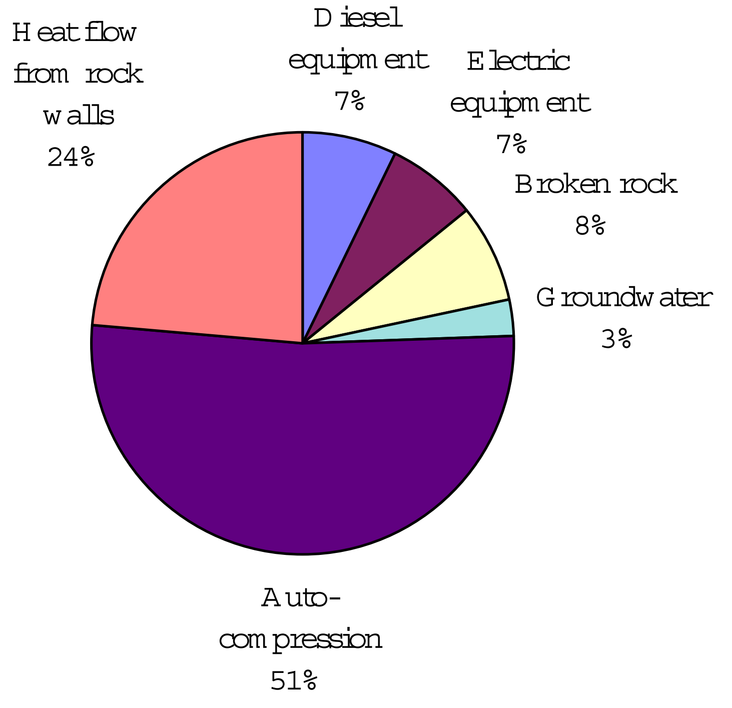

Figure 6 Thermal Work Limit versus air velocity

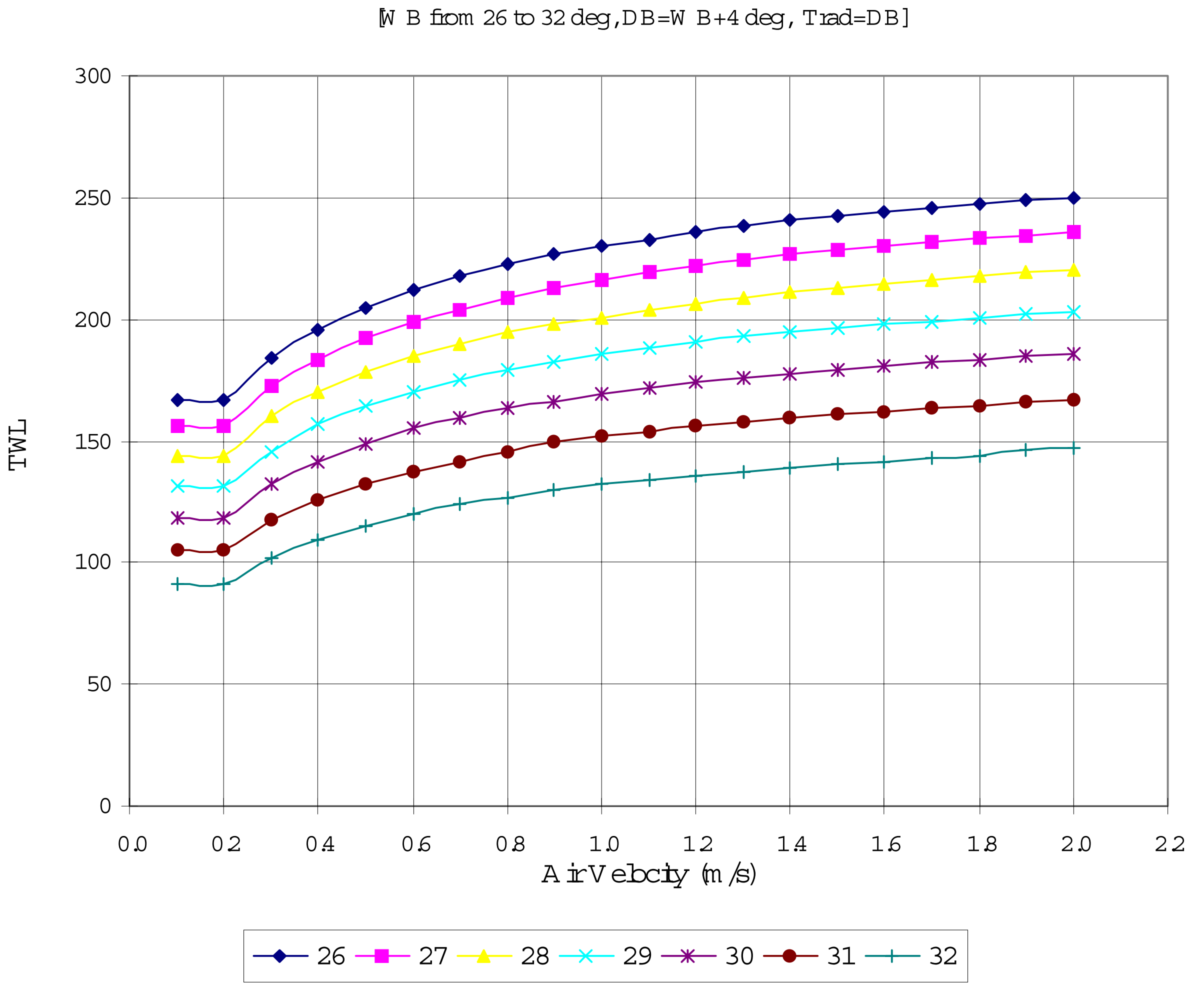

Figure 7 Reduction in airflow required in underground workshop after introduction of refrigerated air

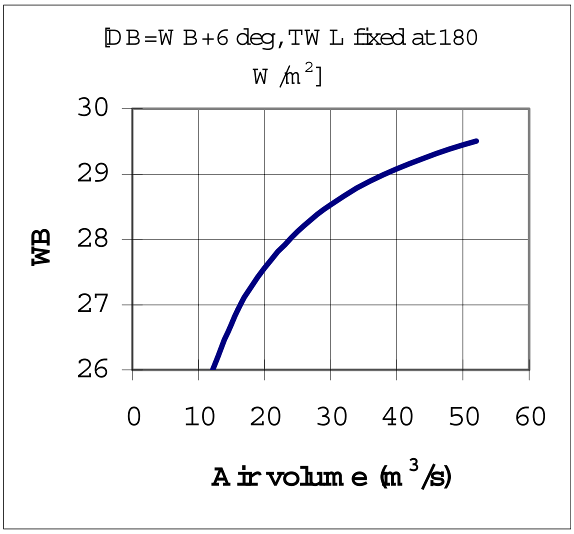

Figure 8 Temperature Distribution at Underground Workplaces