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A review of heat issues in underground metalliferous mines

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ABSTRACT: Underground heat issues are mainly focused on the detrimental effects to a workers health. However, working in hot, humid conditions has other negative effects. Studies have shown that safety, productivity, workforce morale and operating cost are also worsened in these conditions. The human body has several mechanisms for rejecting heat and remaining cool. However, once the air temperature exceeds about 34°C, the only effective mechanism is by evaporation of sweat from the skin. This is assisted by acclimatisation which is the human body's enhanced ability to combat extended exposure to heat. The body has to remain well hydrated when working in heat as even small degrees of dehydration cause significant decreases in the ability to work in heat. There are two ways in which heat load can be reduced: Through use of refrigeration/vent/cooling to reduce thermal stress on workers; Reduce the contribution that heat sources have to underground heat load (e.g. reduce idle time, fleet size, etc). Some of the sources of underground heat have the potential to be more manageable than others. Geothermal heat and heat from autocompression will be found in all mining situations in varying degrees depending on geothermal gradient and surface temperature, however, the use of equipment and blasting may be streamlined to reduce the underground heat load. It is through a combination of the available options that most mines will successfully control their heat related problems. Mt Isa, which has been a focus for heat related study in Australia, has successfully implemented protocols for working in heat. Through combining these with the installation of a surface bulk air cooling plant, Mt Isa has consistently reduced the incidence of heat illness. This is likely to be the most cost effective method of reducing heat load for deep mines in Australia. Shallower mines which may only occasionally encounter hot conditions should consider more portable cooling options. This study will review the heat issues in underground Australian metalliferous mines.

1 Introduction

Heat and humidity are encountered in tropical locations and in deep underground mines, where the virgin rock temperatures and air temperatures increase with depth, principally due to the geothermal gradient and auto-compression of the air column. Both natural and 'man-made' sources contribute to the underground heat load with blasting and equipment operation also significant heat contributors. Some heat sources are able to be managed better than others; heat is, however, one of the constants of underground mining. Management of heat issues, through better engineering and work practice controls, rather than elimination is the way these problems will be overcome.

Considering that Australia's ore reserves continue to much greater depths, it is likely that the major impediments to deep mining will be ambient rock stresses and high temperatures.

2 The Human Body and Heat Exchange

Humans maintain a reasonably constant body temperature (usually between 36°C and 37°C at rest) in spite of wide variations in environmental temperature. Environmental temperature may result in a heat gain or heat loss while metabolic heat, associated with muscular action, increases the body's heat load.

Methods of heat exchange between the human body and the surrounding environment are:

- Convection – which can either be heat loss or gain based on the difference between skin temperature and air temperature,
- Radiation – can also be heat loss or gain based on the temperature difference between the skin and the solid surroundings, and
- Evaporation – is the body's own method of heat removal and is the cooling effect provided when sweat evaporates off the skin. The efficiency of evaporative cooling is highly dependent on the humidity of the surrounding air; higher humidity reduces effectiveness.

3 Major Sources of Underground Heat

3.1 Geothermal Gradient

Generally speaking rocks within 50m of the earth's surface maintain a temperature equal to that of the average air temperature. Between 50m and 100m the gradient is variable because it is affected by atmospheric changes and circulating ground water. Below that zone, temperature almost always increases with depth. However, the rate of increase with depth (geothermal gradient) varies considerably with both tectonic setting and the thermal properties of the rock. Typically the geothermal gradient of the upper crust is between about 15°C/km and 40°C/km.

For dry airways, the heat flow from the surrounding rock to the ventilation air is proportional to the difference between the virgin rock temperature and the air temperature. The rate of heat flow from the rock to the air increases when the airway is wet.

Areas of high rock temperature at a depth of 2 km is shown in Figure 1. Figure 2 indicates the geothermal gradient and rock temperature (at up to 1km depth) of several Australian mining locations.

3.2 Autocompression

Surface air sent down to the workings, through either natural or man-made ventilation, will experience a compression. This means that although the volume of air has been reduced, the amount of heat remains the same resulting in hotter air.

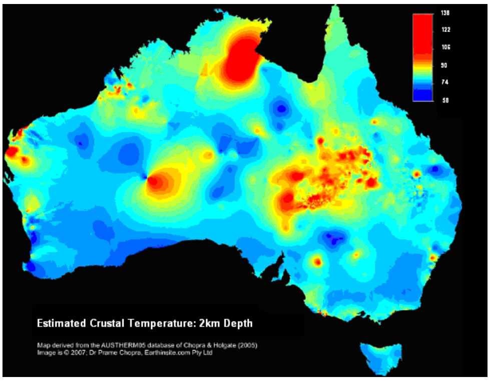

Figure 1. Hot rock temperatures in Australia at 2 km depth (Source: Geoscience Australia)

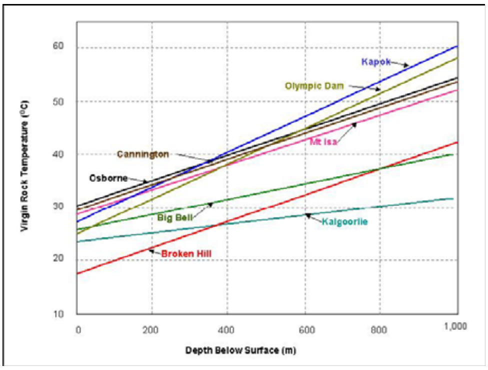

Figure 2. Geothermal gradients at several Australian mining locations (Source: AMC Consultants, 2003)

Temperature will increase due to autocompression by up to 10°C (about 4°C WB is common) per kilometre of vertical depth, whether shaft or decline. This will become a very significant source of underground heat as mines become deeper. Since the effect of autocompression combines with the surface air temperature to contribute to underground air temperature it is clear that this is a very significant source of mine heat, particularly in hot areas of the world.

3.3 Other Natural Sources

Groundwater, service water and oxidation also contribute to the underground heat load. Oxidation's heat contribution is almost negligible however the flow of water into mining excavations contributes significantly to the heat load due to the ease with which water passes heat to air, mainly through increased humidity.

3.4 Explosives

It is estimated that as much as 90-95% of the energy released in blasting eventually finds its way into the underground environment as heat. It is probable that some of the heat produced will be carried away with the blasting fumes out of the development end and some will remain in the broken rock which may be released prior to and during rock removal. The proportion of heat removed by each process is a function of rock fragmentation, the ventilation arrangements and the mining cycle.

3.5 Mechanical Processes

The use of electricity and other mechanical processes adds to the heat load of underground mines. This includes the operation of fans, hydraulics, compressed air and any friction related heat.

Diesel engine efficiency is generally estimated at 33%. The remaining two-thirds are released as heat into the underground environment. For example, a diesel truck operating on a level gradient and producing 200 kW of engine power would emit about 400 kW of heat. This is a very significant contribution to total heat load in a typical highly mechanised Australian underground operation. Loaders, trucks, jumbos, explosives transport vehicles and four wheel drive vehicles all use diesel powered combustion engines.

3.6 Heat Source Summary

Figure 3 shows the major contributors to the underground heat load at Mt Isa's Enterprise mine. This is fairly typical of Australian underground mines with autocompression, in combination with the surface temperature, accounting for about half of the total heat load.

4 Underground Heat Issues

4.1 Thermal Stress in Workers

In mining, as in other industries, the exposure of workers to very hot conditions is unhealthy and unproductive. Persons working in hot, humid work sites tend to be inefficient. Dexterity and coordination, the ability to observe irregular, faint optical signs, ability to remain alert during lengthy and monotonous tasks, and the ability to make quick decisions are adversely affected by heat strain (US Department of Labour).

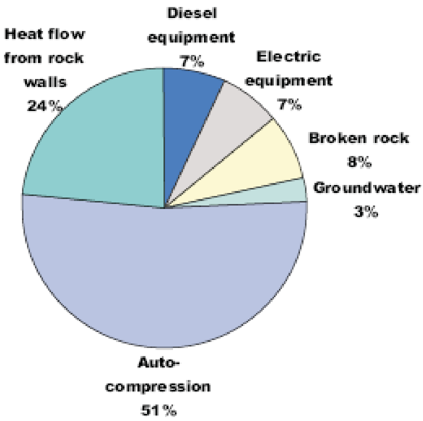

Figure 3. Mt Isa underground heat contributors

Risk factors for developing heat illness are: small body mass (< 50 kg), poor physical fitness, lack of heat acclimatisation, obesity, some legal and illegal drugs and a variety of medical conditions.

4.2 Heat Stroke

Heat stroke is often fatal and is distinguished from the less severe condition of heat exhaustion by multi-organ tissue damage, caused by more severe or prolonged elevations in body temperature.

On the basis of his study Wyndham (1965) recommended, 'a strong endeavour should be made to reduce the wet-bulb temperatures in all working places to 28.9°C and below' and 'no working place should exceed 31.1°C wet bulb temperature'.

From this study it can be seen that the incidence of heat stroke is ten times higher between 28.9 - 31.1°C than between 26.7 - 28.8°C.

4.3 Heat Exhaustion

Heat exhaustion is caused by the inability of the circulatory system to simultaneously supply sufficient blood flow to the skin to achieve adequate heat loss, and to supply the vital organs and exercising skeletal muscle. It is usually due to hypovolaemia resulting from varying degrees of water and salt loss.

Donaghue, Sinclair and Bates (2000) undertook a one-year study of heat exhaustion in deep underground metalliferous mines in tropical arid Australia during which time they observed 106 cases of heat exhaustion. The following results were obtained:

- The seasonal occurrence of heat exhaustion with a spike of 147 cases per million man-hours during February. This trend was also observed in the US mining industry.
- Higher incidence at depth: a ratio of 3.17 cases below 1200m depth for every 1 above 1200m.
- The median wet bulb temperature for all observed heat exhaustion cases was 29.8°C. Less than 5% of cases occurred at web bulb temperatures below 25ºC.

4.4 Dehydration and Rehydration

Some studies, reported by Bates and Matthew (1996), have shown:

- Dehydration of 1 to 2% of body weight results in a 6 to 7% reduction in physical work rate.
- Dehydration of 3 to 4% of body weight results in a 22% to 50% reduction in work rate, for "moderate" and "hot" environments respectively.
- Mental performance (mental function, visuomotor skills and arithmetic tests) begins to decrease at 2% dehydration and thereafter is proportional to the degree of further dehydration.

Brake (2001) reports that the majority of studies have concluded that underground mine workers typically only replace half of the water they lose as sweat unless they are following a drinking program. Reporting to work well-hydrated and then drinking sufficient fluids during the shift would substantially reduce heat illness in mine workers. There is some evidence that workforce education without a formal dehydration policy is not likely to be effective.

4.5 Related Issues

In addition to damage to worker health, Brake (2001) states that excessive heat stress is also known to affect:

- Safety: heat is known to affect concentration, hand-to-eye coordination, mental acuity, and other neurological functions and is therefore a known contributing factor to accidents. It is probably significantly under-recognised as a contributing factor to many industrial accidents in mines.
- Productivity: in thermally stressful environments, work must be carried out at a slower pace to avoid overheating the body. Heat stress therefore results in reduced output.
- Morale: where work must be conducted day after day under significant levels of thermal stress, morale falls. Among other problems, this results in an increase in absenteeism and turnover of staff, with its problems of loss of skills, lack of care, etc. Workers are also less amenable to workplace change when they believe that one of the key issues in the workplace, the heat stress, is not being taken seriously by management. Therefore, chronic levels of heat stress frequently result in frustration and poor workforce attitudes.
- Cost: due to the lower productivity, safety, health and morale, operating costs increase where the workforce is under significant thermal stress.

4.6 Acclimatisation

Repeated or continuous exposure to hot conditions induces physiological adaptations, which reduces the strain caused by hot underground conditions. This process is referred to as acclimatisation (occasionally acclimation) and occurs naturally (with exposure) in the vast majority of underground miners. A 1988 study into acclimatisation found that the following occurred in acclimatised persons:

- Reduction in heart rate when working in heat from 153 to 127 beats per minute,
- Core temperature when working in heat reduced from 38.8°C to 38.1°C,
- Sweat becomes more dilute, with sodium concentration down by 29%,
- More rapid onset of sweating, up by 15%,
- Blood volume increased by 21%.

Most of the effects of acclimatisation are developed within 7 days, but continue to 14 days and beyond. Acclimatisation has a major impact on the ability to work in heat (both cognitive abilities and physical abilities). Less is known on the time required to lose acclimatisation, but 7 to 21 days is a consensus (Brake, Donoghue and Bates, 1998).

Current acclimatisation practice involves employees starting with a reduced work load and increasing this over several days.

5 Heat Controls

5.1 Ventilation

Up to the present, the strategy for the control of heat has been to eliminate as much as possible through the use of ventilation, cooling, and refrigeration. The problem, however, is that this is an extremely expensive approach. As mines become deeper and more complex, the air resistance increases, thus requiring much more energy to power the ventilation system (Udd, 2006). AMC Consultants (2003) state that it can be seen that increasing the air velocity has very limited effect on the air cooling power, once the wet bulb temperature exceeds about 32°C.

Ventilation carries a heavy burden as it is used to provide fresh air to workings and is responsible for removing heat, blasting gases and diesel fumes. Ventilation is perfectly suited to these tasks for most mines up to about 800m deep. As mining depth increases towards 1000m and beyond, the ability of a ventilation system to perform these duties diminishes; the ability to remove heat and cool the underground workforce is reduced most rapidly. At these depths engineers may consider the advantages and disadvantages of adding refrigeration and cooling potential to the ventilation system.

5.2 Refrigeration

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 wet bulb temperature solely through autocompression without taking into account any other heat loads at all (Brake, 2001).

For workplaces above the critical depth, the cheapest method of cooling is flooding the workplace with air. This 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), refrigeration is required (Brake, 2001). Some questions to be asked include:

- 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?
- How much will it cost (capital and operating)?

5.3 Localised Cooling

Air-conditioned cabins on equipment and cooling vests are local cooling methods capable of reducing the heat load on individual workers. They are however not final solutions to the problem of underground heat.

Localised underground refrigeration is generally considered ineffective due to the high mobility of Australian underground mines.

5.4 Avoiding/Reducing Heat Problems

At the design stage mines should plan on having mining excavations that are only as large as required to accommodate the equipment. The transfer of heat from the rock mass into the air will be reduced through a reduction in the area available for heat transfer.

Mines should also move from the practice of providing the total quantity of the air required to ventilate a mine all the time to the provision of air “as needed and when needed”. A ventilation on-demand system has been shown to result in significant cost savings (Udd, 2006). This is particularly true when using refrigeration for air cooling; through the greater use of ventilation doors and seals air flow could be channeled to different workings as required.

Udd (2006) also raises the following points which have the potential to reduce heat load if solutions can be found: The industry needs to consider how equipment can be used at optimal efficiency, and with the minimal production of waste heat and pollutants. Can idling for long periods be avoided? Can more efficient fuels and processes of carburetion be used? Can pieces of equipment be eliminated through better fleet management? Can internal combustion engines be replaced with alternative sources of power, such as fuel cells?

Perhaps the easiest and cheapest way to reduce the incidence of heat illness in underground workers is simply education. It is likely that a significantly low proportion of underground miners even have a basic knowledge of the effects dehydration and working in heat has on the human body. These topics should be raised regularly at pre-shift meetings and it is recommended that formal protocols be put in place at all mine sites; these protocols should be accompanied by some form of testing regime, either random or mandatory depending on the level of heat load at the particular mine.

6 Conclusion

The best solution to controlling underground heat is likely to be a mixture of available technologies. Bulk air cooling for the entire mine (targeting specific areas where possible) makes economic sense for most hot operations. For those areas which are above acceptable work heat limits (as determined by the heat stress meter), a personal cooling vest may be issued. These technologies, while they may successfully reduce the underground heat load, may be ineffective at reducing the incidence of heat related illness if they are not coupled with a strong campaign of employee education regarding the need to report to work in a hydrated state and to maintain this throughout the shift. Working in heat protocols, potentially based on those successfully implemented in Mt Isa's Enterprise mine, will be the cornerstone upon which a future of consistent heat illness reduction will be built.

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