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# Deep mine cooling, a case for Northern Ontario: Part I

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ABSTRACT

Cooling energy needs, for mines in Northern Ontario, are mainly driven by the mining depth and its operation. Part I of this research focusses on the thermal energy loads in deep mines as a result of the virgin rock temperature, mining operations and climatic conditions. A breakdown of the various heat sources is outlined, for an underground mine producing 3500 tonnes per day of broken rock, taking into consideration the latent and sensible portions of that heat to properly assess the wet bulb global temperature. The resulting thermal loads indicate that cooling efforts would be needed both at surface and underground to maintain the temperature underground within the legal threshold. In winter the air might also have to be heated at surface and cooled underground, to ensure that icing does not occur in the inlet ventilation shaft-the main reason why cooling cannot be focussed solely at surface.

## 1. Introduction

Mining at depth creates new challenges not only in extracting the ore at such a depth but also in maintaining the working environment within safe working temperatures. Intake ventilation air increases in temperature as it auto-compresses on its way down the shaft [1], at a rate of approximately 10 °C/km. So for a mine 3 km below the mean sea-level, the increase in temperature due to the compressibility of the air would be in the range of 30 °C. Depending on the geothermal gradient at the mine's location, there might also be some heat uptake from the surrounding rock mass, especially at deeper levels where the virgin rock temperature is higher [2].

The American Conference of Governmental and Industrial Hygienists (ACGIH) guidance on wet bulb global temperature (WBGT) for work levels and work regimen (Table 1) indicate that working temperatures exceeding 26.7 °C, at a moderate working level, should be subjected to a work-rest regimen. A work-rest regimen requires a proportion of the time working and resting every hour of work, with the proportions determined by how much the temperature exceeds 26.7 °C. Longer periods of time spent at rest lowers production rates and so efficacy of the mine's operation. Cooling is thus required to ensure that the working temperature is below the 26.7 °C threshold for which a work-rest regimen is necessary. Which form of cooling, surface or sub-surface cooling, would be better suited to provide the coolth necessary for deep underground mining?

This research aims to (i) analyse the sources of heat contributing to the temperature underground and (ii) determine the cooling delivery methods that would be effective in maintaining the WBGT (temperature) below the work-rest temperature regimen threshold. This includes investigation of individual and combined surface and sub-surface cooling. Since this research is focused on mining operations in Northern Ontario, Canada, climatic conditions typical of the region were considered, with sub-zero temperatures in winter and moderate temperatures in summer.

## 2. Heating sources

### 2.1. Auto-compression and geothermal gradient

As a fluid flows down a shaft its potential energy is converted into enthalpy, resulting in an increase in temperature (by auto-compression). At the same time, heat present due to geothermal flux and radiometric decay in the surrounding rock leads to heat transfer from the rock to the fluid. The virgin rock temperature underground is indicative of the geothermal heat transfer. In Northern Ontario, at 3000 m depth, the virgin rock temperature (VRT) is approximately 55 °C [3]. The geothermal step can be taken to be 57.1 m/°C, based on the geothermal resource assessment of Bristow et al. and Grasby et al. [4,5]. The heat uptake depends not only on the geothermal step but also the age of the shaft, its dimensions and its wetness fraction.

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**Table 1**
ACGIH guidance on wet bulb globe temperature (WBGT) values for work levels and work regimens.

| | Whole body working level | | |
|---|---|---|---|
| Descriptor | Light | Moderate | Heavy |
| Rate of work (W) | 244 | 349 | 488 |
| Exemplified by | Sitting/standing, light hand or arm work | Walking with moderate lifting or pushing | Pick and shovel |
| Work regimen | TLV WBGT temperatures | | |
| Continuous work | 30.0 °C (86 °F) | 26.7 °C (80 °F) | 25.0 °C (77 °F) |
| 75% work, 25% rest, each hour | 30.6 °C (87 °F) | 28.0 °C (82 °F) | 25.9 °C (78 °F) |
| 50% work, 50% rest, each hour | 31.4 °C (89 °F) | 29.4 °C (85 °F) | 27.9 °C (82 °F) |
| 25% work, 75% rest, each hour | 32.2 °C (90 °F) | 31.1 °C (88 °F) | 30.0 °C (86 °F) |

**Table 2**
Sensible and latent heat loads from underground tunnel.

| Depth (m) | 1500 | 2000 | 2500 | 3000 | 3500 |
|---|---|---|---|---|---|
| Virgin rock temperature (°C) | 29.3 | 38.0 | 46.8 | 55.5 | 64.3 |
| Dry surface temperature (°C) | 34.7 | 35.2 | 35.6 | 36.1 | 36.5 |
| Wet surface temperature (°C) | 27.9 | 28.0 | 28.1 | 28.2 | 28.3 |
| *Wetness fraction 0.00-dry* | | | | | |
| Sensible heating power (kW) | −1120 | 591 | 2303 | 4014 | 5726 |
| Latent heating power (kW) | 0 | 0 | 0 | 0 | 0 |
| Water added to air (kg/s) | 0 | 0 | 0 | 0 | 0 |
| *Wetness fraction 0.25-moderately dry* | | | | | |
| Sensible heating power (kW) | −7538 | −6152 | −4766 | −3381 | −1997 |
| Latent heating power (kW) | 6771 | 7114 | 7458 | 7802 | 8148 |
| Water added to air (kg/s) | 2.779 | 2.921 | 3.062 | 3.204 | 3.346 |
| *Wetness fraction 0.50-wet* | | | | | |
| Sensible heating power (kW) | −13,955 | −12,895 | −11,836 | −1077 | −9719 |
| Latent heating power (kW) | 13,542 | 14,229 | 14,917 | 15,606 | 16,295 |
| Water added to air (kg/s) | 5.559 | 5.842 | 6.125 | 6.408 | 6.692 |

Tunnel dimension 5 m × 5 m of total length 12 km at given depth, for varying wetness fraction and maintained air condition DB = 35 °C, WB = 28 °C and rock with thermal conductivity 4.5 W/(m °C), rock density 2700 kg/m$^3$ and heat capacity 950 J/(kg °C). Air velocity assumed to be 2 m/s in all openings. Geothermal step 57.1 m/°C and rock temperature at surface = 3 °C.

The temperature change due to the conversion from potential energy to enthalpy is dependent upon the following derivation:

$$(h_2 - h_1) = \frac{1}{2}(v_2^2 - v_1^2) + g(z_2 - z_1)$$

$$\text{But} \quad (h_2 - h_1) = c_p(t_2 - t_1) \text{ and } \frac{1}{2}(v_2^2 - v_1^2) = 0$$

$$\text{Therefore} \quad (t_2 - t_1) = g(z_2 - z_1)/c_p$$

where $h$ is the coolant enthalpy, $v$ is the coolant velocity, $z$ is the depth, $t$ is the coolant temperature and $c_p$ is the specific heat capacity of the coolant.

The change in temperature for air, water and ice cooling medium, according to their respective specific heat capacities (1005, 4187 and 2111 J/(kg °C)), is 9.76 °C/km, 2.34 °C/km and 4.65 °C/km respectively. The coolth stored in each of the cooling mediums, taking the outlet temperature (after heating through the mine tunnel) to be 28 °C, is −25, −105 and −450 kJ/kg for air (at 3 °C), water (at 3 °C) and ice (at −1 °C). Considering the change in potential energy, the energy stored in the media for the same conditions would be 4, −75 and −420 kJ/kg for air, water and ice respectively.

So, at 3 km depth, air which is surface cooled to 3 °C (no lower, to prevent icing damage to the hoisting system) is not able to provide any cooling, rather it is a source of heat to the underground workings. Table 2 illustrates the resulting heat loads at varying depths underground, taking into consideration the potential energy conversion and the geothermal heat gradient. Results show that with a higher wetness fraction the air enthalpy is also higher, mainly due to the latent heat from evaporation of the water.

### 2.2. Diesel mobile plant

Mobile plant, essential in underground mining operations, include LHDs (load–haul–dump), haulage trucks, and service/utility trucks (including drills, bolters and scalers). Some mines are slowly transitioning to an electric fleet primarily to reduce ventilation requirements resulting from exhaust emissions of the diesel engines; yet, most mines in Northern Ontario still operate with a majority diesel mobile plant. Table 3 illustrates the installed capacity of the diesel mobile plant in some mines in Northern Ontario. These machines not only generate combustion product gases and diesel particulate matter but also produce substantial heat [6].

The heat generated from the diesel mobile plant depends on the duty cycle of the equipment as well as the engine's efficiency. Thus not all of the heat entering the air as a result of diesel combustion does so as sensible heat. The heat output from the diesel mobile plant is a combination of latent and sensible heat. The latent heat component is defined as a product of the water added to the air (kg/s) and the latent heat of the water at the wet bulb temperature (MJ/kg). The sensible heat is the difference between the total heat generated from the diesel engine (delivered useful engine power, MW/engine efficiency, %) and the latent heat.

Taking diesel to comprise $C_{12}H_{23}$ on average, its complete combustion reaction is:

$$C_{12}H_{23} + 84.5(0.79N_2 + 0.21O_2) \rightarrow 12CO_2 + 11.5H_2O + 66.8N_2$$

Which corresponds to a mass-based air-to-fuel ratio (AFR) of 14.6 and means that for every kilogram of fuel combusted, 1.239 kg of water is released into the air (the water-to-fuel ratio).