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Reducing Heat Stress Exposure in Mines

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ABSTRACT
Heat management must be maintained within the mine working environment to minimize stress on equipment and personnel. Proper application of engineering protocols and work practice controls will have a direct impact on the health and safety of workers and on productivity. Using monitoring stations placed in strategic locations throughout the mine to capture the environmental conditions, various strategies can be used in the planning and prevention of potential hazard exposure. Economic analysis is used to select the most feasible strategy for heat stress control.

1. INTRODUCTION

Heat management is an important factor as mines expand to meet the demand of their growing workforce and extraction rates. The introduction of new equipment and manpower puts additional demands on the ventilation system that is often the primary means of heat control. When mines plan to place additional significant heat sources into the ventilation system a proper methodology used to monitor, establish, and control heat stress with economically viable solutions must be established.

This paper presents a step by step methodology for 1) identifying heat sources, 2) establishing a heat monitoring program, 3) calculating heat loads underground, 4) applying heat management strategies, and 5) selecting engineering solutions to heat control.

A detailed case study, based on a heat stress management study conducted for an underground potash mine is presented to illustrate the application of the proposed strategy.

2. HEAT MANAGEMENT METHODOLOGY

A proposed methodology for establishing a heat management program is presented. In the methodology, heat sources are identified, data is collected from environmental monitoring stations and calculated heat loads are assessed using ventilation modelling software. Application of specific management control strategies allows one to eliminate heat stress and improve safety.

2.1 Identification of heat sources

All heat sources must be identified in the area of interest and quantified in terms of heat load. Such sources include strata heat, auto-compression, ground water, machinery (loaders, trucks, drills, conveyors, scrapers, pumps, fans, transformers), blasting, rock movement, oxidation, cables, pipelines, lights, human metabolism, etc.

2.2 Establishment of a heat monitoring program

There is a wide range of environmental monitoring programs that are commonplace throughout the mining industry. Mining regulations typically set minimum standards regarding the monitoring and recording of the environment factors relating to heat found within the underground environment. The basic method frequently employed is the use of handheld monitoring equipment, which is checked and recorded at predetermined locations and on a set schedule. Additional monitoring often only occurs as the result of a change to the ventilation conditions. This type of monitoring often presents a level of accuracy that is sufficient to meet regulatory requirements, but may not provide enough detailed information to account for fluctuating conditions that can range from acute cases to seasonal in nature. When an area within the mine is identified as a potential hazard from heat accumulation, additional monitoring is required to ensure the conditions the workforce is entering into are managed to minimize heat stress exposure. Additionally if there is heat sensitive equipment, reducing the environmental heat conditions will often promote equipment function as well as extend equipment life. In order to capture enough information to accurately describe the conditions found within the subject area of concern a minimum monitor recording frequency must be met based on potential daily and in some cases hourly fluctuations. Currently there are a number of stand-alone environmental monitors that can be set to monitor conditions at intervals set by the user and placed in the field for real time observation and data collection.

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2.3 Calculating heat loads underground

In order to assess the heat load within the underground environment, there are different methodologies that may be employed in order to use the appropriate heat management technique. Heat stress is often considered as a factor of the wet bulb globe temperature when considering the effects of heat on the workers in the mine.

Wet bulb globe temperature (Cº) WBGT, can be calculated within the mine environment with the following equation;

$$wet\ bulb\ globe\ temperature = 0.3t_{gt} \times 0.7t_{wb}$$

Where, t_{gt}(Cº) is the globe temperature and t_{wb}(Cº) is the wet bulb temperature.

In order to assess the energy that is contained within the air in the underground environment, the enthalpy of the system can be calculated, which takes into account the moisture content of the air. Additionally the sigma heat can also be calculated, which takes into account the energy content less the moisture content. Both of these methods to describe the energy contained within the air are considered on the dry basis (kJ/kg dry air).

In order to calculate the enthalpy of the system the enthalpy of the air (kJ/kg) (h_a) and the enthalpy of the vapour (kJ/kg) (h_v) must be combined.

$$h = h_a + h_v$$
$$= 1.005\ t_{db} + W(2501.6 + 1.884 * t_{db})$$

In order to calculate the apparent specific humidity W (kg/kg dry air) the following equation must be used;

$$W = 0.622\ \frac{P_s}{P_b - P_v}$$
$$P_s = 0.6105 \exp\left(\frac{17.27 * t_{db}}{237.15 + t_{db}}\right)$$
$$P_v = P_s - 0.000644 * P_b(t_{db} - t_{wb})$$

In the above equations, t_{db}(Cº) is the dry bulb temperature, P_s (kPa) is the saturation vapour pressure, P_b (kPa) is the barometric pressure, and P_v (kPa) is the vapour pressure.

The enthalpy can then be applied to the mass flow (kg/s) (M_f) in order to find the heat flow (Watt) (q_f) in the system. The following calculation assumes no change in moisture to the system.

$$q_{f=} M_f(\Delta h)$$
$$M_{f=}Q * w$$

Where M_f is the mass flow (kg/s), Δh is the sigma heat change (kJ/kg), Q is the flow rate (m^3/s), and w is the air density (kg/m^3).

In a ventilation system where there is a change in moisture the heat flow can be found using the sigma heat on a dry basis (S).

$$q_{f=} M_f(\Delta S + B)$$
$$S = h - 4.187 * W * t_{wb}$$

Where, B (C^{o-1}) is a term which depends on the process involved and on the change in moisture content.

Another method of calculating heat loads within the mine environment is by calculating the heat load losses, based on equipment found within the excavation of concern. This method is useful for both reactive heat management planning and predictive heat management. In order to assess the heat losses from equipment, a detailed equipment survey must be conducted on the equipment found within the area of concern. This included the stationary and mobile equipment, the infrastructure used to power the system, and the utilization of the components within the area. It is advisable to break down the area of concern into smaller segments based on changes in features contained within the excavations, or physical changes in the excavation itself. The strata, the excavation, and the changes in moisture content can also have significant impacts on the heat load prediction based on equipment heat losses, so it is important to understand the behaviour of the rock type as well as any significant changes in moisture content within the excavations. This process is described in section 3.

2.4 Applying heat management strategies

The application of a heat management strategy will serve to limit the level of health risk associated with the total heat load imposed on a worker underground. Heat management strategies include refrigeration (bulk air cooling), localized refrigeration (spot coolers), ventilation, administrative controls (air conditioned cabins, cooling vests, acclimatization, rest areas), and engineering controls (controlling/reducing heat at source, shielding, insulation).

2.5 Comparing and selecting engineering solutions on heat control

Selection of the ideal solution for heat control requires an engineering and economic analysis of alternatives. The solution is more likely a combination of strategies and available technologies. The combined application of engineering and administrative controls, together with selected work practices are effective means of reducing excessive heat exposure.

3. CASE STUDY

3.1 Area of study

A management program of heat generated from pumping infrastructure in a Saskatchewan potash mine has been established. The study area is 5.6 kilometers of underground excavations within series ventilation and recirculation circuits. There are over 20,515 kW of electric motors resulting in 305,000 Watts of lost energy to atmospheric heat. In addition to these motors there are 49.6 kilometers of electrical power cables and the associated electrical controls and transformers, which also lose energy to heat throughout the area.

3.2 Identification of heat sources

In order to identify the locations and sources of heat, the study area was broken down in 14 zones. Each zone was further broken down into 20 meter sections to be used for future computational modeling. Within each section the heat source components were identified. The Heat Management Study Area and zone locations are identified in Figure 1. The primary sources of heat include strata, electrical cable, transformers, motors and settling tanks.

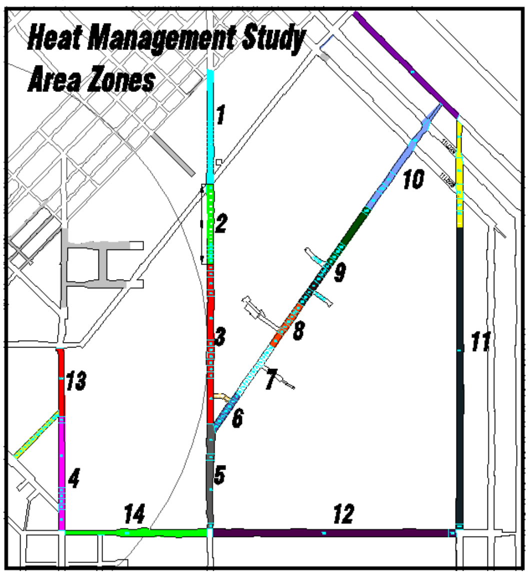

Figure 1: Heat Management Study Area.

3.3 Monitoring program

In the case example used within the potash mine, due to the relatively close proximity to the incoming shaft air there are hourly fluctuations as a result of changes to the surface temperature supply air. As a result of the required high frequency of recordings, a network of environmental monitoring stations were essential in order to capture the characteristics of the air as it moved throughout the study area. The installation of 14 Accutron Climatrax stations in conjunction with data loggers allowed for the monitoring of the following environmental factors: dry bulb temperature, wet bulb temperature, relative humidity, and barometric pressure. These parameters are then applied to determine all important pyschrometric properties. In order to find regional changes within the study area, selecting the appropriate locations to monitor was critical. The study area was broken down into zones that were considered heat source areas and heat sump areas. Observing the areas that had the greatest impact on the area allows for targeting of heat control applications. In addition to the supply air, the surrounding stratum also has an impact on the environmental conditions. To better observe the rock behavior on the air, it was necessary to capture the transfer of heat both into and out of the rock as it behaves as both a source of supply and removal of heat. In order to do this, heat fluctuation plates were installed against the strata to monitor the transfer of heat in and out of the rock. To further improve upon the observation of the rock characteristics, the virgin rock temperature can aid in the identification of the limits to which the rock can act as a source or sump of heat. In the study of the potash mine, 15.25 m long vertical and horizontal bore holes were established to capture this information. Temperature probes were located at 1.5 m, 3 m, 6 m, and 15 m to monitor heat fluctuation with depth.

3.4 Heat load calculations

To calculate the energy lost to the atmosphere as heat, the efficiency of the equipment was calculated at full load and continuous use. This was applied to all sources of heat with the exception of the electrical cables, which are based on 60% of full load. The primary sources of heat energy result from losses with transformers and pumping equipment. The estimated flow of heat is summarized in Table 1.

Table 1: Summary of heat load study.

Summary of Heat Load Study		
Area Number	Total Loss (W)	Total Loss (BTU/hr)
1	187,435.5	639,556.6
2	202,534.2	691,075.5
3	35,620.1	121,541.0
4	82,022.8	279,873.4
5	6,710.6	22,897.6
6	129,160.3	440,713.1
7	224,794.4	767,030.4
8	17,166.5	58,574.5
9	150,918.0	514,953.6
10	485,040.0	2,227,047.1
11	20,239.0	69,058.4
12	10,212.1	34,845.2
13	10,815.3	36,903.3
14	19,789.0	67,522.7
Total Heat Loss	1,582,457.88	5,971,592.33

Survey data was collected at the beginning and end of each zone in order to calculate the change in enthalpy and sigma heat for each zone. The data that was required in order to do the calculations included: dry bulb, wet bulb, relative humidity, pressure, and density. The environmental monitors that were set up with the areas were programed to record this data on a 10 minute interval that could then be averaged at intervals that best suited the needs of the mine. This data could then be used to calculate the heat loads within the system (Table 2)

Table 2: Survey Data.

Survey Data											
Location	Dry Bulb (C°)	Wet Bulb (C°)	RH (%)	Pressure (kPa)	Density (kg/m³)	Ps (kPa)	Pv (kPa)	W (kg/kg dry air)	Cp (kJ/kg mix)	h (kJ/kg dry air)	S (kJ/kg dry air)
1 in	32.9	20.7	33	107.8	1.21	5.0053877	4.158425	0.025162215	1.052405613	97.57	94.10
1 out 2 in	33.5	21.1	33.3	107.8	1.23	5.1765363	4.315689	0.026157355	1.054280456	100.75	97.08
2 out 3 in	37.4	22.7	28.6	107.7	1.23	6.417911	5.398337	0.033152608	1.067459513	122.86	117.67
3 out	31.7	21	38.4	107.8	1.23	4.6777726	3.934944	0.023734315	1.049715449	92.65	89.50
4 in	28.1	19.7	45.6	107.9	1.23	3.8040593	3.220363	0.019242499	1.041252868	77.40	75.13
4 out	29.6	19.8	41.3	107.8	1.23	4.1491112	3.468764	0.020815751	1.044216875	82.98	80.40
5 in	29.5	19.3	38.7	107.8	1.23	4.1252894	3.417173	0.020501446	1.043624724	82.07	79.54
5 out	29.8	19.5	38.4	107.8	1.23	4.197114	3.482055	0.020905192	1.044385382	83.42	80.81
6 in	30	19.6	38.4	107.8	1.23	4.245599	3.523598	0.021164507	1.04487393	84.29	81.63
6 out 7 in	32.3	20.1	32.6	107.8	1.23	4.839173	3.99221	0.024117469	1.050437312	94.26	91.00
7 out 8 in	32	20.4	35	107.7	1.22	4.7578784	3.953316	0.023886847	1.050002821	93.36	90.15
8 out 9 in	31.7	20.3	35.3	107.8	1.22	4.6777726	3.886348	0.023441198	1.049163217	91.90	88.79
9 out 10 in	32.9	20.9	33.8	107.7	1.21	5.0053877	4.173082	0.025275494	1.052619031	97.86	94.38
10 out	34.1	21.3	31.9	107.7	1.21	5.3527408	4.464948	0.027135048	1.05612243	103.89	100.02
11 in	30.9	19.9	36.2	107.7	1.23	4.4698588	3.706912	0.022335524	1.047080126	88.23	85.34
11 out	30.1	19.5	37.2	107.8	1.23	4.2700237	3.534138	0.021232823	1.045002639	84.57	81.89
12 in	30.1	19.5	37.1	107.8	1.23	4.2700237	3.534138	0.021232823	1.045002639	84.57	81.89
12 out	29.5	19.4	38.4	107.8	1.23	4.1252894	3.424115	0.020543097	1.043703194	82.18	79.64
13 in	31	20.5	36.9	107.8	1.23	4.4954007	3.766457	0.022677948	1.047725254	89.21	86.27
13 out	31.8	20.6	36.9	107.8	1.23	4.7043434	3.926804	0.023691316	1.04963444	92.64	89.49
14 in	29.2	19	38.2	107.8	1.23	4.0545363	3.34642	0.020063268	1.042799196	80.64	78.19
14 out	28.1	19.7	45.6	107.9	1.23	3.8040593	3.220363	0.019242499	1.041252868	77.40	75.13

3.5 Heat management strategy application

In order to manage the heat produced within the workings, there are two goals that should be met. Firstly, minimizing heat stress conditions to personnel, and secondly reducing heat exposure to equipment.

In order to minimize heat stress conditions to personnel, a work plan that decreases work in high wet bulb globe temperatures according to heat stress guides may be a viable option. The heat stress guide listed in Table 3, outlines working time lengths and job type that can safely be performed based on the environmental conditions. There are limitations to this type of heat management plan, as it does not lower heat exposure to heat sensitive equipment and may not be economically or practically feasible based on the length or type of work being performed.

Table 3: Wet bulb Globe Temperature Index (Section 70, Occupational Health and Safety Regulations, 1996, Saskatchewan).

Wet Bulb Globe Temperature (WBGT) Index				
Work Load	Work Rate			
	Continuous	15 minutes rest per hour	30 minutes rest per hour	45 minutes rest per hour
Heavy	up to 25Cº	25Cº up to 26Cº	26Cº up to 28Cº	28Cº up to 30Cº
Moderate	up to 27ºC	27Cº up to 28Cº	28Cº up to 29Cº	29Cº up to 31Cº
Light	up to 30Cº	30Cº up to 30.6Cº	30.6Cº up to 31.4Cº	31.4Cº up to 32.2Cº

A second option may be setting up spot cooling within the workings to remove the additional heat produced by the equipment. In the case study the location that would see the largest local benefit and to air traveling downstream is zone 2.

In order to set up a cooling plant in zone 2 the following parametric design is conducted.

The mass flow (M_f) entering into zone 2 is 29.6 kg/s
The specific humidity entering into zone 2 (W_1) is 0.025 kg/kg
The enthalpy entering into zone 2 (h_1) is 95.04 kJ/kg
Air to be cooled to 27.8°C

Using a psychometric chart and 27.8°C as the chosen output, the following outgoing enthalpy and specific humidity were found.

The specific humidity leaving zone 2 (W_2) will be 0.20 kg/kg

The enthalpy leaving zone 2 (h_2) will be 78kJ/kg

The specific enthalpy of water (h_{w2}) at 27.8°C is 123.5 kJ/kg

By installing the temperature probes into the rock, the ambient virgin rock temperature of both the salt and potash members were found to be 27.1°C, this is the lower limit of the attainable cooling before the rock becomes an additional heat source for the excavation, limiting the effectiveness of the cooling.

The cooling load requirement (Q) can be found using;

$$Q = M_f * [(h_1 - h_2) - (W_1 - W_2) * h_{w2}]$$

The resultant cooling load is 489kW or 139.2 tons of cooling by an installed cooling plant.

With the installation of a chiller plant within the underground environment, the cost of the plant must be taken into consideration. The initial capital expenditure is the upfront cost, but the cost of operation should be assed. The cooling plant efficiency can be assed based on the coefficient of performance (COP). This allows a basic assessment of the cost of running the plant.

A typical cooling plant that could be used within this location is a water cooled electrically operated positive displacement cooling plant. According to Energy Design Resources the COP for this type of plant, would be approximately 4.20. The energy requirements to run the plant would be;

$$energy\ requirement_{cooling\ plant} = \frac{cooling\ capacity\ requirements}{COP}$$

This results in 116.4 kW of energy required to run the plant. The annual cost of operation can then be calculated based on continuous operation at the cost of delivery and kWh usage. The cost of continuous usage at this mine for the case study is 0.065 $/kWh.

$$cost_{cooling\ plant} = energy\ requirement_{cooling\ plant} * energy\ cost_{continuous\ usage} * run\ time$$

As a result the annual cost of running a cooling plant in this location will be $66,278.

It is also possible to estimate the cost of cooling any future additional equipment to the area. Based on the equipment survey, a common motor that is used within zones 2, 7, and 10 has a heat loss of 15 kW based on motor efficiency. Using the same principle the cost of cooling additional motor installs would approximate $8,541 per motor. This would allow for the estimate of the additional cost of cooling the zones as additional equipment is added.

4. CONCLUSIONS

Heat management plans are growing in importance when it comes to the health and safety of the workforces within the mines. There are strategies that can be used to minimize the effects on both people and equipment, but the costs of the plans must be realized. There are costs associated with both the efficiency of the work being done as a result of the heat conditions through avoidance. There are also costs that occur as the result of actively attempting to cool the working areas. These costs must be understood and assed to achieve the greatest impact on the environmental conditions within the mine environment.

5. REFERENCES

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