HEAT MANAGEMENT IN THE PUMPING INFRASTRUCTURE AREA
OF AN ESTERHAZY MINE

by

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Abstract

Heat management in mines is a growing issue as mines expand physically in size and depth and as the infrastructure grows that is required to maintain them. Heat management is a concern as it relates to the health and safety of the workers as set by the regulations of governing bodies as well as the heat sensitive equipment that may be found throughout the mine workings.

In order to reduce the exposure of working in hot environments there are engineering and management systems that can monitor and control the environmental conditions within the mine. The successful implementation of these methods can manage the downtime caused by heat stress environments, which can increase overall production.

This thesis introduces an approach to monitoring and data based heat management. A case study is presented with an in depth approach to data collection. Data was collected for a period of up to and over one year. Continuous monitoring was conducted by equipment that was developed both commercially and within the mine site. The monitoring instrumentation was used to assess the environmental conditions found within the study area. Analysis of the data allowed for an engineering assessment of viable options in order to control and manage the environment heat stress. An option is developed and presented which allows for the greatest impact on the heat stress conditions within the case study area and is economically viable for the mine site.
Acknowledgements

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Chapter 1

Introduction

1.1 Thesis Objective

The objective of this thesis is to develop heat management strategies that may be implemented both within the focus area and further applied throughout the rest of the active working areas.

1.2 Heat Management Plan Methodology

This thesis has achieved the objectives outlined above by taking the following steps:

1) Perform extensive background research on the subject of heat management, using world best practices as well as intuitive processes based on data.

2) Construct and use instrumentation that can collect data based on heat flow and transfer, including:
   a) Environmental qualities of the airflow
   b) Heat transfer in and out of the rock
   c) Baseline virgin rock temperatures

3) Monitor conditions within the study area for a period up to 1 year.

4) Develop a heat management method that is based on collected data that is economically and practically viable.
2.1 Basics of Ventilation Thermodynamics

Mine ventilation thermodynamics considers heat and temperature and how it relates to the work and energy that is applied to the mine air flow. There is a natural ventilation process that occurs in many mines, particularly with deeper mines, which is increased with the addition of primary and auxiliary ventilation infrastructure. As air enters into the supply shaft, the air undergoes auto compression, which results in increased temperature. The air is then heated further by the surrounding rock at depths and mechanized equipment. This heated air is then released through the exhaust shafts, aiding the upwelling with work provided by the heated air. This provides the main three areas of interest regarding the ventilation thermodynamics of a mine.

The downcast shaft air has an increase in pressure and temperature as it descends. This is the result of gravitational compression. In shafts where the surrounding rocks have minimal to no heat transfer to the air, the change in temperature can be found using Equation (1):

\[(t_2 - t_1) = 0.00962(Z_1 - Z_2)\]  

(1)

where:

- \(t_x\) = temperature at sample location \(x\), (°C)
- \(Z_x\) = elevation at sample location \(x\), (m)
This equation is used to find the dry bulb adiabatic lapse rate, which gives a geothermal gradient of roughly 1 Cº per 100m of elevation. This does not include heat transfer caused by the evaporation of water.

Once the airflow has reached mine level workings, the airflow will experience a decrease in pressure as it travels throughout the horizontal workings, but also an increase in temperature. This is the result of air picking up heat from the surrounding rock strata. It is possible with time that the surrounding rock strata will experience a state of equilibrium with the air temperature; as a result the large heat exchanges may be limited to fresh workings, or with temperature fluctuations influenced from surface. Heat flow in horizontal workings can be calculated, assuming no evaporation, using Equation (2):

\[ q = C_p(t_2 - t_1) \]  

(2)

where;

\[ C_p = \text{heat capacity of dry air, (kJ/kg.Cº)} \]

\[ q = \text{heat flow, (kJ)} \]

If there is no transfer of the latent heat of water being exchanged through evaporation in an upcast shaft, the air entering into the shaft usually has little variability in its temperature. The same equation used to calculate the downcast heat flow can also be applied to find temperature change in the up cast shaft.

The natural ventilation process (NVP) has significant impacts on the effectiveness of ventilation practices within the mine environment. The geothermal gradient with depth is a major
contributor to the natural mine ventilation. As the adiabatic process occurs, heat from the rock strata warms up the air. This warming of air then leads to a decreased density, promoting upcast flow in the return shaft due to the difference in pressures. The free energy is provided from heat energy stored in the rock. This can then be converted into mechanical energy to promote upwelling of air in the shaft, known as natural ventilation energy (NVE). If the rock stratum is in fact cooler than the air flowing through it, this process can have negative effects on promoting airflow through the system. This thermodynamic process is important when assessing system energy requirements to move air. The basics to the natural ventilation thermodynamic process of dry air, is given in Equation 3 as follows:

\[
NVP = \rho_{md}g(Z_1 - Z_2) - \rho_{mu}g(Z_1 - Z_2) \tag{3}
\]

where:

\(NVP=\) Natural Ventilation Pressure, (Pa)

\(\rho_{md}=\) mean density of downcast air, (kg/m\(^3\))

\(\rho_{mu}=\) mean density of upcast air, (kg/m\(^3\))

\(g=\) gravity constant, (m/s\(^2\))

\(Z_1=\) elevation of shaft surface, (m)

\(Z_2=\) elevation of shaft bottom, (m)

2.2 Basics of Fluid Mechanics

Fluid mechanics can be divided into two areas, fluid statics and fluid dynamics. Within the mine environment, the study of the forces applied to the air, acting as a fluid, are referred to as fluid mechanics.
Fluid statics observes the pressure distribution in a stationary fluid and the effects on the solid surfaces, floating bodies, and submerged bodies. When the fluid velocity is zero, pressure variations occur only in the vertical direction, as a factor of the weight of the overlying fluid. The pressure can be observed as a factor proportional to the density, gravity, and depth change. This can be witnessed at the surface of the earth as the overlying air applies a force in a vertical direction on the earth as an atmospheric pressure. This pressure \( P \) can be expressed as a force applied to an area as \( \frac{N}{m^2} \), or as a Pascal (Pa). (Bahrami, 2009).

Fluid dynamics are observed within a fluid in motion, or flow, and how it acts within and upon the surrounding environment. The dynamic pressures are influenced by the velocity, pressure, densities, and temperature of the fluid as a function of space and time (Eckert, 2006).

Within the mine environment it is common to measure the flow of air as a factor of volume per time \( Q \). Flows are frequently measured with the units \( \frac{m^3}{s} \), however in multi-level mines, there may be a large range of densities as overlying atmospheric pressure changes with depth. In these cases, the measurement of mass flow \( M \) may be more appropriate using \( \frac{kg}{s} \) units in order to find a balance of flows within a mine system.

Bernoulli’s equation is used to find the types of energy found within moving fluid. Bernoulli’s equation does not consider the effects of friction and is expressed as incompressible flow. As the fluid travels in motion there are three forms of mechanical energy that occur. The first is kinetic energy of the moving mass. This is the amount of work done as the fluid accelerates from rest. Work done \( WD \) is a factor of the amount of force \( N \) applied over a distance \( m \), which is expressed in terms of units of Nm or Joules \( J \). This is expressed by Equation 4:
\[ WD \text{ (kinetic energy)} = M \frac{u^2}{2} \quad (4) \]

where:
\[ u = \text{velocity, (m/s)} \]
\[ M = \text{mass, (kg)} \]

Potential energy is a factor given the variations with elevation of the traveling fluid. The work done is the amount of energy required to move the fluid to an elevation (z) against the effects of gravity (g) above the starting point (expressed by Equation 5) where;

\[ WD \text{ (potential energy)} = mgz \quad (5) \]

The third type of mechanical energy of fluids traveling in an excavation is flow work. Flow work is the result of the energy maintained within a traveling fluid. This is observed as pressure induced as a result of velocity. The pressure does not change within the excavation, however, as the fluid exits the excavation it maintains the potential and kinetic energy as a velocity pressure, as determined by Equation 6:

\[ WD \text{ (flow work)} = \frac{P_m}{P} \quad (6) \]

where:
\[ P = \text{pressure, (Pa)} \]
\[ m = \text{mass, (kg)} \]
When examining the flow along the excavation, it is safe to assume that the mass of the fluid will not change. As a result, it may be removed from the equation to find the total energy as a factor of the mass of fluid (J/kg). Since Bernoulli’s equation also assumes that density will not change due to incompressibility of the fluid, the equation can be altered to Equation 8:

\[
\text{Bernoulli’s equation: } \frac{u_1^2 - u_2^2}{2} + (Z_1 - Z_2)g + \frac{p_1 - p_2}{\rho} = 0 \quad (8)
\]

Fluids flowing through excavations are working against friction created by the walls and objects within the excavations as they pass through. Frictional flow acts as a drag within the fluid. When this occurs, it is known as viscosity, which slows down the fluid flow as frictional forces act against it. The ideal fluid as defined by Bernoulli’s equation has no viscosity included. As a result of frictional flow, some of the mechanical energy that is lost in Bernoulli’s equation is transferred into heat energy. This can be accompanied by a pressure drop and is known as frictional pressure drop \(F_{12}\). Bernoulli’s equation can be rewritten to include this frictional pressure drop (Equation 9) as:

\[
\frac{u_1^2}{2} + Z_1g + \frac{p_1}{\rho} = \frac{u_2^2}{2} + Z_2g + \frac{p_2}{\rho} + F_{12} \quad (9)
\]
Frictional losses within an excavation will change based on the type of flow behavior. These are laminar and turbulent flow. Laminar flow is observed when flow is broken down into distinct levels or layers. The parallel flows have very limited to no mixing occurring between the flow layers. Turbulent flow has complete mixing of the airflow. Typical flows experienced within the mine are considered turbulent in nature, with strong mixing occurring within excavations. In order to predict the flow type, the Reynolds Number (Re) has been established (Equation 10).

There are two distinct types of flow that can be defined by the Reynolds Number. Reynolds Numbers less than 2000 are typically descriptive of laminar flow, while numbers above 2500-3000 are descriptive of turbulent flow.

\[
Re = \frac{p \cdot u \cdot D}{\mu_{air}} \quad (10)
\]

where;

\[D = \text{diameter, (m)}\]

\[\mu_{air} = \text{air dynamic viscosity, (kg/m.s)}\]

The air dynamic velocity is given by Equation 11:

\[
\mu_{air} = (17.0 + 0.045 \cdot t) \cdot 10^{-6} \quad (11)
\]

where;

\[t = \text{temperature, (C°)}\]
2.3 Basics of Psychrometry

Dry air has a uniform composition of gas concentrations. The percent composition is constant across the surface of the earth. However, due to changes in local pressure and temperature, water vapour gas compositions can vary significantly as water exists in all three states. The study of the moisture content in air is called psychrometry.

The psychrometric conditions that occur within the mine environment should be taken into consideration, as the humidity in the air can have a profound effect on the thermodynamic processes. The moisture content within the air and mine environment has a direct influence on heat energy use, as it influences the latent and sensible heats of air. Additionally the effects on the human body relating to heat stress need to be monitored and conditions must be met to minimize the dangers of working in hot environments.

Within the mine environment, evaporation occurs where moisture is exposed by the rock or air inflows. The evaporation process increases the energy contained within the air-vapour mixture. This energy is called latent heat and results in a decreased dry bulb temperature with heat energy being transferred from the air to the moisture contained within the air. This transfer of energy results in the increase in the wet bulb temperature, which is an important parameter for quantifying humidity in the air. If there is no moisture available for evaporation, the heat energy results in an increase in dry bulb temperature, known as sensible heat.

In order to assess the moisture content of the air \( W \), the vapour content of the air is measured in terms of kilograms of water vapour per kilogram of dry air. This is an important tool to measure the moisture evaporated from exposed water or dropped out of suspension through condensation within the mine environment, and moisture content is given by Equation (12):
\[ W = 0.622 \left( \frac{P_v}{P_b - P_v} \right) \]  \hfill (12)

where;

\[ P_v \] is the vapour pressure of the air at its dew point, (kPa)

\[ P_b \] is the measured barometric pressure, (kPa)

When surveying environmental conditions, relative humidity (RH) is a commonly measured factor. Relative humidity measures the level of saturation within the environment as a percentage, however this is relative to the air dry bulb temperature and will fluctuate as a result of the addition or removal of heat. Relative humidity determination is made using Equation (13):

\[ RH = \frac{P_v}{P_s} \times 100 \]  \hfill (13)

where;

\[ P_s \] is the saturation vapour pressure, (kPa)

When the air is at maximum moisture content capacity, the system is at saturation. The vapour pressure at saturation \( (P_s) \) is not a factor of any additional gases within the air, but instead is a factor of the temperature of the surrounding gases. Conditions within the mine environment are very rarely at saturation. In order to assess the thermal capacity of the moist air in the mine, or specific heat of moist air \( (C_{p\text{ air vapour mixture}}) \), the following equation (Equation 14) can be used.
\[ C_{p\text{ air vapour mixture}} = C_{p\text{ dry air}} + C_{p\text{ water vapour}} \times W \] (14)

where;

\[ C_{p\text{ dry air}} = \text{specific heat of dry air at constant pressure, } (1005 \frac{J}{kg\cdot^\circ C}) \]

\[ C_{p\text{ water vapour}} = \text{specific heat of water vapour at constant pressure, } (1884 \frac{J}{kg\cdot^\circ C}) \]

In ventilation systems where heat sources are introduced, the ability to measure the heat flow \( q \) from the equipment to the air is important to quantify the amount of heat energy added to the ventilation circuit. In order to raise the temperature of 1kg of air 1°C, the flow equation is denoted by Equation (15):

\[ q_{\text{air}} (J) = \text{mass} \times C_{pa} \times t_d \] (15)

where;

\[ t_d = \text{dry bulb temperature, } (^\circ C) \]

The result of the heat flow of the water and heat flow of the moisture can then be added to find the enthalpy added to the system. Enthalpy is the total of all heat energies in the system, which includes sensible heat, latent heat, and super heat energies. This represents all system heat sources and is an effective tool to measure heat, and found on a dry basis using the following equation (Equation 16):

\[ h = 1.005t_{db} + W(2501.6 + 1.884 \ t_{db}) \] (16)
where; 
\[ h = \text{heat energy within the air vapour mixture on a dry basis, (kJ/kg)} \]
\[ t_{db} = \text{dry bulb temperature, (°C)} \]

Sigma heat (S) is also a commonly used measurement of heat flow within a ventilation system. Sigma heat takes into account the wet bulb, assuming that an adiabatic saturation process has occurred within the airstream, without the concerns of evaporation or condensation which would have significant impacts on the dry bulb temperature. This allows the enthalpy to be calculated without considering sensible heat effects in the system. As a result it is a strong indicator of heat transfer from energy sources to surrounding air, as determined using Equation 17:

\[ S = h - 4.187 * W * t_{db} \]  \hspace{1cm} (17)

2.4 Sources of Heat in Underground Mines

Within the mine environment there are numerous sources of heat. The air may be conditioned on surface before entering the mine shaft. In these cases it is usually warmed to prevent freezing in the shaft in the colder months and cooled in the summer to minimize the effects of already warm air entering the mine. The most common sources of heat found in the mine environment are as follow: auto compression or adiabatic compression, heat from the rock strata, frictional heating of air, blasting, machinery, evaporation of moisture, electrical infrastructure, human metabolism, oxidization of timber and sulphide ores, and ground movement (Bardswich, 1965).

Heat generated from auto compression and released by the rock strata are the two main sources of heat found within the mine. The adiabatic lapse rate is usually rounded to 1°C per 100 m of
depth, and the geothermal gradient can vary significantly from mine to mine with depth (McPherson, 1993). There may be spot locations where significant amounts of heat generation occur due to localized equipment or infrastructure, however, on the mine scale, the depth of the mine and the geothermal gradient will dictate the passive mine temperature. This is characterized by the virgin rock temperature (VRT).

Table 1- Virgin Rock Temperatures and Gradient with Depth (McPherson, 1993)

<table>
<thead>
<tr>
<th>Area</th>
<th>Surface</th>
<th>Gradient</th>
<th>VRT at 1,500 m</th>
<th>Max VRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kidd Creek (Canada)</td>
<td>1.5</td>
<td>1.12</td>
<td>18.3</td>
<td>35.1 (3000m)</td>
</tr>
<tr>
<td>Sudbury (Canada)</td>
<td>2.5</td>
<td>1.66</td>
<td>27.4</td>
<td>35.7 (2500m)</td>
</tr>
<tr>
<td>Witwatersrand (South Africa)</td>
<td>18.0</td>
<td>0.90</td>
<td>31.5</td>
<td>54.0 (4000m)</td>
</tr>
<tr>
<td>Bushveld (South Africa)</td>
<td>21.5</td>
<td>2.20</td>
<td>54.5</td>
<td>65.5 (2000m)</td>
</tr>
<tr>
<td>Enterprise, Mt Isa (Australia)</td>
<td>28.0</td>
<td>2.00</td>
<td>58.0</td>
<td>66.0 (1900m)</td>
</tr>
</tbody>
</table>

Recently there has been a shift in the underground workings to move from diesel equipment, which has historically been tasked with the heavy lifting and transportation jobs, to electric equipment. Electric vehicles such as scoops, haul vehicles, and man carriers are becoming more prominent in the mine environment and are becoming additional sources of heat. This is not limited only to the equipment itself, but also to the infrastructure required to power and charge the vehicles within the mine environment. Mines, in an attempt to work within the diesel equipment utilization and diesel particulate matter regulations, are turning to electric vehicles to increase their fleet capacities within the mine without the need to increase airflow requirements. This is an additional single heat source scenario that may become more common in future mine environments.

2.5 Effects of Heat on People Working Underground

The environmental heat conditions must be considered when sending people into hot environments. The effects of heat stress on individuals can result in a variety of ill effects. The
most common diagnosis, as a result of individuals working in hot environments, from most to least dangerous are: heat stroke, heat exhaustion, heat cramps, and heat rashes. Heat stroke is a life critical response to heat, where the body’s internal temperature rises above 40° Centigrade, potentially resulting in death. Heat exhaustion is caused when the body reaches temperatures above 38° Centigrade, with the individual often feeling dizzy, nauseous, weak, and suffering from headaches. Heat cramps can also be induced by the hot environment as the workers experience muscle pains and cramping due to loss of body salts, through the sweating process. Heat rash is a common issue in moderately hot environments, where red blotchy areas occur on the skin with significant sweating (OSHA, 2014).

The age and fitness level of the worker can drastically change the physiological effects of heat on the body. Younger and fitter workers have a greater ability to handle the heat through increased sweating and thermoregulation within the body than older and less fit workers (Hardcastle et al, 2013).

Additionally, the clothing that is worn by the workers will have an effect on the ability of the workers to cool themselves through sweating. Lighter, loose fitting clothing is better for promoting sweating, however with some personal protective equipment standards there may be limitations on the type and fitting of clothing available.

There are a variety of methods used to assess heat stress exposure. The most commonly used is the wet bulb globe temperature. The wet bulb globe temperature is a parameter based on the air temperature, air velocity, radiant heat, and the ability for the body to cool itself through sweat evaporation. Within the mine environment the calculation used to assess the wet bulb globe temperature to apply it to the wet bulb globe temperature index is provided by Equation 18:
Wet Bulb Globe Temperature = 0.7 * wet bulb temperature + 0.3 * dry bulb globe temperature

The resultant temperature can then be applied to the Wet Bulb Globe (WBGT) Index, as found in (Saskatchewan Labour, 2000) and used to determine a rest schedule for workers (see Table 2).

Table 2- Rest Schedule based on the WBGT Index (Saskatchewan Labour Standards Act, 2000)

<table>
<thead>
<tr>
<th>Wet Bulb Globe Temperature (WBGT) Index</th>
<th>Work Rate</th>
<th>Work Rate</th>
<th>Work Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work Load</td>
<td>Continuous</td>
<td>15 minutes rest per hour</td>
<td>30 minutes rest per hour</td>
</tr>
<tr>
<td>Heavy</td>
<td>Up to 25.0°C</td>
<td>25.0°C up to 26.0°C</td>
<td>26.0°C up to 28.0°C</td>
</tr>
<tr>
<td>Moderate</td>
<td>Up to 27.0°C</td>
<td>27.0°C up to 28.0°C</td>
<td>28.0°C up to 29.0°C</td>
</tr>
<tr>
<td>Light</td>
<td>Up to 30.0°C</td>
<td>30.0°C up to 30.6°C</td>
<td>30.6°C up to 31.4°C</td>
</tr>
</tbody>
</table>

This guideline is used to acclimatize workers to hot work environments and minimize the effects of heat on the workers. According to the Saskatchewan Labour Standards Act, 2000, heavy work refers to intermittent lifting, pushing or pulling, and hard sustained work such as assembly line activities where workers are paced by machines and cannot stop. Moderate work is defined as work done in a sitting position, but that requires heavy arm and leg motion, or work done while standing and involving moderate lifting or pushing activities. Light work is defined as sitting or standing work at a machine or bench that requires mostly arm work (Saskatchewan Labour, 2000).
In addition to the negative health impacts on the workforce due to heat stress conditions, the overall productivity of the workforce may decrease within a hot environment. The mental and physiological symptoms of heat stress decrease worker productivity. When this is coupled with frequent breaks to minimize negative health effects of the hot environment, it becomes economical to find ways to cool the environment to optimize performance by the workforce.

**2.6 Effects of Heat on Underground Equipment and Infrastructure**

Heat stress in the workplace is not limited to the effects on the workers. The equipment and infrastructure in the underground workings are also negatively affected by extreme temperatures. Most individuals are aware of the basic heat transfer system in a vehicle in the form a radiator to remove excess heat from the engine to the surrounding atmosphere. The reality is that most equipment found in the underground environment has some heat negating system that is used to protect the heat sensitive components.

As part of regular preventative damage maintenance, equipment found within the underground workings is monitored on a regular basis to ensure that it is working within a normal range of temperatures. If the equipment is found to be above normal temperature conditions, maintenance must be performed to prevent damaging the equipment. This is common practice on electrical equipment such as belt drives, pumps, transformers and diesel equipment, including trucks, loaders, and scoops.

All electrical equipment gives off heat as a byproduct of their operation based on efficiency. Electrical equipment that is sensitive to heat may incorporate active heat removal systems. Typically these are direct systems such as a fan blowing across the sensitive components, or indirect through heat transferring systems as found in air-conditioning units. A transformer is an example of a piece of electrical equipment with a temperature rise rating. Transformers operating
above their normal operating points can see damage to the insulation, creating hotspots and decreasing the operating life, as a result creating an addition to operating costs in downtime and equipment (Bajracharya et al, 2010). Diesel equipment will have a heat displacement system to remove heat from the engine to prevent overheating. This is common practice on all mobile equipment within the underground environment.

The rock strata is a potential source of heat which can also be affected by the heat produced within the mine. The direction of the heat flow, in or out of the rock, can be defined as its behavior as a heat source or heat sump. The heat released by the rock within the mine can be defined by the age of rock, movement, oxidization, and potential hot water sources (Thompkins, 1962). The type of rock and solidity is also an important factor when assessing the effects of heat on the mine rock strata. Solidity can have a drastic influence on the heat flow within the rock.

The more solid the rock mass the higher the heat conductivity. When rock is more porous, fewer points of contact within the grains of rock lead to lower conductivity and insulative properties. The conductivity of the rock can also be influenced by the introduction of moisture in the porous rock strata. If the pore spaces in the rock are filled with water, then the rock strata conductivity will increase, promoting heat transfer (Robertson, 1988).

As rock strata goes through periods of heating and cooling due to changes in environmental conditions, the rock may undergo strain, according to its coefficient of thermal expansion. A rock stratum is composed of mineral grains, resulting in the potential for thermal cracking to occur at the grain level in response to shear stresses. Rising temperature may also contribute to the rock’s ability to deform and creep (Van Buskirk et al, 1983). This is important when considering the placement of heat generating equipment within the mine, as it may result in further installations of ground control infrastructure to manage the moving rock as the drift temperature increases.
2.7 Analysis of Ventilation Networks

When analyzing the ventilation system of the mine, the network of branches that makes up the ventilation system needs to be considered. Areas of the mine that are dead ended or sealed off with minimal leakage do not need to be considered in the network. However, the starting and ending points of the mine, represented by the shafts, do need to be included.

The Hardy Cross method is the most commonly used ventilation network method of analysis within the mine environment. To begin the evaluation, an updated mine ventilation plan is required with all the fans, doors, regulators, and other ventilation controls being assessed. The number of joints and branches must be defined based on the layout and each branch must have its natural ventilation pressure and air density included. Resistances should be calculated as determined using Equation 19;

\[
R_i = \frac{w_{st} w_{t}}{w_{t, o}} - R_{t, o}
\]  \hspace{1cm} (19)

where;

\[ R_i \] = standardized resistance for branch \( i \), \((N \cdot \frac{s^2}{m^8})\)

\[ R_{t, o} \] = observed branch resistance, \((N \cdot \frac{s^2}{m^8})\)

\[ w_{t, o} \] = observed branch density in the branch, \((\frac{kg}{m^3})\)

\[ w_{st} \] = reference standard density, \((\frac{kg}{m^3})\)
Once the resistances have been found, an estimation of airflow throughout each network branch and pressure across each fan location should be completed. When estimating the flows and pressures across the networks, Kirchhoff’s First Law must be followed, where all flows in a junction must equal all flows out for a zero balance.

Next the ventilation network must be divided into a system of meshes. The minimum number of meshes is defined by Equation 20:

\[ M = B - J + 1 \] (20)

where;

- \( M \) = minimum number of meshes
- \( B \) = number of branches
- \( J \) = number of junctions within the network

With the meshes defined, the total ventilation network should be represented.

Kirchhoff’s Second Law is also critically important as it relates to all energy transforms which take place. In the system that is a closed mesh, the sum of flows must also equal zero. This can be represented by the following equation (Equation 21):

\[ \Delta \left( \frac{u_i^2}{2} \right) + \Delta z_i g + W_{fi} = \int V dP + F_i \] (21)

where;

- \( \Delta \left( \frac{u_i^2}{2} \right) \) = the change in kinetic energy along the branch, (Nm/kg)
- \( \Delta z_i \) = the change in elevation along the branch, (m)
\[ g = \text{the acceleration of gravity, (m/s}^2) \]

\[ W_{f_1} = \text{the work input by fans in the branch, (Nm/kg)} \]

\[ \int V dP = \text{the flow of work done along the branch, (Nm/kg)} \]

\[ F_i = \text{the mechanical energy transformed by turbulence within the branch, (Nm/kg)} \]

Within each mesh, a correction factor should be used to balance the system pressure and mass flow. When the correction factor has been found for each branch, the flows in each branch should be corrected. To ensure a positive result, a clockwise direction analysis around each mesh should be followed. Once completed, the correction factors and resultant flows should be rechecked until a balance in the system is reached (De Souza, 2009).

The Hardy Cross method should be used following regulatory ventilation checks to ensure compliance in minimum flows and to identify inefficiencies within the ventilation network.

### 2.8 Ventilation Simulation Packages

The manual method of analysis of ventilation networks in a mine can be very time consuming. With the advancement of computational methods, there are ventilation simulation software packages available that can quickly model the mine environment. There are a number of benefits to using the commercially available packages. The ability to model large scale mines with a significant number of meshes cuts down the calculation time, and the ability to model outside of pressures and flows gives the mine ventilation engineer tools to predict additional ventilation characteristics including heat, contaminants, and gases.

Two commonly used software programs available today are VnetPC and VentSim. They both have their benefits for modeling ventilation networks, but vary in their ease and limitations.
VnetPC, created by Mine Ventilation Services (MVS), allows the mine engineer to build the mine on a .dxf platform and import data into the software. The individual network parameters can then be entered into the program in a tabular based system. The data must be collected within the mine to ensure accuracy and proper calibration of the model. These parameters include: fan curve data and friction factor, length, area, and perimeter parameters. The pressure, air flow, and resistances are all calculated within the software, with the ability to be further manipulated for calibration purposes. There is also the ability to view the fan operation cost and efficiency easily, giving the user the opportunity to model various fans and curves. The modeled outputs should be checked against regular surveys to ensure accuracy. MVS also has additional packages that model mine thermodynamics (ClimSim), duct simulation (DuctSim), and mine fire conditions (MineFire). The ability to model fires within an interactive model is a particular asset when it comes to mine planning regarding mine evacuations and emergency procedures and can be an invaluable tool for mine rescue teams.

VentSim, created by Chasm Consulting, is interactive ventilation modeling software that is more visually oriented for the user. VentSim works with the same data parameters as VnetPC. Model creation works within a simplified process where the user has the ability to import the mine plan with various filtering capabilities to ensure continuity within the ventilation meshes. VentSim has a variety of levels of purchase within the same program. The top upgrade allows the user to model the following: contaminant diesel particulate matter, gases, heat, radon, and mine fires in addition to ventilation flows and pressures. Similar to VnetPC, an economic and efficiency assessment can be done on the mine easily and parameters can be changed to look at different options within the mine ventilation network.
The mine ventilation software packages available have a distinct advantage in mine modeling opposed to the manual method regarding the time spent doing calculations. The critical factor when modeling the mine environment is to ensure that the model is accurately calibrated and that the parameters entered into the model reflect the actual mine environment. Additional monitoring and data collection on a regular basis is critical to maintain model calibration. The ability to model various scenarios can be invaluable as well and an excellent teaching and presentation aid. These advantages of mine ventilation modeling can be an invaluable tool to the mine ventilation engineer.

2.9 Ventilation Monitoring Equipment

In order to do accurate ventilation modeling and planning, proper ventilation monitoring equipment is critical. Technology has advanced from rudimentary handheld instrumentation to the advanced remote monitoring systems available today. Commonly monitored ventilation factors are as follow: airflow, pressure, air density, gas concentrations, diesel particulate matter, dust, temperature, and humidity.

Minimum airflow requirements are set by regulatory bodies to minimize the potential negative health effects of noxious gases, containments, and heat. As a result, airflow is one of the most commonly monitored environmental factors in the underground environment. Airflow is calculated by applying the air velocity to the calculated or known area of the excavation. Air velocity instruments include: smoke tubes, pitot tubes, hotwire anemometers, velometers, and vane anemometers.

The most frequently used types of handheld airflow monitoring equipment are hotwire and vane anemometers. Hotwire anemometers work by heating up a very fine wire. The air passing across
the instrument has a cooling effect on the wire related to the air velocity. Hotwire anemometers are frequently used in very low velocity airflows and are used as part of a point based transverse survey, where the excavation cross section is broken down into sections where the measurements are taken to find an average drift velocity. Vane anemometers work by placing the vane into the airflow where the spinning vane has a revolution counter that can be converted into an air velocity. The vane anemometer can also be used in a point transverse survey however it is more frequently used to conduct a continuous traverse survey. A continuous traverse survey is completed by taking constant measurements of the air velocity as the instrument is moved across the excavation, covering as much of the surface area as reasonably possible and averaging the measurements. Sonic anemometers are a lesser used method of monitoring airflow, but are becoming more prevalent in the mining community as the technology advances. Sonic anemometers are typically permanently installed stations that have two sensors sited to measure across a drift that send an ultra-sonic wave between sensors. The time that the ultra-sonic wave takes to travel from one transducer to the other is used to calculate resistance through the airflow and calculate an air velocity. The lack of mobility of the instrumentation means that a mine must have many sensor stations in order to conduct a proper total airflow survey of the mine and subsequently is this method is often an ancillary means of monitoring airflow.

Pressure within the mine environment is important for ventilation network analysis and sizing ventilation equipment and controls within the mine. The trailing hose method is a common method used for measuring pressure loss through an excavation. In a horizontal mine, the hose is laid down from one point to another, with one end connected to a manometer. This is an effective method to measure differential pressure where there is minimal to no change in elevation. It is also possible to do a pressure survey using a barometer, which measures atmospheric pressure. In
order to conduct a barometric survey, an instantaneous reading must be taken on surface and underground at various monitoring locations throughout the mine.

Air density is a necessary factor in determining mass flows within a system. Air density is a factor of pressure. Air density cannot be directly measured but can be calculated by using the Equation 22:

\[ w = \frac{P}{RT} \]  \hspace{1cm} (22)

where:

- \( P \) = pressure, (Pa)
- \( R \) = air constant, (287.045 J/kg*K)
- \( T \) = temperature, (K)

Gas monitoring is critical to mine environmental monitoring, particularly where there is the risk of gas release from the rock strata or from the combustion engines used within the working environment. It is important that the workforce has a supply of fresh air to minimize the hazards of noxious gases through removal or dilution. The most frequently used methods of mine gas monitoring are through use of stain tubes and electronic gas detectors. Stain tubes work by passing a known amount of air across a chemical compound that reacts with a specific gas to be observed. The quantity of chemical that is reacted within the tube indicates the concentration of gas within the environment. Electric gas monitors are available commercially as both handheld and remote sensing equipment. The electronic gas detectors work both as passive and pump style units. Passive detectors require direct contact with the gases being monitored, while the pump style monitors draw air across the sensors to monitor the air quality. Gas concentrations, time
weighted average limits and instantaneous threshold limits are determined in parts per million or as a percentage and are set by the mine regulatory bodies.

Diesel particulate matter and dust are both collected through the same process and equipment. The type of filter used within the collection device dictates the type of sample collected based on particle size. Gravimetric sampling is frequently used to collect suspended particles within the air. They are used for both location sampling and personal samplers. A personal gravimetric sampler allows for the collection of particulate matter that the worker is exposed to over a period of time as they complete their various tasks. Air is drawn by a pump into a cyclone assembly and across a filter. The known flow rate and time can be then applied to the additional weight added to the filter for trapped particulate and used for determination of a time weighted average of exposure to the contaminant. The dust can be analyzed for any hazardous materials trapped within the filter. This is common practice for diesel particulate matter sampling.

Air temperature is frequently monitored in the underground environment and is a limiting factor associated with heat stress which can regulate work rest cycles. Air temperature is monitored in respect to dry bulb, wet bulb, and wet bulb globe procedures. The dry bulb thermometer monitors the ambient air temperature free from the effects of radiative heat and moisture. The wet bulb measurement takes into account the amount of moisture in the air and the effects of evaporative cooling on the thermometer. Additionally there is the wet bulb globe thermometer which is affected by the evaporative effects of water as well as radiative heating that may be occurring. This method utilizes a black outer globe surrounding the thermometer that absorbs any radiative heat.
The air humidity is critical when monitoring the mine environment. At higher concentrations of moisture in the air, the body has a more difficult time cooling through sweating and evaporative processes. The relative and absolute humidity in the air can be determined through the use of a psychrometer. Psychrometers include both a wet bulb and dry bulb. For the psychrometer to work effectively, air must pass over the sensors at a minimum velocity of 3 m/s. The recorded dry bulb and wet bulb temperatures can then be applied to a psychrometric chart at a known pressure to find the absolute and relative humidity conditions (De Souza, 2009).

2.10 World’s Best Practices on Heat Control in Underground Mines

South African mines are among the deepest mines in the world. The geothermal gradients found in the gold and platinum mining regions range from 1.0°C to 2.2°C per 100m respectively. The depths of the mines range between 1500m to the world’s deepest mines in the Witwatersrand region at depths of 4000m. As a result of the increased heat from the geothermal gradients and drawing air from an already warm surface environment, South African mines are leaders in the best practices of heat control in mine environments.

In deep hot mines, air coolers are generally located on surface at the main underground air intakes to cool the air before it enters the mine fresh air supply. Secondary air coolers may also be positioned within the mine as heat is picked up. The air conditioning efforts that take place underground through the use of air coolers are typically condenser evaporative in nature. This heat removal process produces a sum total of heat, which is then removed. As a result, the heat created from the process and the removed heat must be sent to surface, often utilizing the exhaust air circuits.
Alternatively, refrigeration units can be used to cool water that is piped underground. The water is cooled to 4°C before it is sent underground to be used in the air cooling process. The heat is then transferred from hot air to the water which is then pumped back to surface to effectively remove the heat from the mine environment. In addition to cooled water, ice may be sent underground, which provides an energy savings as it takes advantage of the latent heat of ice for a smaller volume of water to pump to surface (Roman et al, 2013).

In addition to methods of cooling the environmental conditions directly, conditioning of the workforce to work within the hot environment is practiced in mines where cooling is not economic or practically feasible. As a worker is exposed to high temperature conditions over time, the body increases its tolerance to working within such conditions. Any worker being exposed to the high temperatures must be allowed enough time to gradually adjust or acclimatize to such temperatures and minimize overheating. The South African mining industry standard for acclimatization recommends a six day adjustment period where the worker will be exposed to the heat for 50% of the time on the first day and will work their way up to 100% time exposure over the next 5 days. If a worker is away from the work site for nine or more days, then they must go through another acclimatization process, however it is an abbreviated 4 day acclimatization process which begins at 50% and finishes at 100%.

There are some mines that take advantage of opportunistic cooling methods based on the geographic location of the mine. Mines located in areas where winter months bring lengthy periods of subzero surface conditions may extend cooling in the winter into the summer through the use of ice stopes. Water frozen during winter months in supply air stopes is used to cool the air in the summer months as the ice melts. Heat energy is transferred from the warm air to the ice, leaving behind the water. This water is then pumped out through drainage lines to surface.
Mine in Sudbury, Canada is currently using this method to cool the fresh air entering the mine (Millar, 2014).

Although these practices are used in extreme heat environments, they are not the dominant applications used to control heat in shallower mines or mine environments with less drastic fluctuation in temperature. In most cases where local cooling of hot environments is necessary, the planned mixing of flows of hot and cooler air can regulate the heat exposure of the work force. The mixed flow process uses known volumes of air with differing environmental factors to produce a calculable final thermally-regulated airflow product. This provides the ventilation engineer with a tool to design airflows to control heat in the mine environment.
Chapter 3

Ventilation System in the Study Area of the Esterhazy Mine

3.1 Layouts of the Area of Interest

The area of study that looks at the heat flow within the mine ventilation system, presented in Figure 1, is limited to the drifts that contain the main pumping infrastructure to the pump-up wells within the potash mine. The total drift length encompasses 5649 m of total excavation distance. There are excavations that are located within the study area which are omitted from data collection due to inaccessibility as a result of poor ground conditions. These areas are identified in Figure 1 as NO ACCESS areas. The zone attributes, which include the number of people expected to work in zones in a work day, ventilation attributes, and infrastructure features can be found in Table 3. The pumping clusters are located within zones 2, 5, and 7. The electrical clusters, which include the transformers and electrical sleds which power the pumps, are located in zones 1, 4, 7, and 12. The remaining zones include limited equipment, with electrical equipment and cables running through the study area in its entirety. The primary air movers to the system are located in zone 8, with two 93 kW, 1219.2-533.4-1770, which are 200 series half bladed Joy fans. They provide in excess to 113 m$^3$/s to the system with two jet booster fans located in zones 3 and 14.
Figure 1- Heat Management Study Area Zones
3.2 Ventilation

3.2.1 Airflow

Figure 2 presents the distribution of airflows in the area of study. The potash mine operates on 138.4 kg/s (113 m³/s) of downcast air to provide fresh air, cool, and remove contaminants within the mine environment. This air is spread out between all active faces and rehabilitation areas. The downcast air is supplemented by an additional 34.7 kg/s of recirculated air back from the exhaust circuit. The heat management study area is supplied by a combination of fresh and cascaded air circuits. There is also a short loop recirculation circuit that is made up of circuit D in Figure 1. The air mass flows are indicated in Table 3 and Figure 2. The airflow throughout the study area has very little change on a day to day basis. There are some limited leakages around the periphery of the study area that can cause small disruptions in flow, however care is taken to ensure minimal leakages through the maintenance of seals.

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Location</th>
<th>Wet Bulb globe Temperature (°C)</th>
<th>Mass Flow (kg/sec)</th>
<th>Cross Section of Excavation (m²)</th>
<th>People Present in Work Day</th>
<th>Time in a Day People are Present (hours)</th>
<th>Pumping Cluster Present (Y/N)</th>
<th>Electrical Clust Present (Y/N)</th>
<th>Brine Settling Tank Location (Y/N)</th>
<th>Dust Concerns (Y/N)</th>
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Table 3- Study Area Attributes

Table 3 presents the study area attributes including the locations, wet bulb globe temperature, mass flow, cross section of excavation, people present in work day, time in a day people are present, pumping cluster present, electrical cluster present, brine settling tank location, and dust concerns. The data is organized by circuit and includes 14 different locations.
Figure 2- Ventilation Flows Within Study Area

3.2.2 Barometric Pressure

The large horizontal excavations of potash and low resistances result in minimal pressure differentials across the study area. The pressure on surface at the head frame is roughly 975mbar while at the mine workings the pressure is 1103mbar. Typically the range of pressures experienced throughout the circuit ranges from 1100 to 1106 mbar. There are seasonal changes with typically lower pressures encountered in the summer months.
3.2.3 Gases

The use of cascading air and recirculation circuits results in some minimal gas accumulation. The air exhausting out of the brine storage area has been exposed to diesel equipment and waterborne gases. Typical levels for oxygen and carbon dioxide are 20.9% and .06% respectively. Carbon monoxide and nitrogen dioxide gases, resulting from the diesel equipment, are usually in the 1ppm and 0.2ppm range respectively. The stored brine contains trace amounts of hydrogen sulphide gas, which has been observed in the 0-0.4ppm range within brine containment areas. When the fresh air from the shaft combines with the trace amounts of carbon monoxide, nitrogen dioxide, and hydrogen sulphide, dilution renders the gases undetectable with the handheld equipment used to monitor gases. Rarely is an accumulation of noxious gases detected within the pump-up infrastructure system due to the limited diesel use throughout the areas. The study area has limited risk associated with gasses through ventilation recirculation with limited to no use of diesel engines with primarily electrical equipment used.

3.2.4 Dust

Dust is a common issue within a potash mine, however the supply air to the study area is composed of air that has had limited exposure to active working faces. The minimal dust created from rehabilitation miners does not have a direct impact on the study area. There is a main line belt conveyor that is located in the exhaust of Zone 1. As a result the dust from the conveyor does not enter the study area. Historically the airflow was reversed in Zone 1 in order to add additional airflow to the system. With the installation of additional electrics in Zone 1 and pumping equipment in Zone 2, the air was reversed to minimize the negative effects of dust on equipment. This limits the airflow direction in Zone 1, as the airflow may not be reversed, as an opportunity to extend any recirculation in the system or bring in exhaust air for additional flow. Any air beyond Zone 1 is considered to be contaminated with dust.
3.2.5 Diesel Particulate

Industrial hygiene testing was done in the winter of 2013, which incorporated the workers found within the study area. The industrial hygiene NIOSH 5040 testing procedure was done with in-house testing equipment and verified by a third party laboratory. The diesel particulate matter testing is to be conducted every 3-5 years, with additional testing to be redone after a significant change to the diesel fleet underground. The results for the entire mine area were below the diesel particulate matter concentration limit of 0.16 mg/m³ level set by the mine’s internal policy and MSHA regulations. The low levels can be attributed to the low diesel utilization levels and high dependency on electrical-based equipment throughout the study area.

3.2.6 Heat Conditions

As a result of multiple sources of supply air to the test area ventilation circuit, the heat and psychrometric conditions are managed to limit exposure to the workforce. The areas downstream of the electrical and pumping clusters are predominantly affected by the heat released from the equipment. These areas are frequently used for travel purposes, but very limited work takes place for any significant period of time. Historically lower flows have led to heat stress conditions, with the increased flow rates through cascading and recirculation circuits’ heat stress conditions being limited to localized locations. The worker concentrations and time spent in the zones on an expected basis are found in Table 3, with highest work activity being located around the zones with pumping and electrical clusters. A seasonal variation in downcast temperature has been observed through the wet bulb temperatures observed in Table 3 as well as by measured dry bulb and wet bulb temperatures. During the winter months the air is heated to 2°C through glycol heat exchangers. The shaft is also equipped to cool the glycol heat exchangers to cool the air entering
the mine shaft. This system has issues with its consistency and effectiveness. At times, some air may bypass the heat exchangers in the summer months through the head frame doors. This ranges from minimal leakages to roughly half of the down cast airflow. As a result, the surface temperature variations are reflected in the underground environment during the summer months more drastically.

### 3.2.7 People and Infrastructure

The infrastructure that makes up the study area of the potash mine includes 3 pump clusters and 4 electrical clusters, identified in Table 3. Within the system, there are three settling tanks to remove debris suspended within the brine. In addition to the settling tanks, exposed brine is located in overflow sumps and pump drainage systems to collect leakage. The power cables, which run from the power supplies to the electrical equipment, are suspended against the excavation back. Also located in the back are lighting fixtures to aid in the visibility around the pumping structure. The pumps are the brine movers, which move the brine through the underground environment to the pump-up wells connected to surface. The conduit for brine flow is through Sclair piping, which is hung from the walls and back, which are found throughout the study area.

There is a dedicated workforce that is responsible for the day to day maintenance and repair of the pumping infrastructure. There is a team of 18 individuals that are found throughout the area. The vast majority of the work takes place within zones 1-8, where the pumping and electrical clusters are located. The work that takes place is considered light to moderate based on the heat stress index used when considering rest periods during heat stress conditions. Environmental monitors are located throughout the study area for worker reference, and working in a hot environment is part of regular routine training for the employees. The workforce has a range of ages and physical fitness that must be considered when designing a ventilation system to reduce
heat stress conditions. The ranges of employee ages are from 20 to 62 years of age for persons that work within the pumping infrastructure area and who range from physically fit to poor physical conditions. As a result the oldest and least physically fit employees set the basis of the heat stress conditions.

3.2.8 Main Areas of Interest for Heat Management

The health and safety of the workforce is the most critical objective of the heat management plan. First and foremost, minimizing the heat stress conditions for the individuals found throughout the study area, where concentrations are at the highest, is the goal. Sites that contain workers are located within Zones 2, 4, 5, 6, and 7. These areas contain the greatest number of pieces of equipment that require preventative and reactionary maintenance work. As a result workers may spend significant amounts of time within these areas. The typical type of work that takes place in these Zones can be considered light in physical nature, with some short periods of moderate to high demanding work that take place on an irregular basis.

Secondary to the health and safety of the workers is harmful impacts on heat sensitive equipment. There is a large number of electrical and pumping equipment located in Zone 2-7. The electrical clusters that are made up of electrical transformers, breakers, and programming equipment are affected the most negatively by the excess heat and have systems within their compartments to remove heat. Zones 4 and 7 are two of the most critical areas for heat management regarding equipment. Within Zone 7 are the electrics that power a large portion of the pumping infrastructure. Zone 7 is located on the exhaust side of the circuit, which leaves it in a vulnerable position for increasing temperatures. An overall decrease in temperatures across all zones would be particularly noticed here.
Chapter 4
Preliminary Work to Improve Conditions

4.1 Historical Ventilation Methods

The study area historically had the pumping infrastructure and electrics centrally located in Circuit A. The pumping and electrical infrastructure found in Circuits B and C were part of an expansion project that was started in 2012 and completed in January of 2013. There was very little data collected within the study area prior to the ventilation improvements that have taken place, resulting in limited data prior to 2011. The average mass flows of air from the monthly surveys in limited locations are found in Table 4. Historically the study area was ventilated almost exclusively through cascaded ventilation from Brine Storage Exhaust, with very little fresh air supply. Additionally, Zone B was an unused excavation requiring minimal ventilation.

The primary air mover for Circuit A was a 112 kW free standing fan located in Zone 8. Additionally there were significant leakages through unmaintained seals to production areas on the east side of the study area. In 2013, after the completion of the additional pumping infrastructure in Circuits B and C, there was a need for additional air flow in order to maintain adequate ventilation to remove and manage heat.

Table 4 Averaged Historical Mass Flows in Study Area

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Zone</th>
<th>2011</th>
<th>2012</th>
<th>2013 (March)</th>
<th>2013-2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Fresh Air</td>
<td>15</td>
<td>45.7</td>
<td>43.9</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>63</td>
<td>67.4</td>
<td>74</td>
<td>145</td>
</tr>
<tr>
<td>C</td>
<td>10</td>
<td>39.6</td>
<td>46.3</td>
<td>43.9</td>
<td>67</td>
</tr>
<tr>
<td>D</td>
<td>13</td>
<td>21.4</td>
<td>33</td>
<td>30.1</td>
<td>72</td>
</tr>
</tbody>
</table>
4.2 Ventilation Adaptations and Improvements

In 2012 long term strategies to manage the ventilation in the study area commenced. The initial work focused on the containment of the fresh air supply that was being lost to other areas of the mine through the implementation and maintenance of ventilation seals to unused and unmaintained excavations the lead away from the study area. Additional bulkheads and ventilation doors were installed in areas around the study area to maintain critical control points. This streamlined the ventilation pathways and minimized losses. A large part of the maintenance program for the ventilation networks and controls to the system was focused on educating the workforce. Minimal ventilation training historically would mean that seals, which were not inspected regularly by ventilation personnel, may be damaged and their damage would remain unreported for extensive periods of time. Through the ongoing training and ventilation engagement, the turnaround time for damaged seals and standard upkeep was significantly improved.

In 2013, after the evaluation and completion of the ventilation control placements, the primary air mover in Zone 8 was replaced with twin 56 kW fans, which were bulkheaded into the excavation. The replacement of the 112 kW free standing fan with the twin 56 kW bulkheaded fans occurred in June, 2013. The fans were then subsequently half bladed and re-pitched for optimization in August of that year. The data presented in Figure 3 was collected from a data logger attached to a crack extensometer in Zone 7 that was located against the back above an electrical cluster located at the end of the zone. The dry bulb temperatures (°C) indicated a significant drop in temperature resulting from the initial changes in air, as well as the work performed to the air movers after the initial implementation. As the air quantity required for the new installation exceeded the supply capacity, a recirculation circuit was developed which is currently maintained as Circuit D.
Figure 3 Historical Ventilation Adaptions and Improvements Circuit A Zone 8
Chapter 5

Quantify the Sources of Heat within the Pumping Infrastructure Area of the Mine

5.1 Identification of Heat Sources

The study area is made up of electrical and mechanical equipment required to transport brine from the brine storage areas within the mine to surface for disposal. Within the study area there are 4 four identified circuits, described in Chapter 3, that are made up of 16 identified zones. These zones, which are the focus of this study, make up 78% of the total excavations within the study area. The area has 12% of the total length that are bare excavations used for storage or travel. The remaining 10% of the area is inaccessible due to lack of cavern maintenance.

In order to break down the sources of heat, the zones were initially subdivided into branches that were less than 20m in length, a practice that is used for the ventilation software ClimSim by Mine Ventilation Services Inc. Within each 20m branch the heat source components were identified. The 20m branches allowed for individual point sources of heat to be applied to system. The areas shortened into branches of 20m allowed for the addition or removal of heat by the surrounding rock as the air moves throughout the area. After the collection process, the 20m branch method was dropped for the zone analysis method. It was found that certain characteristics of the excavation, such as wetness and age, had dramatically more influence on the outcome than the heat load identifications over the individual branches, when the sum total of the branches was applied to the zone.

To identify the sources of heat, an equipment survey was conducted throughout the 15 zones recognized as containing heat sources. The equipment heat source lists for all zones are located in the equipment appendix. To verify sources of heat and sources of heat removal an infrared
camera was used to visually detect differing surface temperatures. As a result some items that were initially identified as potential sources of heat were negated. Junction boxes, which include breakers, contactors, feeders and disconnect switches, were excluded from the list and had an equivalent length based on the length of cable within the box added to the total length of the zone. Additionally the Sclair piping, used to transport brine from the brine storage areas to the pumps, were removed from the list after a temperature survey was conducted along the pipe length. The piping temperature survey showed that the Sclair pipe external temperature would take on the temperature of the surrounding air, suggesting that the effects of friction within the pipe and brine temperature had minimal effects of heating the surrounding air and effectively insulated the brine from the external air temperature. Table 5 illustrates the heat load losses calculated from the equipment survey. Zone 16 is the only zone free of any electrical or pumping equipment, resulting in an expected heat load loss of 0. Alternatively Zone 7 has the highest concentration of pumps and electrical equipment, resulting in the largest calculated heat load losses throughout the study area.
5.1.1 Cable Heat Load Calculations

The study area consisted of a measured 46960 m of cable. The cable types are listed in the equipment appendix (Appendix D), which include the AWG, voltage, number of cores, amperage and core resistance of each type. The heat losses supplied to the environment were calculated based on the resistances of the cables cores, with 100% of the losses of electrical energy within the cable being converted to heat, using the following equation (Equation 23) (White et al, 2004);

\[
W_{\text{loss per m}} = (I \times 1.575)^2 \times R \times Cor
\]  

(23)

where:

\[I = \text{rated current, (amps)}\]
R = resistance value, \( \frac{\Omega}{m} \)

Cor = number of cores in the cable

This equation assumes a diversity factor of 60%, where the average load in the cable over time is 60% of full load. The calculation used in Equation 23 assumes an ambient temperature of 26°C. The losses increase by an average of 2.3% when the ambient temperatures increase to 32°C. There are also some differences in cable type due to insulation variation. According to White et al (2004) these variations are less than 10% of the overall losses. The calculated power (heat) loss per meter for all cable types surveyed within the study area can be found in the equipment appendix (Appendix D).

**5.1.2 Transformer Heat Load Calculations**

To provide power to the pumping infrastructure there are banks of transformers set up in areas throughout the study area. The transformer numbers along with the Kilo-Volt-Amps (KVA) and power factors are provided in the equipment appendix (Appendix D). During the survey of the transformers the temperature rise, KVA, and power factors were collected. The transformer efficiencies can be found in table 6 from White et al, 2004. Transformer and total heat total losses were determined using Equations 24 and 25:

\[
W_{\text{transformer heat loss}} = \text{no load losses} + \text{full load losses} \times LF^2
\]  

(24)

where;

\[LF = \text{the fraction of full-load current, between 0-1 (full load assumed, therefore 1)}\]

\[
\text{full load losses} = pf \times kVA \times 1000(1 - \frac{n}{100})/(2 \times LF \times \frac{n}{100})
\]  

(25)
where:

\[ pf = \text{power factor} \]

\[ LF = \text{load factor for peak efficiency, (0.35 or 0.5)} \]

\[ \eta = \text{efficiency from Table 6} \]

Table 6- NEMA TP1 Efficiencies (White et al, 2004)

<table>
<thead>
<tr>
<th>Kilo-Volt-Amps</th>
<th>Efficiency %</th>
<th>Efficiency %</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Type, Low Voltage, 75°C</td>
<td>Dry Type, Medium Voltage, 75°C</td>
<td>Liquid Immersed, Medium Voltage, 85°C</td>
</tr>
<tr>
<td>15</td>
<td>97</td>
<td>96.8</td>
<td>98</td>
</tr>
<tr>
<td>30</td>
<td>97.5</td>
<td>97.3</td>
<td>98.3</td>
</tr>
<tr>
<td>45</td>
<td>97.7</td>
<td>97.6</td>
<td>98.5</td>
</tr>
<tr>
<td>75</td>
<td>98</td>
<td>97.9</td>
<td>98.7</td>
</tr>
<tr>
<td>112.5</td>
<td>98.2</td>
<td>98.1</td>
<td>98.8</td>
</tr>
<tr>
<td>150</td>
<td>98.3</td>
<td>98.2</td>
<td>98.9</td>
</tr>
<tr>
<td>225</td>
<td>98.5</td>
<td>98.4</td>
<td>99</td>
</tr>
<tr>
<td>300</td>
<td>98.6</td>
<td>98.5</td>
<td>99</td>
</tr>
<tr>
<td>500</td>
<td>98.7</td>
<td>98.7</td>
<td>99.1</td>
</tr>
<tr>
<td>750</td>
<td>98.8</td>
<td>98.8</td>
<td>99.2</td>
</tr>
<tr>
<td>1000</td>
<td>98.9</td>
<td>98.9</td>
<td>99.2</td>
</tr>
<tr>
<td>1500</td>
<td>---</td>
<td>99</td>
<td>99.3</td>
</tr>
<tr>
<td>2000</td>
<td>---</td>
<td>99</td>
<td>99.4</td>
</tr>
<tr>
<td>2500</td>
<td>---</td>
<td>99.1</td>
<td>99.4</td>
</tr>
</tbody>
</table>

A temperature correction factor must be applied to the full load loss calculation (Equation 25), which takes into account that the transformers used in the pumping infrastructure circuit are dry type transformers as indicated on their name plate. The transformer temperature correction factor equation (Equation 26) is shown (White et al, 2004).

\[
\text{temperature correction factor} = \frac{T_K + T_{REF}}{T_K + 75°C}
\]  (26)
where;

\[ T_K = 234.5^\circ C \] for copper windings

\[ T_{REF} = \text{reference temperature shown in Table 7} \]

**Table 7- Limits for Temperature Rises for Dry Type Transformer Units (White et al, 2004)**

<table>
<thead>
<tr>
<th>Insulation System Temperature Class(C°)</th>
<th>Average Winding Temperature Rise (C°)</th>
<th>( T_{REF} ) - Standard Reference Temperature (C°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>75</td>
<td>95</td>
</tr>
<tr>
<td>150</td>
<td>90</td>
<td>110</td>
</tr>
<tr>
<td>180</td>
<td>115</td>
<td>135</td>
</tr>
<tr>
<td>200</td>
<td>130</td>
<td>150</td>
</tr>
<tr>
<td>220</td>
<td>150</td>
<td>170</td>
</tr>
</tbody>
</table>

\[ \text{no load losses} = pf \times kVA \times 1000 \times LF \times \left( \frac{100}{\eta} - 1 \right) - LF^2 \times \text{full load losses} \quad (27) \]

With 100% utilization of the transformers throughout the excavations the dry type transformer calculations can be found in the equipment appendix (Appendix D).

**5.1.3 Motor Heat Load Calculations**

Throughout the areas there are a number of motors that are predominantly found on pumps. There are two primary types of pumps that are used for brine transport throughout the excavations, Siemens and TECO. During the motor survey process, the name plate information was collected, which included the horse power, rpm, and efficiency parameters for each. Motors that run periodically with minimal use have been excluded from this list. This includes motors
for compressors and hydraulic pumps. The full list of motors found throughout the study area can be found in the equipment appendix (Appendix D).

Using the known motor efficiencies, the heat losses can be calculated using Equation 28:

\[
W_{\text{motor losses}} = hp \times 745.7 \times \left(\frac{100}{\eta}\right) \times (1 - \frac{\eta}{100})
\]  

(28)

where:

\(hp\) = delivered power

\(\eta\) = motor efficiency, (%)

With 100% utilization of the motors, the power loss can be found in the equipment appendix (Appendix D).

### 5.1.4 Sump Settling Tank Heat Absorption Calculations

Brine settling tanks are used to drop the larger pieces of debris out of the flowing brine before advancing the brine to the high pressure pumps. These are large brine containers with significant surface areas exposed to the excavation. In order to calculate the amount of heat removed through the settling process, the brine temperature at the entrance and exit of the tanks was measured to find the temperature change. The volume and flow rates were also measured. In order to calculate the heat difference (kJ/kg), the heat capacity and density of brine at 260g/kg salinity at 30°C was required. The mine site has in house lab testing the mill’s brine reclamation circuits found a heat capacity value of 2979.88 J/Kg°C, which was used in Equation 29.

Additionally, the temperature of the brine leaving the settling tanks to be pumped to surface was critical to recognize any heat sump potential. In order to calculate the heat flow from the atmosphere into the sump tanks, as shown in Table 8, Equation 29 was used (De Souza, 2009):

\[
q_f = M_f \times C_p \times \Delta t
\]  

(29)
where:

\[ q_f = \text{the heat flow in the system, (W)} \]

\[ M_f = \text{mass flow, (kg/s)} \]

\[ C_p = \text{heat capacity, } \left( \frac{J}{\text{kg°C}} \right) \]

\[ \Delta t = \text{change in temperature, (°C)} \]

Table 8- Sump Tank Heat Flow

<table>
<thead>
<tr>
<th>Location</th>
<th>Volume (m³)</th>
<th>Flow rate (m³/s)</th>
<th>Heat Capacity (J/kg K)</th>
<th>Density (kg/m³)</th>
<th>Enter Temperature (°C)</th>
<th>Exit Temperature (°C)</th>
<th>Energy Absorption (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 3</td>
<td>1507.58</td>
<td>0.379</td>
<td>2979.88</td>
<td>1192.10</td>
<td>28.20</td>
<td>28.27</td>
<td>29,163.42</td>
</tr>
<tr>
<td>Zone 4</td>
<td>1381.25</td>
<td>0.379</td>
<td>2979.88</td>
<td>1192.10</td>
<td>27.59</td>
<td>27.65</td>
<td>23,068.60</td>
</tr>
<tr>
<td>Zone 7</td>
<td>1507.58</td>
<td>0.379</td>
<td>2979.88</td>
<td>1192.10</td>
<td>27.33</td>
<td>27.88</td>
<td>216,268.09</td>
</tr>
</tbody>
</table>

5.2 Instrumentation of Heat Sources

A detailed instrumentation program was developed to permit quantification of all heat sources in the area. The locations of the instrumentation are presented in Figure 4. The instrumentation was focused primarily around areas of high heat losses to the atmosphere, but environmental monitoring was conducted throughout the entire study area. There were some limiting factors to where monitors could be installed. The biggest obstacle was based around accessible 120V power, as it was required for the environmental monitors. As a result some of the locations had disruptions in power over the course of the study due to power outages and loss of power. Additionally, as some of the equipment was located in high traffic areas, there were monitors that were damaged as a result of being contacted by diesel equipment. Efforts were made to ensure the safe operation of the equipment that best represented the drift environmental conditions, while
limiting the power disruptions and minimizing the chances of being damaged. All the equipment that was used for this study was designed for the study, some of which was repurposed as it applied to the rock type and environment. The environmental monitors had to be outfitted with data loggers, as they are an add-on to a larger system that monitors air flow. As a result, the data logging outputs were not as specified by the manufacturer and a large time period was spent working with the manufacturer to overcome this obstacle and ensure that the equipment was properly calibrated. The heat flux plates that were used for the study are plates used in soil heat transfer, but, with some modifications described in Section 5.2.2, they were made to accurately monitor heat flow in and out of the rock strata. Lastly, the virgin rock temperature probes were designed and built for this study.

5.2.1 Psychrometric Properties Monitoring
The data for analysis was collected with the use of Accutron Climatrax multi variable sensors and HOBO data loggers (Onset®). The Climatrax units are capable of measuring and displaying dew point, heat index, relative humidity, pressure, dry bulb temperature, wet bulb pressure, wet bulb globe temperature, and air density parameters. The data was then collected using a data logger. The data logger performs a measurement every 10 seconds from the Accutron instrument, and data is stored in CSV files for viewing. The five environmental factors monitored are dry bulb temperature, wet bulb temperature, relative humidity, pressure, and wet bulb globe temperature. The monitoring units and data logger were mounted onto a 1.5 meter stand with power supply provided by an extension cord and were placed strategically throughout the circuit at the beginning and end of the areas. Prior to placing the monitoring stations throughout the circuit, a thorough investigation of adequate mixing due to turbulence in the air was conducted in order to assess if the flow was laminar or turbulent. In order for the instrumentation to accurately represent the area it is placed in, measurements must be taken to ensure that homogenous environmental characteristics within the cross section of the drift are being assessed. This was
done by applying transverse point surveys using a calibrated handheld digital psychrometer. Once a suitable location was selected, the monitor was engaged and the location was recorded. In addition to the Climatrax units, manual surveys were completed at regular intervals to look at various scenarios to account for changes in power and ventilation flow and the manual data was assessed against the collected data. The checks that were completed with calibrated manual equipment were used to confirm the stationary logging equipment’s accuracy. These surveys recorded the relative humidity, dry bulb temperature, wet bulb temperature, pressure, and air density conditions. During the study time period a number of the Climatrax units were damaged by mobile equipment resulting in less coverage in some areas. In the event that a unit was damaged in a zone that was identified as being a location of heat stress potential or a zone with pumping or electrical clusters, efforts were made to relocate monitors to those zones with minimal expected heat stress conditions or low traffic zones. As a result there is a better representation of the areas of concern in the data collected.

5.2.2 Ventilation Monitoring

Airflow was monitored using a hand held vane anemometer as well as stationary monitors placed in zones fresh air supply (3 and 6) to monitor air flows. Manual surveys were conducted regularly and their results were checked against the stationary monitoring equipment results. Airflow was consistent throughout much of the study area due to the installation of bulkhead fans located in zone 8, which provided a mass flow of 145kg/s. In the event that a disruption of ventilation was to occur, the individuals working in the affected areas were well trained to respond to the incident and correct the issue. As the seals located throughout the study area are primarily solid seals, there was little leakage to be concerned with. In the event that there was a power disruption to the fans, the workforce in the area was proficient at resetting the power and checking the flows against the expected flows displayed by the air flow monitor located in Zone 6.
5.2.3 Heat Rock Absorption Monitoring

The heat absorbed by the rock was monitored through the use of Hukseflux HFP01 heat flux plates and MadgeTech dataloggers. The heat flux plate monitoring equipment used was an adaptation of soil thermal conductivity testing equipment. The back and walls of the excavation where the environmental monitors were placed in Zones 6, 8, and 14 were the locations at which the heat flux plates were installed. In order to ensure accuracy of the instrumentation, two heat flux plates were installed in close proximity to each other at the selected locations to ensure accuracy. The surface for the instrumentation to be attached to was prepared by grinding down the rock salt to a flat even surface. This was done with a grinding wheel and fine grit. The site had to be free of voids and irregularities to ensure complete contact with the plate. The site then had a thermally conductive adhesive applied as a medium between the heat flux plate and the surface. This ensured that there was no free space to disrupt transmission of heat. The locations where the plates were installed in the back were primarily composed of NaCl, with some KCl. The wall locations were composed of more KCl. Attempts were made to install the plates in the floor, however the floor conditions were not ideal for the installation of the plates and would have been at a higher risk of damage from moisture and traffic. In order to assure accuracy of the equipment and installation, the heat flux plates were installed initially in pairs and measurements verified through redundancy.

5.2.4 Heat Settling Tank Absorption Monitoring

The heat absorbed by the settling sump locations was monitored through the use of TidbitT Waterproof Temperature Data Logger (Onset®). The temperature data loggers were submerged in the tanks at the entrance and exit of the tanks to monitor the temperature changes across the tanks with time. Flow meters were located on the tank supply, allowing for the brine flow to be
monitored. The recorded temperatures did not see any significant fluctuation from the point of entry and were averaged for the purpose of this study. Due to the turbulent nature of the brine flow, limited access to the tanks for monitoring purposes limited the data to be used for this study.

5.2.5 Virgin Rock Temperature Monitoring

The virgin rock temperature is an important variable when modeling heat flow in a mine environment, as it describes the interaction of the rock and the environmental conditions. In cases where the rock strata is warmer than the air, heat flow is from the rock to the air, and inversely when the rock is cooler. This also sets limitations to the cooling potential effectiveness to the underground environment. As the cooling strategies drop the temperature, approaching the rock strata temperature, the cooling practice becomes less effective. Historical data was available, however the data was limited and was taken only at shallow depth. For the purposes of testing the virgin rock temperature, two drill holes were constructed. The first was drilled horizontally into the potash member to a depth of 15m. The second was drilled at a downward angle into the floor salt. Within the holes, four thermocouples were secured at depths away from the collar of 1.5m, 3m, 6m, and 15m within ABS piping, with access holes being cut into the ABS piping where the thermocouples were seated in order to access the rock strata temperature. The ABS piping was then filled with spray foam up to the locations of the thermocouples in order to allow free access to the air and rock strata only at the predetermined depth. Additionally the outside of the ABS was wrapped in insulation up to within a foot of the thermocouple location and the rest of the void space between the thermocouples, protected by the insulation, was filled with spray foam insulation between the ABS and rock strata, effectively sealing the thermocouples at the required depth and allowing them free access to the virgin rock for temperature monitoring.

Figure 4 illustrates the locations of the monitoring equipment locations found throughout the study area.
Figure 4- Heat Management Area Instrumentation Locations Map
Chapter 6

Sources of Heat Data Analysis

6.1 Data Gathering and Processing

Several methods were used to collect and process the data from the study area. Manual surveys and trended point surveys were used to monitor the environmental conditions. Trended surveys were taken using instrumentation built and placed throughout the study area. The trended data took into account the environmental changes regarding the wet bulb temperature, dry bulb temperature, wet bulb globe temperature, relative humidity, pressure, heat flow into the rock, and virgin rock temperature. The manual surveys were taken to ensure that the logging stations were representing the Climatrax units environmental characteristics of the drift. The manual surveys were taken as a cross section and averaged. The numbers were then compared to the readings on the point survey instrumentation to observe accuracy.

The Climatrax units, which were used to monitor the wet bulb temperature, dry bulb temperature, wet bulb globe temperature, relative humidity, pressure, and density, were checked weekly with handheld monitors to ensure accuracy and data logging function. The information from the data logger could be extracted using onset data logger software and exported in a .csv file for viewing and processing. The air density was recorded manually for future calculations. The data collected through the Climatrax units is extremely valuable when assessing the response time as conditions change in the mine environment. The data collected from these units was the primary source of information on the heat stress conditions and heat flow throughout the study area. The Climatrax environmental monitoring stations were built as standalone units that required a power source. The environmental monitors were attached to a 1.5m stand with the probe having unobstructed access to the airflow. The Climatrax units were 24 volt powered units. The power came from a
120V/24V power supply that was mounted to the base of the stand. The power supply was then plugged into the closest 120V supply. The units were built with a 45m extension to reach the nearest outlet. In some cases, extensions were made in order to reach farther when required. The Hukseflux plates were strategically placed throughout multiple survey zones. The plates measure the amount of heat energy in W/m² in bidirectional flow to show the rock acting as a heat source or as a heat sump. The data on the heat transfer into or from the rock was routinely checked to ensure accuracy between the plate sets, with the data being exported to .csv files for viewing. This data is important to assess the rock’s ability to remove heat from the zones to decrease the overall heat energy within the system. The combination of the plates with the Climatrax units allows the observer to see the relationship between the environmental conditions and the rock heat transfer, which was necessary to establish that the rock strata was acting as both a source of heat and a heat sump depending on the environmental conditions. In order to ensure accuracy of the heat flux plate locations, the heat flux plates were installed in pairs in the back and monitored for several weeks to ensure confidence in their installation.

There were two virgin rock probes installed in the study area within Zone 6. They were installed by drilling 15m drill holes and installing thermocouple probes at depths of 1.5m, 3m, 6m, and 15m depths in these holes. They were logged using HOBO data loggers and exported for .csv file viewing. This data is important for use with various mine climate modeling software’s available on the market, for establishing a virgin rock temperature, and for observing the rock strata interaction with environmental conditions.

The two parameters that were used to establish environmental monitoring of the pumping infrastructure study area were the enthalpy of the air and the wet bulb globe temperature. The enthalpy of the air allowed for the observation of energy accumulation at points throughout the
system that can be removed or inserted, and the wet bulb globe temperature is the basis for heat stress assessment in the Saskatchewan labour regulations. Heat stress is stated to occur at various working conditions above a wet bulb globe temperature of 25°C when working under a continuous heavy work load.

In conjunction with the data collected using the trended point surveys, the manual surveys were used to take snapshots of the heat flow \( (q_f) \) in the system. Measurements of the dry bulb temperature, wet bulb temperature, pressure, and density were collected during these surveys. In order to estimate the heat flow of each zone, the enthalpies \( (\Delta h) \) were calculated and applied to the mass flow \( (M_f) \).

6.2 Circuits

The heat management study area has four primary ventilation circuits (A through D) that are made up of 16 Zones, which can be viewed in Figure 1. The circuits are made up of supply air, which have different enthalpies and mass flows, depending on the origins. The circuits have different heat sources and sumps depending on the components found with their system. The main driver of the four ventilation circuits is located on the exhaust side of Zone 8. There are two fans in parallel that are bulkheaded in place to maintain the flows throughout the study area. There are also free standing fans located in zones B, C, and D that assist in sustaining the airflow.

6.2.1 Circuit A (Zones 12, 4, 5, 6, 7, 8, and Shaft Supply Air)

Circuit A is initiated in the supply air delivery from the shaft and flows through Zone 12. The air that leaves Zone 12 then enters into Zone 4. Zone 4 is primarily composed of air from Zone 12, however 26% is exhaust air from Zone 3. After the air is mixed in Zone 4, it flows through Zones 5, 6, 7, and 8. Circuit A is important in that it contains 3 of the 4 main pumping clusters in the study area. Zone 5 has one pumping cluster, while Zone 7 has two. The main electrical
infrastructure to power the pumping clusters is located in Zone 4 and at the end of Zone 7. Zone 6 and Zone 8 are composed of very few heat sources and are primarily storage or travel ways. On the exhaust side of Zone 8 there are two fans bulkheaded in parallel, but they do not have any direct impact as heat sources to the circuit.

6.2.2 Circuit B (Zones 2 and 3)

Circuit B receives its supply air from the partial exhaust of Zone 16. The air that flows through Zone 2 then flows into Zone 3, and from here all of the exhaust of Zone 3 enters into Zone 4 and becomes part of Circuit A. Zone B has a pump cluster that is located in Zone 2, and this is the primary source of heat for this circuit. Zone 3 has very few heat sources, with the exception of a free standing fan.

6.2.3 Circuit C (Zones 11, 10, 9, 16, 1, and Brine Storage Exhaust)

Circuit C is primarily supplied with air that is exhausted from the brine storage regions of the mine, with a small addition of fresh air supplied from the shaft through Zone 11. This air then flows through Zone 10 and into Zone 9. The air that leaves Zone 9 is split into two branches. 85% of the air remains in the C ventilation circuit, dumping into Zone 16, while 15% is lost to the mine. After the air travels through Zone 16, it then splits again, with 85% of the air being exhausted into Zone 2 (Circuit B) and 15% continuing to flow on to Zone 1. From Zone 1 it is then exhausted into the mine workings. There are electrical components for the pumping clusters located in Zone 10 that make up the primary heat sources for the area, as well as a free standing fan that is located at the end of Zone 10. Zone 9 has very few heat sources and Zone 16 has none. Zone 16 had been recently rehabilitated and is free of any heat sources. The primary heat source that is found within the ventilation circuit is found in Zone 1, which contains the electrical infrastructure components for the Zone 2 pumping cluster.
6.2.4 Circuit D (Zones 13, 14, and 15)

Circuit D is composed entirely of recirculated air that has exhausted out of Zone 8. The air that is exhausted from Zone 8 has 50% entering back into Circuit D and 50% being exhausted out into the mine workings. The air that enters into Zone 13 travels to and through Zone 14 and into Zone 15. The air exhausts out of Zone 15 and mixes with shaft air and then reenters into Circuit A. These three zones are relatively free of heat sources with the exception of a free standing fan located in Zone 14.

6.3 Shaft Supply Air

The fresh air supply that enters into the study area plays a vital role in the heat management of the various zones. The air supplied from the shaft sets the baseline for the analysis, with heat being added or removed from the airflow as it travels throughout the mine. Figure 5 shows the enthalpy of the shaft supplied air over a 10 months period of observation. There are seasonal trends that occur over the course of the study period. Enthalpies developed for the winter months appear to be relatively flat, with consistent values. This is the result of the heaters in the shaft that warm up the air to 2ºC within the head frame, before entering into the shaft. In May the data shows the enthalpies increasing, which is the result of the heaters being turned off and the unconditioned air being allowed to enter the shaft. This effect continues until mid-June, when the chiller on surface is turned on to cool the air prior to entering the shaft. As a result the trend line becomes flat and a consistent enthalpy is observed. This continues until the end of August, when the environmental conditions on surface begin to see a drop in enthalpy that is reduced until late September when the heaters are turned back on to heat up the air. This seasonal trend sets the baseline for the environmental conditions within the mine and the seasonal variation can be observed throughout all 16 zones. Figure 6 shows the wet bulb globe temperature of the shaft supplied fresh air. The wet bulb globe temperature also follows the same trend as the enthalpy throughout the seasons. It is worth mentioning that there are conditions that exist from June until August where the wet bulb
globe temperatures from the supplied air are already in heat stress conditions. This is an important factor when addressing heat stress conditions in other zones.

Figure 5- Enthalpy of Shaft Supplied Air February 2015 to November 2015

Figure 6- Wet Bulb Globe Temperature Shaft Supplied Air February 2015 to November 2015
6.4 Brine Storage Exhaust

The secondary supply of air to the system is air that is exhausted from the brine storage area of the mine. This air has had an opportunity to travel throughout the workings to pick up moisture, heat, humidity and contaminants as it passes through the working faces before entering back as an air supply in a cascaded system. The resultant data presented in Figures 7 and 8 show that there has been very little heat added to the air. In fact the enthalpy and wet bulb globe temperatures are lower in the exhaust supply air than in the fresh air provided from the shaft. This presented an opportunity for the cascaded air to provide a more influential role in determining the mixing ratios with the shaft supply air to lower the baseline heat energy content within the air that is provided to the study area. Additionally this shows that the air provided from the shaft has an opportunity to have additional heat removed from it before it enters into the mine system. As with the shaft supplied air, there are visible seasonal trends that occur, with the highest enthalpies and heat stress conditions occurring in the summer months. There is only one time period in August where the air wet bulb globe temperature is above the heat stress minimum of 25C°, with the remainder of the year showing that air is supplied at below heat stress conditions.
Figure 7- Enthalpy of Secondary Exhaust Supply January 2015 to March 2016

Figure 8- Wet Bulb Globe Temperature Secondary Exhaust Supply January 2015 to March 2016
6.5 Heat Flow Analysis

Table 9 displays the four ventilation circuits, broken down into their individual zone components that show the range of enthalpies, wet bulb globe temperatures, and average mass flow rates in each zone. This information illustrates the accumulation or reduction of heat energy that occurs as the air passes through the ventilation circuits. Trended data for the Enthalpies and Wet bulb globe temperatures for the locations may be viewed in Appendix A.

Table 9- Circuit Zones Range of Enthalpies and Wet Bulb Globe Temperatures

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Location</th>
<th>Enthalpy (kJ/kg)</th>
<th>Wet Bulb Globe Temperature (ºC)</th>
<th>Mass Flow (kg/sec)</th>
<th>Equipment Heat Loss (kJ/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Fresh Air</td>
<td>91-107</td>
<td>20.1-25.3</td>
<td>57</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>68-206</td>
<td>20.5-26.3</td>
<td>107</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>90-99</td>
<td>20.9-24.5</td>
<td>145</td>
<td>129.2</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>97-114</td>
<td>22.3-26.4</td>
<td>145</td>
<td>224.8</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>103-143</td>
<td>23.4-29.0</td>
<td>145</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>105-123</td>
<td>23.7-27.2</td>
<td>145</td>
<td>636.0</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>115-181</td>
<td>24.8-34.1</td>
<td>145</td>
<td>57.1</td>
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<tr>
<td>B</td>
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<td>n/a</td>
<td>n/a</td>
<td>38</td>
<td>202.5</td>
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<tr>
<td></td>
<td>3</td>
<td>97-127</td>
<td>22.7-28.3</td>
<td>38</td>
<td>35.6</td>
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<tr>
<td>C</td>
<td>11</td>
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<td>n/a</td>
<td>13</td>
<td>19.8</td>
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<tr>
<td></td>
<td>Brine</td>
<td>86-109</td>
<td>19.2-25.3</td>
<td>54</td>
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<tr>
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<td>10</td>
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<td>n/a</td>
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<tr>
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<td>107-123</td>
<td>23.9-26.8</td>
<td>67</td>
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<td></td>
<td>16</td>
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<td>60</td>
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<tr>
<td></td>
<td>1</td>
<td>109-169</td>
<td>23.7-31.1</td>
<td>22</td>
<td>187.4</td>
</tr>
<tr>
<td>D</td>
<td>13</td>
<td>90-118</td>
<td>21.7-26.5</td>
<td>72</td>
<td>237.9</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>90-115</td>
<td>21.7-26.9</td>
<td>72</td>
<td>12.2</td>
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<tr>
<td></td>
<td>15</td>
<td>n/a</td>
<td>n/a</td>
<td>72</td>
<td>20.2</td>
</tr>
</tbody>
</table>
6.6 Circuit A Ventilation Analysis

The information provided in Table 9 shows that the low end of the enthalpy range within Circuit A is comparable to that of other circuits within the study area. This is a result of the proximity of the study area to the shaft, as the fresh air must travel 1000m through excavations before it enters into Circuit A, allowing the rock and the air to interact as they approach equilibrium through heat transfer. This is similar to the trend observed in Zones 13 and 14, as the recirculated air interacts with the rock strata, transferring energy into the rock as the air and rock move towards equilibrium. The high end of the enthalpy range is typically lower than experienced in the other zones, within the study area and this circuit. As the air has had very few opportunities to interact with heat sources these results are expected. The fresh air supplied from the shaft also has the lowest range of wet bulb globe temperatures experienced in the circuits and zones, due to the lack of interaction with heat sources. In addition to the lack of exposure to heat sources, the minimal contact with water allows the air to maintain a lower humidity, which has a direct influence on the wet bulb globe temperature.

The next zone in this circuit is 12 which is composed of 53% fresh air and 47% recirculated air. Following Zone 12 is Zone 4. Zone 4 is made up of 74% Zone 12 air and 26% Zone 3 air, which is exhausted from Circuit B. As a result the composition of the enthalpy and wet bulb ranges are more influenced by the air exhausting from Zone 12. The resulting range of enthalpies is from 90 kJ/kg to 99 kJ/kg, which is among the lowest experienced in the study area. It is important that the enthalpy of the air entering into this zone be kept at a low level as it is the source of air for the remaining zones within the circuit. The range of wet bulb globe temperatures is 20.9°C to 24.5°C, which is below heat stress conditions. During the study period, there was a loss of monitoring capabilities at the peak of the summer months, so it is very possible that this zone did
experience heat stress conditions as it follows the seasonal trends experienced throughout the study area.

The air flowing from Zone 4 into Zone 5 had enthalpies ranging from 97 kJ/kg to 114 kJ/kg. This increase in enthalpy is the result of heat energy losses from the equipment located in Zone 4. The primary sources are electrical sleds and transformers that power the pumps in Zone 5. There is also a sump located in this zone that may result in buffering the enthalpy rise, as heat energy is converted into latent heat. The wet bulb globe temperature range for this zone was 22.3°C to 26.3°C. This zone experiences heat stress conditions from May to October. This zone is also contains a pumping cluster that is the second highest contributor of heat in the study area.

Zone 6 receives the exhaust air from Zone 5. The resulting range of enthalpies is from 103 kJ/kg to 143 kJ/kg. This is among the highest enthalpy ranges experienced throughout the ventilation circuits. The wet bulb globe temperature range experienced in this zone was 23.4°C to 29.0°C. This is well into heat stress conditions and requires monitoring of exposure lengths and workloads. However, this drift has very few contributors to the heat load. A monitoring station was placed in the middle of this zone in order to observe the interaction of the heat load with the strata. As a result of the interaction with the rock strata, the enthalpy range mid-zone dropped to a value range of 106kJ/kg to 128kJ/kg, with a wet bulb globe temperature range of 23.5°C-27.7°C. This interaction with the rock will be discussed further in Section 6.5.

The next zone in this circuit is Zone 7, where the air entering the zone has an enthalpy range of 105kJ/kg to 123kJ/kg. This signifies an overall drop in the range of enthalpies from Zone 6. The lack of heat contributors in the previous zone led to this decrease. The wet bulb globe temperature range was 23.7°C to 27.2°C, which presents consistent heat stress conditions for this zone that extends for the majority of the study period, with brief declines in wet bulb globe
temperature conditions below heat stress conditions in February. Within Zone 7 there are two pumping clusters and electrical infrastructure components that make it the highest heat source contributor throughout the study area.

As a result of the significant contributors to heat existing in Zone 7, Zone 8 has the highest range of enthalpies of all the zones with a range of 115kJ/kg to 181kJ/kg. The wet bulb globe temperatures in this zone also range from 24.8 C° to 34.1C°, being almost exclusively in heat stress conditions throughout the study period. Any reduction in heat in the study area would see the greatest benefits within this zone. The exhausted air from Zone 8 is then split, with 50% of the air being sent back into Circuit D and 50% being sent off to the mine workings.

6.7 Circuit B Ventilation Analysis

The second circuit to be examined is B. The air is supplied when 63% of Zone 16 air is split and sent to Zone 2. Although Zone 16 does not have any contributors of heat sources, Zones 10 and 9 have significant sources, which result in a range of enthalpies from 55kJ/kg to 177kJ/kg. This is a result of the heat content from the air exhausting out of the brine storage areas. Zone 2 contains a pumping cluster that is a major source of heat losses to the air, which is then exhausted to Zone 3. Zone 3 receives its air entirely from Zone 2. The resultant range of enthalpies is 97kJ/kg to 127kJ/kg, from heat energy picked up from the Zone 2 pumping cluster. The wet bulb globe temperature range is 22.7C° to 28.3C°. The ranges experienced for both enthalpy and wet bulb globe temperature have a great deal of fluctuation, with the trends experiencing more on the upper limits. There are a number of dramatic drops that are experienced that can be attributed to personnel working on the pumping infrastructure. Because of the significant heat produced by the pumps there are short term changes that are made for a couple of hours to bring down the heat
stress conditions, long enough for work to be safely performed. The exhaust air from Zone 3 is all contributed to circuit A and represents 26% of the Zone 4 overall flow.

6.8 Circuit C Ventilation Analysis

The ventilation circuit C is composed of two sources of air. The primary source of air is exhaust air from the brine storage area of the mine, which accounts for 67% of the air to the circuit. The remaining 33% is composed primarily of fresh air from the shaft that flows through Zone 11. Zone 11 has minimal contributors to the heat load of the circuit. Manual surveys of the zone have shown enthalpies that range from 85 kJ/kg to 99kJ/kg. This decrease in enthalpy from the shaft supplied air can be attributed to standing brine that is often found in this zone. This a particularly wet zone, as brine that has leaked out in Zone 12 often overflows into this zone, causing the travel way to be damp. The resulting manual surveys of the wet bulb globe temperature show values of 21.2°C to 22.7°C which is consistent with the enthalpies as latent heat of vaporization removes sensible heat from the air. The low air flow may also be a contributor to the low enthalpies and wet bulb globe temperature, as the rock removes heat energy from the air, with minimal additional heat sources.

The exhaust from Zone 11 and the brine storage area mix to form the flow in Zone 10. Zone 10 has an electrical substation that forms part of the pumping area electrical infrastructure and is the main heat source for the area. The ranges of enthalpies from Zone 10 are 86.9kJ/kg to 109.1 kJ/kg. The wet bulb globe temperature range for this area is 19.6°C to 25.0°C.

The exhaust air from Zone 10 then travels into Zone 9. This zone contains the main electrical infrastructure for a pumping cluster outside of the study area; it also contains a free standing fan that assists in the airflow. The environmental monitor for this zone was damaged and collected
limited data. The ranges of enthalpies collected were from 107kJ/kg to 123kJ/kg. This represents a significant amount of energy within the air and, as a result, the wet bulb globe temperature ranges from 23.9°C to 26.8°C. The time period the monitor was collecting data was during the spring months, and, as a result of seasonal trends, it could be expected this range could extend beyond the shown data, with manual surveys showing a greater range than presented in Environmental Monitor Appendix.

Air exhausted from Zone 9 splits into two flows, where 90% of the flow continues on in the circuit in Zone 16, while 10% of the flow is exhausted into the mine workings. Zone 16 is a rehabilitated excavation that lacks any sources of heat. The manually measured enthalpy found within Zone 16 ranges from 92kJ/kg to 99kJ/kg. The wet bulb globe temperature was measured to range from 24.0°C to 24.6°C. This can be associated with the rock strata absorbing the heat energy. The rehabilitation of the entry took place before the start of this study, which may have led to increases in absorption rates by the rock, resulting in decreased enthalpy and wet bulb globe temperature ranges. The exhausted air from Zone 16 splits, with 37% continuing on to Zone 1 and 63% forming the flow associated with Circuit B. Zone 1 exhausts 37% of circuit C flow into the mine workings. The information collected in this zone by the environmental monitors shows an enthalpy range of 109kJ/kg to 169kJ/kg and a wet bulb globe temperature range of 23.7°C to 31.1°C. The trended data shown in Environmental Monitor Appendix Figure A-25 do not show the typical seasonal trends as experienced in the other zones in the study area. This is the result of an air direction reversal that occurred in the month of June. The air had been previously provided from the mine workings to the zone and flowed into Zone 2, Circuit B. However the reversal effectively turned the air from a supply to an exhaust, increasing the overall enthalpy and wet bulb globe temperature. The effects can be observed in the trended data of Zone 3 in Environmental Monitor Appendix Figure A-19, where the seasonal trends are not
observed up to the month of June. Within Zone 1 are the main electrical infrastructure components that are powering the pumping infrastructure in zone two with significant heat load contributors.

6.9 Ventilation Circuit D Analysis

Ventilation Circuit D is a recirculation circuit that was established to provide a greater flow to Circuit A. Additionally, Circuit D was established in an attempt to utilize the transfer of heat into the rock over a distance long enough to return the heat content in the air to conditions found in the supply fresh air from shaft.

Zone 13 is the first accessible area in the exhaust air from Zone 8. Zone 8 splits with 45% of the air returning in the recirculation circuit. The areas after Zone 8 and before Zone 13 have been deemed inaccessible. This area prior to Zone 13 does not contain any heat sources. The range of enthalpies experienced in Zone 13 range from 90kJ/kg to 118kJ/kg, which suggests that from the point of exit in Zone 8 to the reentry in Zone 13 there has been a substantial drop in enthalpy. The wet bulb globe temperature ranges from 21.7°C to 26.5°C, with the heat stress conditions following seasonal trends and with the highest wet bulb globe temperatures measured in the summer months. There is a decrease in both the enthalpy and wet bulb globe temperatures that extended beyond the seasonal trends beginning in the month of September. Further investigation is required in order to identify the cause, however, with inaccessibility of the area between Zone 8 and Zone 13, makes it impossible to assess the area.

The exhaust air from Zone 13 is sent to Zone 14. Zone 14 contains very few heat sources, with the exception of a free standing fan located at the beginning of the zone. The enthalpy range for this zone is 90kJ/kg to 115kJ/kg, with the enthalpy being consistently lower than in Zone 13. This
is to be expected as the rock removes the heat from the air. The wet bulb globe temperature range is 21.7°C to 26.9°C, with heat stress conditions occurring in the summer months.

Zone 15 is the last zone in ventilation Circuit D. The air from Zone 14 is sent to Zone 15, before reentry back into Circuit A. There is a free standing fan that makes up the main component of heat sources to the zone, with heat continuing to be transferred into the rock strata.

6.10 Heat Flux Direct Measurements

There were instruments installed throughout the study area that were used to observe heat transfer between the rock and the air. These instruments were heat flux plates and virgin rock probes. Heat flux plates were installed in Zones 6, 8, and 14. The information provided a tool to assess the rock’s ability to act as a source or a sump for heat. One plate was placed in the roof salt for monitoring and one was placed in the potash member for monitoring. The average observed rates of heat absorption can be found in Table 10. The trended data collected from the heat flux plates can be found in Appendix B.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Average Rate (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 Roof Salt</td>
<td>2.5</td>
</tr>
<tr>
<td>6 Potash</td>
<td>6.3</td>
</tr>
<tr>
<td>8 Roof Salt</td>
<td>3.1</td>
</tr>
<tr>
<td>8 Potash</td>
<td>13.2</td>
</tr>
<tr>
<td>14 Salt</td>
<td>1.2</td>
</tr>
<tr>
<td>14 Roof Salt</td>
<td>4.3</td>
</tr>
</tbody>
</table>

6.10.1 Zone 6 Heat Flux Plates

In Zone 6, the plate installed on the back in the roof salt experienced an average rate of absorption of 2.5 W/m²; however the location over the study period had a range that extended
from 17W/m² to -9W/m². The heat flux plate installed in the potash member experienced a range of 22.8 W/m² to -2.8W/m², with an average of 6.3 W/m². The trended data followed the temperatures that were subjected to the drift. When there was a sudden substantial increase in temperature to the drift the heat flux plates observed a marked increase in absorption rate. As the temperature of the drift experienced a sudden drop in temperature the rock would become a source of heat to the drift. Slow seasonal changes to the temperature could not be attributed to changes in heat flux rates. Zone 6 is part of Circuit A that has many sources of heat spread out throughout the study area. The rock here plays an important role in removing some of the heat from the air before it exhausts into Zone 7. The rock will also behave as a dampener to offset any sudden increases or decreases in temperature that may affect the zone. The results of the heat flux plate data are available in Environmental Monitors Appendix Figures B1-B6.

6.10.2 Zone 8 Heat Flux Plates

In Zone 8 the heat flux plates exhibited the same characteristics as observed in Zone 6. The average rates of absorption were higher on average relative to Zone 6. The average rate of absorption in the back salt was 3.1W/m² and the rate of absorption in the wall potash was 13.2W/m². This higher average can be attributed to a higher temperature differential between the air and the rock strata than in Zone 6. The range of absorption rates for the salt was 18W/m² to -30W/m². The range in the potash strata was 48W/m² to -17W/m². These are the largest ranges experienced between the three zones and it can be attributed to the largest range of temperatures experienced throughout the study area. The rates experienced here are also important in understanding the rock’s ability to absorb large quantities of heat energy from the air, but may also redistribute the heat energy back into the drift. This should be considered when evaluating entry times when sending the workforce into a drift that has temporary modifications to decrease the heat stress conditions.
6.10.3 Zone 14 Heat Flux Plates

The heat flux plates in Zone 14 were located at the end of Zone 14 to observe the rock absorption rates in a recirculation circuit. The average flux rate in the back was 1.2W/m² and the average flux rate of the plate installed on the wall was 4.3W/m². The range of absorption for the back and wall were 30W/m² to -3W/m² and 56W/m² to -2W/m² respectively. As the observed dry bulb temperatures are reduced in this zone, the absorption rate range also decreases to reflect the lessened variation in temperature between the rock strata and air temperature.

6.10.4 Zone 6 Virgin Rock Probes

In Zone 6 there were two rock probes installed in order to capture the virgin rock temperature. There was a probe installed down into the floor salt and horizontally out into the potash seam. The average temperatures with distance away from the excavation can be found in Table 11. The rock probes indicated that there was very little variation with temperature at depth. The greatest variation in rock temperature range occurred at a depth of 1.5m. There can some very small variation exhibited on a dampened scale with depth, suggesting that there is some minimal influence on the rock at a further depth of 15m. The temperature difference between the rock salt and potash does dissipate with distance to an average temperature of 27.1°C. This suggests that in order for the rock and air to maintain equilibrium the air temperature would have to be reduced to 27.1°C dry bulb in the absence of moisture. Full virgin rock probe trended data can be found in Appendix C.

Table 11- Average Temperature of Rock with Depth from Excavation

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>1.5</th>
<th>3</th>
<th>6</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potash (°C)</td>
<td>29.9</td>
<td>29.3</td>
<td>28.5</td>
<td>27.1</td>
</tr>
<tr>
<td>Floor Salt (°C)</td>
<td>30.1</td>
<td>29.5</td>
<td>28.6</td>
<td>27.1</td>
</tr>
</tbody>
</table>
6.11 Discussion

The heat energy within the ventilation circuits that make up the study area are influenced by a number of factors. The heat load produced by the equipment that makes up the pumping infrastructure is the primary source of heat that creates the heat stress conditions throughout the environment. The heat load that is added to the air can be observed as the air travels throughout the zones accumulating heat as it passes by the pumping and electrical infrastructure. This is the heat energy that is the focus of the heat management plan.

The amount of heat lost by the equipment is not the entire head load to be managed through ventilation processes. The rock strata that makes up the excavation is constantly attempting to meet a temperature equilibrium state with the air temperature, with heat transferring in and out of the rock with fluctuation temperatures. Rock stratum is able to absorb some of the excess heat as it transfers the heat away from the rock surface. This was observed with rock temperature probes that were installed up to the 15m from the open excavation in the rock salt and potash members. The virgin rock temperature approaches 27°C and can ultimately be used as the baseline for further calculations. The heat flux plates that were located at the three sample locations in Zones 6, 8, and 14 further showed and measured the capabilities of the rock stratum in heat absorption. The rates of absorption averaged 3.2W/m² over the three locations. This is critical in assessing the amount of exposed rock required within a recirculation circuit to reduce the heat load.

Alternatively the rock may also behave as a source of heat when conditions exist that lead to a drop in air heat load, effectively buffering potential large swings in temperature within the ventilation circuits. There are variations across all three heat flux sites that suggest the equilibrium point is different in all three locations. The equilibrium temperature within Zone 6 is 33.4°C, with higher dry bulb temperatures being absorbed into the rock and heat energy being released from the rock at lower dry bulb temperatures. The equilibrium points at Zones 8 and 14
are 35.5°C and 29.5°C respectively. The rate of absorption changes in relation to the temperature as can be observed within the Environmental Monitors in Appendix B.

In addition to the significant loads across the zones there are also specific points of equipment clusters located within the zones. Within these specific locations, heat stress conditions may exist in relation to the rest of the zone, before the heat is picked up by the turbulent air flow and spread out throughout the zone. In Zone 12 an environmental monitor located mid zone has high enthalpy and heat stress conditions, although both the beginning and end of the zone have significantly lower measured and calculated conditions. This event occurs at multiple locations throughout the other zones. These locations should have further consideration for spot coolers, to ensure that the environmental conditions are met to avoid heat stress.

The largest influence on the enthalpy and wet bulb globe temperature is from the supply air from the shaft. There are seasonal trends that can be observed throughout all of the zones. The environmental conditions throughout July and August on surface are not being sufficiently cooled to reduce the air temperature below heat stress conditions. Additionally the temperatures that air is being heated to over the winter months may be in excess to what is required to see the greatest benefits within the mine workings. The greatest benefit to the ventilation system may come from redesigning the heating and cooling system within the head frame. A redesign of the heating and cooling system may result in a reduction of heating costs in the summer and a reduction of heat stress conditions within the months experiencing heat stress conditions.

The second source of supply air to the study area is exhaust air from the brine storage area that is cascaded back into the system. The environmental conditions that make up the heat load are lower than found from air supplied by the shaft. The lowered heat stress conditions and enthalpy
allows an opportunity for a redistribution of mixed flows. The rebalanced flows could potentially reduce the heat stress conditions as part of the other calculated opportunities discussed or as a separate strategy.
Chapter 7
Heat Management Plans for the Study Area of the Esterhazy Potash Mine

7.1 Areas of Concern

The information collected during the gathering, processing, and analysis creates the baseline for which the heat management plan is created. The information that shows the high heat energy concentrations and hot environmental conditions where workers are present are main areas of interest. There are a number of restrictions that do not allow for a potential full utilization of all the areas to their greatest potential. These are primarily due to the ground conditions that exist in old entries and power limitations, by both coverage and capacity.

The ground conditions that exist beyond Zone 8 and at the end of Zone 8 have deteriorated to the point that access is no longer permitted into these areas. As a result ventilation infrastructure cannot be placed in these areas beyond the current structures, which include ventilation seals made of muck and steel. A large portion of the ground conditions that exist from the shaft bottom to the study area are unmaintained and for the purposes of this study will be excluded from any additional work.

Electrical power for any additional ventilation infrastructure necessary for heat management can be accessed throughout most areas, with the exception of those inaccessible due to ground conditions and Zones 11, 14, 15, and 16. These four zones are currently without the electrical infrastructure to power up any substantial ventilation equipment without additional work and cost for setup and distribution.
The areas that have been identified as potential locations for focused efforts are the zones and circuits that experience the highest levels of heat stress conditions. These zones are primarily located within Circuit A. The conditions occur starting with the fresh air from shaft and the seasonal cycles, which accounts for 39% of the supplied air to the circuit. Also found within this circuit are the highest heat losses to the atmosphere, located in Zone 7 at 636 kJ/s and a wet bulb globe temperature of 34.1°C in the downwind Zone 8. Strategically finding the right management plan for this circuit is the highest priority as it has a combination of highest heat stress and highest number of workers present. Zones 2 and 3 in Circuit B are the second highest priorities, as they have the second highest density of workers present and experience conditions that are seasonally in heat stress. Zone 1, which is located in the exhaust of Circuit C, is the next highest priority as it experiences seasonal wet bulb globe temperatures that range from 23.7°C to 31.1°C. Zone 1 does experience the worker presence that is found in the two prior circuits, but does have significant electrical infrastructure, whose temperature exposure should be monitored and controlled to maintain proper functioning of the equipment. The zones that Circuit D is composed of are not of any significant concern at this point of the study, with no future plans that may apply to this study. There is very insignificant worker exposure to this area and minimal equipment sited there.

There are several methods that can be used to manage the heat in the zones throughout the study area. There are opportunities that involve heat control at the source, both at surface and underground, as well as the management of heat by controlling the airflow.

### 7.2 Heat Control at the Source

Heat management by controlling the environmental conditions at the source have significant impacts on the resultant conditions downstream. The data that has been gathered has identified that there are seasonal variations in temperature that suggest the air entering the mine shaft in the
summer months is within heat stress conditions before it reaches working areas. Secondly, the data also suggests that the rock mass has a significant role in the resultant air temperature as the rock strata and air heat content attempt to reach equilibrium. This gives two scenarios of heat control at the source that must be considered; first heat control at the shaft, in the headframe or shaft bottom, and secondly spot coolers located in the zones with the greatest need for heat management. The type of chiller used for comparison is a glycol based. Glycol systems are often used in dual purpose air conditioning heat exchanger systems within mines, for both cooling in the summer and heating in the winter. The ability to use glycol for dual purpose as well as the lower freezing point then water gives glycol systems an advantage in many mining environments.

7.2.1 Heat Management at the Shaft

Data collected from the shaft fresh air supply, located 1000m away from the shaft bottom, shows that during the summer months the air reaches wet bulb globe temperatures above 25°C. A wet bulb globe temperature above 25°C enters into the heat stress range and therefore must be addressed. There are two locations to remove this excess heat using cooling processes; at the headframe and shaft bottom. There are limitations to both locations. On surface the efficiency of heat stress removal is less due to the increase of heat content with adiabatic compression as the air descends. This can be calculated using Equation 30:

\[
\Delta T = \frac{\text{mass} \times \text{gravitational acceleration} \times \text{distance}}{\text{specific heat of air}}
\]

where;

\(\Delta T\): Change in temperature, (°C)

Mass: 1Kg of air

Gravitational constant: 9.8, (\(\text{m/s}^2\))

Distance: 1000, (m)

Specific heat of air: 1005, (\(\text{kJ/kg}^\circ\text{C}\))
The shaft at the Esterhazy potash mine is 1km in depth, allowing for a dry bulb temperature rise of 9.8C° under dry conditions.

In order to find the cooling load required for the refrigeration plant on surface, the cooling load must be calculated using the environment conditions found on surface and the conditions expected at shaft bottom.

The temperatures in the headframe have been collected from Environment Canada, showing the mean daily temperature (climate.weather.gc.ca) at the mine site near Yorkton, Saskatchewan (see Figure 9). This data shows that, from the end of June to the end of September, it can be expected that the air temperatures will reach above 20C° on surface, and will be subject to additional heating due to addition of the heat from adiabatic compression.

![Surface Mean Daily Temperature 2015](image)

**Figure 9 - Yorkton Surface Mean Daily Temperatures 2015**

The highest (not mean) temperature recorded in 2015, shown in Figure 9, was on August 11 at 31.1C°. In order to calculate the cooling load required, this will be considered the maximum achievable source temperature. The dry bulb temperature of the virgin rock within the mine is
27.1°C, which will be considered the lowest dry bulb temperature achievable. In order to account for the temperature increase occurring in the shaft as the air descends the lowest possible temperature to be cooled to will be decreased by 9.8°C to 17.3°C. The cooling load (kW) needed to achieve this can be determined using Equation 31, as follows:

\[ Q_{\text{cooling load}} = M_f \cdot [(h_1 - h_2) - (W_1 - W_2) \cdot hw_2] \]  

Using psychrometric data for air-water-vapour mixtures to find the cooling load, and the known data collected, the following variables are found:

The mass flow \( M_f \) on surface is 148.0 kg/sec.

The specific humidity \( W_1 \) on surface is 0.026kg/kg.

The enthalpy of the air on surface \( h_1 \) was 97.82kJ/kg.

The air is to be cooled to 17.3°C.

Using a psychrometric chart and 17.3°C as the chosen output, the following outgoing enthalpy and specific humidity were found.

The specific humidity \( W_2 \) will be 0.010kg/kg.

The enthalpy of the air \( h_2 \) will be 46.5 kJ/kg.

The specific enthalpy of water \( hw_2 \) (17.3°C) is 72.34 kJ/kg.

The amount of refrigeration that would be necessary to cool the air to below heat stress conditions during the peak summer months experienced would be 7421.2kW or 2110 tons of refrigeration.

**7.2.2 Spot Cooler in Fresh Air Supply**

There is a second option available to cool the supply air to the study area, which is to set up a cooling system in the air directly from the shaft in addition to the current cooling system that is in place. This would involve setting up a cooling plant in the shaft fresh air flow. This would decrease the sizing requirements of the cooling system that would be required within the headframe, as it would apply cooling to a much smaller mass flow of air and would see minimal
fluctuations to conditions as experienced on surface, while targeting the specific areas of interest.

The major drawback of this system is the disposal of the removed heat. Although it is possible to create a separate ventilation system to dispose of heat generated by the removal and operation of the refrigeration plant, a more suitable solution may be the use of brine to remove the heat. The feasibility of this method has been explored with industry leaders in refrigeration systems and, with minor modifications to the existing brine pumping system, a brine sump for heat removal could be placed where the existing de-brining lines already exist.

Using the cooling load calculation used to size the cooling plant required on surface, the following variables were determined based on data collected within the mine environment at the supply air environmental monitor.

The highest dry bulb temperature experienced in the shaft supply air was 33.0°C, which had a wet bulb globe temperature of 26.08°C.

The mass flow ($M_f$) of the supply air is 40.5 kg/sec.

The specific humidity ($W_1$) of the supply is 0.031 kg/kg.

The enthalpy of the air on surface ($h_1$) was 113.81 kJ/kg.

The air is to be cooled to 27.8°C dry bulb, based on the virgin rock temperatures.

Using the psychrometric chart and 27.8°C as the chosen output, the following outgoing enthalpy and specific humidity were determined.

The specific humidity $W_2$ will be 0.020 kg/kg.

The enthalpy of the air ($h_2$) will be 78 kJ/kg.

The specific enthalpy of water $h_w$ (27.8°C dry bulb) is 116.53 kJ/kg.

Given the variables and desired outcomes the cooling load ($Q_{cooling\ load}$) required is 1398 kW or 398 refrigeration tons.
7.3 Heat Control by Airflow Management

There are two processes that have been identified in order to manage the mine heat load through airflow management. These processes consist of the mixing of flows to manage the air sources and their environmental characteristics and further use of recirculation circuits to dissipate heat via the rock strata.

7.3.1 Mix Flow

Heat control by airflow management is an alternative to direct cooling through the use of cooling plants in the shaft and spot coolers in the mine environment. There are opportunities to manage the heat through the mixing of flows to effectively decrease the overall temperature experienced in one drift while increasing the temperature in another to find a balance that is below heat stress conditions in both drifts. The supply air from the shaft has a higher wet bulb globe temperature during the summer months than the air that is exhausted from the brine storage areas within the mine. Strategically mixing the airflows sourced from the shaft and brine storage areas can change the outputs to A and C Circuits. The resulting flows will then have impacts on the downstream Circuits B and D.

In order to look at the mixed flow outputs, the results of the mixed flows will be analyzed in terms of wet bulb globe temperature and enthalpies. In order to assess the final wet bulb globe temperature \( t_3 \) of the mixed airflow created by combining the brine storage exhaust and the shaft supply, the following mixed flow equation (Equation 32) will be used:

\[
    t_3 = t_2 + \frac{m_1 (t_1 - t_2)}{m_3}
\]  

(Equation 32)
The summer average wet bulb globe temperature was collected from the time period of June 1 to October 1 from the shaft supply \( t_1 \) and the brine storage air supply \( t_2 \) to find the final output wet bulb globe temperature \( t_3 \). The mass of airflow from the shaft supply \( m_1 \) will be calculated at different mix ratios to find the final airflow mass \( m_3 \). The mix ratios will be calculated at 100%, 75%, 50%, and 25% of both airflows, with the air flowing into Circuit A. The remaining uncombined airflow from the brine storage area will then be allowed to continue on throughout Circuit C.

The shaft supply wet bulb globe temperature \( t_1 \) is 23.8 °C.

The brine storage supply wet bulb globe temperature \( t_2 \) is 23.7 °C.

The shaft supply air mass flow \( m_1 \) is 57 kg/s.

This shaft supply is combined with the brine storage supplies air \( m_3 \) in amounts of 111 kg/s (100% of brine storage), 97.5 kg/s (75% of brine storage), 84 kg/s (50% of brine storage), and 70.5 kg/s (25% of brine storage).

The resulting wet bulb globe temperature of the mixed flow values are shown in Table 12:

<table>
<thead>
<tr>
<th>WBGT (°C)</th>
<th>100%</th>
<th>75%</th>
<th>50%</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.72</td>
<td>23.73</td>
<td>23.75</td>
<td>23.76</td>
<td></td>
</tr>
</tbody>
</table>

Enthalpies can also be applied to mixed flows in order to assess the final heat content when combining two flows. The enthalpies of the shaft supplied air \( h_1 \) and brine storage supplied air \( h_2 \) have been averaged over the period of June 1 to October 1 in order to calculate the new mixed flow enthalpy \( h_3 \). The following equation (Equation 33) is used in order to assess the mix flows of enthalpies \( h_3 \).
\[ h_3 = \frac{h_1 m_1 + h_2 m_2}{m_1 + m_2} \]  

The shaft supplied enthalpy of the air \((h_1)\) is 98.6 kJ/kg.

The brine storage enthalpy of the air \((h_2)\) is 78.81 kJ/kg.

The mass flow of the air from shaft \((m_1)\) is 57 kg/s.

The mass flow of the brine supplied air will be assessed at flows of 111 kg/s (100%), 97.5 kg/s (75%), 84 kg/s (50%), and 70.5 kg/s (25%).

The resulting enthalpies of the mixed flows values are listed in Table 13.

**Table 13- Mix Flow Enthalpies**

<table>
<thead>
<tr>
<th>Enthalpy (kJ/kg)</th>
<th>100%</th>
<th>75%</th>
<th>50%</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>88.97</td>
<td>90.38</td>
<td>92.24</td>
<td>94.81</td>
<td></td>
</tr>
</tbody>
</table>

7.3.2 Heat Management by Recirculation Passive Heat Removal

The ability for the rock to remove heat from the air has been observed through the monitoring stations as almost half of the air exhausted from Circuit A is brought back into the study area as a recirculated air source. The environmental conditions that exist from the exhaust side of Circuit A are almost negligible by the time the air enters back into Circuit A through Zone 12. Trended data was not available for Zone 15, however manual readings show significant drops in back wet bulb globe temperature and enthalpy from the air entering into Zone 13 by the time it reached the exhaust of Zone 15. The air that passes by the environmental monitors in Zones 13 and 14 shows a reduction in enthalpy as the air travels through drifts with minimal sources of supply heat. Extending this circuit, extending additional lengths to other circuits, or adding additional recirculation circuits to the study area, may prove to be a successful technique in managing heat.
In order to assess the amount of heat energy that can be potentially removed by extending the Circuit D recirculation circuit, the amount of energy currently being removed must be assessed. The average wet bulb globe temperature experienced in Zone 14 was 23.8° C and the average dry bulb temperature was 30.4° C. The results from the data gathering and processing process show that the potash and rock salt strata remove heat at two different rates, with the potash member having a much higher thermal diffusivity than the rock salt, located in the back. Data for the rock salt in the floor is not available, but the absorption rates will be assumed to be similar to the comparable rock strata in the back. In a cross section of an average potash excavation the wall height \( h \) is 2.5 m and the width \( w \) is 13 m. The average heat removal rate for Zone 14 in Circuit D at the given environmental conditions was 1.2 W/m² in the back and 4.3 W/m² on the walls. Therefore, in order to calculate the amount of heat removed by the excavation, the following equation (Equation 34) was used:

\[
\text{heat removal meter excavation length} = \ 2(h)(\text{removal rate}_{\text{wall}}) + 2(w)(\text{removal rate}_{\text{back}})
\]

The amount of heat removed per meter of excavation as the air travels down recirculation Circuit D is 56.2 W/m. This value can then be used in order to extend the recirculation circuits with similar environmental properties.

The same process was applied to two locations in Zone A. The first location evaluated was Zone 6, where the heat removal characteristic was found to be 89.7 W/m. The environmental conditions within this zone were calculated within the minimum heat stress conditions at 25.6° C wet bulb globe temperature average and dry bulb temperature average of 34.0° C. This is
important when assessing the distance required in order to reduce the enthalpy as the air flows throughout the circuit extension by heat absorption at heat stress conditions.

The second location in Circuit A was in the last zone of the circuit, after the air had an opportunity to pick up heat from all sources in the system. Zone 8 had an average wet bulb globe temperature of 27.2°C, well within heat stress conditions. The average dry bulb temperature of the air was found to be 37.2°C. Within these environmental conditions, the average amount of heat being removed from the air was 146.5W/m.

### 7.4 Comparison of Options

In order to evaluate the best option for heat control and management of the study area, the economics, feasibility, and restrictions for the study area must be considered.

#### 7.4.1 Headframe Chiller Economics

The economics for the methods described in Section 7.2 have different associated costs based on the equipment and infrastructure necessary to operate them. The headframe chiller cost of operation can be calculated based on the cost of the cooling plant operation, which is a factor of the energy requirements, the energy cost, and the run time of the plant. This cost is determined using Equation 35.

\[
Cost_{cooling\ plant} = Energy\ Requirements_{cooling\ plant} \times Energy\ Cost \times Run\ Time
\]  

(35)

The Energy Cost of a cooling plant that is under continuous usage is the cost of the delivery of power in kilowatts per hour. The cost of this continuous use of power at the study location is 0.065$/kWh.

The Run Time of the plant is based on the historical surface data in Figure 9 and shows that the cooling plant would need to run for a minimum total of 135 days on surface or 3240 hours.
Energy Requirements_{cooling\ plant} can be found using the cooling load required and the Coefficient of Performance (COP). The Coefficient of Performance is a cooling plants factor of efficiency to remove heat energy. The larger the COP numer, the more efficient the cooling plant. The Coefficient of Performance depends on the type of cooling plant used. A typical cooling plant used in the mine headframe would be a brine or glycol positive displacement cooling plant. This type of plant would have a COP of approximately 4.20 (energydesignresources.com).

The Energy Requirements_{cooling\ plant} is 1766kW as determined by Equation 36.

\[
\text{Energy Requirement}_{\text{cooling\ plant}} = \frac{\text{cooling\ load\ required}}{\text{COP}} \quad (36)
\]

When this is applied to the Cost_{cooling\ plant} the cost of operation of the cooling plant then becomes $372,119 per year at full load, while operating under seasonal conditions.

**7.4.2 Spot Cooler in Excavation Economics**

Spot coolers or refrigeration plants installed within the mine effectively target the problem areas, which guarantee that the areas of concern are effectively treated. There are spot coolers that use latent energy, converting the sensible heat without the extra heat generation of typical cooler or chiller plants. These spot coolers have been used within the study area environment in the past relying on evaporative cooling, but have led to damp conditions in the downstream environment. The air that exits the study area is then cascaded back into the fresh air stream which is supplied to the rest of the mine. As a result the moisture generated by this system would be deposited downstream in active mining areas. This type of system has been avoided in recent times as a result. The use of glycol or brine cooling plants result in the generation of excess heat, however there is an opportunity to deposit this heat into the de-brining sumps to transport the heat to...
surface through the de-brining activities that are ongoing. This allows for a cost effective method of removing the heat from the mine through a process that is already established at no additional cost to the chiller plant operation.

In order to calculate the cost of operation of the chiller plant, the cost of the cooling plant based on the cooling load determined in Section 7.2.2 of 1398 kW will be used. The same process of air cooling that was prescribed for the head frame can be used in conjunction with heat deposition into the brine settling tanks in order to remove the heat to surface. This process has been discussed with Polar Mobility Research Ltd, an industrial refrigeration and cooling corporation, and is considered to be a viable option for the mine environment that would have a similar Coefficient of Performance of 4.20. Installing the chiller in the mine environment would mean continuous operation of the plant, giving a run time of 8766 hours a year. As a result the cost of operation of the cooling plant would be $189,658 per year under full load.

7.4.3 Mix Flow Economics

The mix flow strategy to manage heat uses the airflow from one circuit, in this case Circuit C, and mixes it with airflow from Circuit A in order to achieve a lower enthalpy and better environmental conditions. To mix the flow, installation of a fan in a bulkhead to direct and control the amount of flow is required. The cost of running the fan will be assessed, with the cost of initial capital expenditure excluded. The mine and study area currently have the resources available in order to set up the bulkhead and fan with minimal expenditures on labour resources. In order to assess the running cost on an annual basis, finding the air power and assessing the brake power at 65% fan efficiency will be the method used. In order to find this the following equations (Equations 37 and 38) are used.

\[
\text{Brake Power} = \frac{\text{Air Power}}{\text{Fan Efficiency}}
\]  

(37)
The fan efficiency is assumed at 65%.

The Air Power is found using the Total Head Pressure ($H_{total}$) and the desired flow, $Q$ ($m^3/sec$).

\[ Air\ Power = Q * H_{total} \] \hspace{1cm} (38)

The following Brake Powers, as listed in Table 14, are required for the mix flows:

<table>
<thead>
<tr>
<th>$Q$ ($m^3/s$) (%)</th>
<th>Total Pressure (Pa)</th>
<th>Brake Power (kW)</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>91.7 100%</td>
<td>176</td>
<td>25</td>
<td>14,122</td>
</tr>
<tr>
<td>80.5 75%</td>
<td>136</td>
<td>17</td>
<td>9,571</td>
</tr>
<tr>
<td>69.4 50%</td>
<td>101</td>
<td>11</td>
<td>6,120</td>
</tr>
<tr>
<td>58.2 25%</td>
<td>71</td>
<td>6</td>
<td>3,618</td>
</tr>
</tbody>
</table>

**7.4.4 Passive Heat Removal Economics**

In order to remove heat from the system using the rock strata as the means of removal, extension of the current circuits or addition of the current recirculation circuit is required. In order to extend the current recirculation circuit, there is an additional drift that runs parallel to Zone15 that can be tied into the fresh air supply and extend Zone 14 south. This would add an additional 489m to both Zone 14 and the fresh air supply zones for a total of 978m. This extension would allow the strata to continue to remove heat over the length of the extension as the environmental conditions return to equilibrium. The additional cost of running this system is negligible, as the
initial setup of seals and ventilation stoppings will be the only primary expenditure with no ongoing expenses.

7.5 Restrictions and Feasibility

To investigate the most suitable methodology for the ventilation system in the study area, the restrictions of the area, circuits and feasibilities of the methodologies need to be considered. The use of refrigeration plants for coolers and chillers can be expensive to operate, but highly effective. The opportunity to manage the environmental conditions from surface through the headframe is a common practice in the mining community. The assessment of this method is based on full utilization of such plants over the summer months that are identified to contribute to heat stress. The actual cost associated with the environmental conditions present on surface may be lower than described, as the cost of operation is based on a worst case scenario with a higher utilization factor than may actually be required. Furthermore, this option has few restrictions based on installation or feasibility. The most significant area of concern with this method, as it applies to the study area, is the possibility that ventilation changes in the future could reroute the air to other areas of the mine before the study area gets full benefit of the cooled air from the shaft. The greatest limitation to this method is the lack of control over the immediate study area. This lack of direct impact on the study area with a headframe chiller is due to the distance required for the air to reach the study area. A large majority of the air is sent to other workings before being cascaded back into the system and the shaft direct supply must still travel through 1000m of excavation from shaft bottom before entering into the study area’s fresh air supply. The use of chillers in the underground environment ensures that the needs of the areas of concern are met. As the de-brining infrastructures that exist within the study area will remain in the present locations for the life of mine.
The significant restriction due to the feasibility of the installation of a chiller plant within the study area is the need for removing captured heat from the mine environment. This is possible through the use of the brine settling tanks found throughout the study area. However the chiller plant would be restricted to areas downstream of the heat sources and in close proximity to the settling tanks. The proposed location in the fresh air supply does have de-brining lines within the drift, however there is no settling tank in close proximity to the fresh air supply. The two closest brine settling tanks are located in Zones 2 and 5.

Using ventilation controls within the study area to manage heat has a significantly lower cost. The use of mixed flows to manage heat is possible when there are two or more flows with differing environmental input conditions to produce a new output through a combination of the flows. The restrictions involved with this method are; firstly, there may not be airflows readily available to use and secondly, the amount of air required to make any substantial impact may be very large. The fresh air supply and brine storage exhaust sites have been considered as the location for mix flow, however the impacts are not substantial, with too little difference in environmental conditions to produce drops in conditions that are required. Opportunities to bring in exhausted air back through Zone 1 were also investigated, but ultimately not used as the environmental conditions from heat losses in the zone were considered for reentry into Circuit B Zone 2. Additionally the resultant dust from reversing the air adjacent to a nearby mainline conveyor belt would cause maintenance issues with the electrical infrastructure that would be immediately downwind. Using passive heat removal through the extension of recirculation circuits has the lowest cost of operation, however it has limitations to for heat removal and requires extensive excavation to absorb the heat. The data collected from the study area shows that there are significant amounts of heat removed from the workings that are in direct contact with the zone that has high amount of heat losses by equipment, but lowers as the rock and air
begin to reach equilibrium. The areas that have been exposed to the high heat environmental conditions have also been showing signs of greater stress on the excavations. Mechanisms of ground control have been required in areas where high absorption rates are present as the ground has experienced a higher than normal creep rate. This limits the areas that can be used for recirculation where potential for increased excavation creep has negative implications. The areas using recirculation or extension for passive heat removal must also be accessible for cavern maintenance to keep the airway passages open. As found through the limitations on then excavations that could be used for this study. Additionally the opportunity to create additional excavations is limited due to the location of the study area in proximity to the shaft pillar area.

7.6 Method Selection

Based on the analysis of the options, there is an opportunity to use multiple methods for mine environment heat reduction by minimizing their restrictions and taking advantage of their strengths. The method proposed by this author is the use of a spot cooler in Circuit B, Zone 2 with outputs that will then be calculated with mixed flows entering into Circuit A, Zone 4. This opportunity allows a spot cooler to take advantage of the sump location in Zone 2 while remediating the heat generation of Zone 2 and decreasing the mix flow inputs of Circuit B into Circuit A.

In order to set up a cooling plant in Circuit B, Zone 2 the cooling load must be calculated. The cooling load requirement (Q) can be found using Equation 39, as follows:

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

(39)

The mass flow \(M_f\) entering into Zone 2 is 38 kg/s.
The specific humidity entering into Zone 2 (\(W_1\)) is 0.029 kg/kg.
The enthalpy entering into Zone 2 (\(h_1\)) is 127 kJ/kg.
Air to be cooled to 27.8°C.
Using a psychometric chart and 27.8°C as the chosen output, the following values for 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.
The resultant cooling load is 1668kW 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 also be assessed. The cooling plant efficiency can be assessed 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 literature (Energy Design Resources,
1999) the COP for this type of plant would be approximately 4.20. Using Equation 36 energy
requirements to run the plant can be calculated, resulting in 397 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 of electricity. The cost of continuous usage at this mine for the
case study is 0.065$/kWh. Using Equation 35 calculates an annual cost of running a cooling plant
in this location will be $226,133.
To find the mix flow output, resulting from Enthalpy of Zone 3, the output of the cooling plant 78kJ/kg \( (h_1) \), with a mass flow of 38kg/s \( (m_1) \) can be combined with the range of expected enthalpies from Zone 12. The range of enthalpies within Zone 12 is 68kJ/kg to 206kJ/kg \( (h_2) \), with a mass flow of 107kg/s \( (m_2) \).

Using the Mix Flow Enthalpy equation (Equation 33), the resulting enthalpy of the mixing of flows \( (h_3) \) ranges seasonally from 71kJ/kg to 172kJ/kg, when all of Circuit B exhaust air is added to Circuit A. The addition of a spot cooler allows for direct benefits to occur in two of the most heavily traveled and highest density of workforce areas.

**7.7 Heat Control Monitoring**

In order to effectively manage heat using the methodology prescribed, there are protocols and procedures that must be followed in order to be in compliance with provincial regulations. There are also local mine site procedures that must be implemented in order to monitor and maintain the environmental conditions within the work environment.

Section 70 of the Occupational Health and Safety Regulations 1996 states; that an employer must take effective measures to protect workers from heat stress disorders if it is not reasonably practicable to adequately control indoor conditions or where work is done outdoors. Additionally, the employer must provide suitable equipment if workers are concerned about their thermal conditions (4 Oct 96 cO-1.1 Reg 1 s70). According to Saskatchewan Labour, 2000, the temperature levels should be monitored using the wet bulb globe temperature monitor to assess hot conditions. The work load restrictions for these temperature measurement regulations are listed in Table 15.
Table 15 - Rest Schedule Based on Wet Bulb Globe Temperature Index

<table>
<thead>
<tr>
<th>Wet Bulb Globe Temperature (WBGT) Index</th>
<th>Work Load</th>
<th>Work Rate</th>
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</thead>
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<tr>
<td></td>
<td>Continuous</td>
<td>15 minutes rest per hour</td>
</tr>
<tr>
<td>Heavy</td>
<td>Up to 25.0°C</td>
<td>25.0°C up to 26.0°C</td>
</tr>
<tr>
<td>Moderate</td>
<td>Up to 27.0°C</td>
<td>27.0°C up to 28.0°C</td>
</tr>
<tr>
<td>Light</td>
<td>Up to 30.0°C</td>
<td>30.0°C up to 30.6°C</td>
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</tbody>
</table>

Table 15 can be applied to acclimatized workers, wearing lightweight, loose fitting cotton clothing. Adjustments may be necessary as other situations exist. The work load type is also important as applied to the Wet Bulb Globe Temperature Index. Heavy work, as it applies to the mine, may be any work where there is intermittent lifting, pushing, or pulling (such as a pick or shovel work), or any hard sustained work. Moderate work applies to work that is done while in the sitting position, but requiring heavy arm or leg motions. It may also refer to work done while standing and involving moderate work at a machine or bench, or work conducted while walking about and involving moderate lifting or pushing activities. Light work means sitting or standing or working at a machine that mostly requires arm work. The work rates are also important as they refer to the type of work and rest schedules. Continuous work assumes that short morning and afternoon breaks occur uniformly over an eight hour day and rest breaks are included in all breaks as being scheduled or unscheduled during work. If the climate of the break area is cooler than the working areas then the break rest periods may also be adjusted accordingly.
In order to assess the work areas for heat stress, the engineering department must implement various levels in order to ensure that the workers do not expose themselves to work loads and work rates above prescribed levels. This includes psychrometric surveys that are to be completed at least once a month, with findings being recorded and displayed at worker congregation locations. The wet bulb globe temperatures for the locations throughout the study area are then compared to the wet bulb globe temperature index that is shown in Table 15. Then the continuous work threshold is passed on to the supervisors and workers in the area to ensure that the correct work load and rest periods are implemented.

In addition to the action levels set out by the mine and regulatory bodies, there are opportunities to improve upon the process with additional controls and notifications to alert the workforce to potential heat stress conditions.

### 7.8 Additional Heat Protocols

There are opportunities to expand upon the current monitoring, control, and communications strategy for the heat stress conditions found throughout the study area. The monthly surveys are currently completed with handheld monitoring equipment that is manually recorded for display. With the completion of this research, there will be environmental monitoring equipment that will have digital display available for other uses. The Accutron Climatrax environmental monitors can be put into service in locations of high traffic and constant work for the workforce to provide data for use as a reference point during their daily activities. It is also possible to further highlight the conditions for workers entering into work zones with a notification system that is easily recognizable and visible. A multiple light system tied into the Climatrax units at the entrance of the zones identified as potential heat stress locations could be used as a warning system for the individuals entering into those zones. A system with a red, yellow, and green light
could act to notify the workforce of potential heat stress conditions. The typical work load performed within the study area could be defined as heavy to moderate at times and, as such, the red light could signal heat stress conditions when the wet bulb globe temperature reaches temperatures above 25C°. This could indicate that the workers should monitor the heat conditions once entering the zone and adjust their break schedules accordingly. The second level of heat stress notification could be for a temperature range between 23.5C° and 25C°, indicating that the work areas are not in heat stress conditions but that conditions should be monitored to ensure they do not reach heat stress conditions. Lastly, a green light could be used to signify that the area is at a temperature below 23.5C° and free of heat stress conditions for the work taking place. This type of system would be simple to implement and could be used to train the workforce.

Economically there are also opportunities to improve upon and reduce the annual running cost of the cooling plant underground from $226,133 to a fraction of the cost. The data shows that not all zones of the study area are in heat stress conditions all year round, and that they fluctuate regularly, based on environmental conditions on surface and seasonal trends. This may provide a chance to minimize the cost of a cooling plant by limiting the utilization periods. In order to implement the cost savings strategy with respect to the cooling system, running the system when the workforce is present will maximize the cooling effectiveness versus cost. This can be achieved by having the temperatures or signaling system active and monitoring while workers are accessing a zone, so that a worker could initiate the cooling system before entry. This would effectively drop the run time of the cooling plant to intervals when both the wet bulb globe temperature exceeds the minimum standards and workers are present.
7.9 Discussion

The primary areas of concern have been identified and are located in Circuits A and B. The heat stress conditions are problematic from a health and safety standpoint in addition to equipment maintenance. Heat stress conditions must be mitigated and addressed using some method relating to effectiveness and cost efficiency. A method that is not very expensive, but does not work effectively is not viable. Additionally a method that works extremely well but is very expensive may also be rejected. Evaluating potential solutions has allowed for development of an economically feasible project that has a high degree of effectiveness to be applied to the study area. This study area has the unique characteristic of having available a viable heat disposal and transport mechanism within the heat stress areas, which under normal mining operations may not be possible due to the high associated costs. The ability to utilize a spot cooler within circuit B at a point where the air is able to drop the wet bulb globe temperatures while removing the heat from the system allows the heat load in the system to effectively drop and make use of mixed airflow to combine with fresh air from the shaft and successfully drop the heat load entering into Circuit A. This system also has a positive feedback loop as there exist benefits to a recirculation circuit with air that already has a reduced heat load. The costs associated with this system are also a fraction of the costs of a headframe chilling plant, with the targeted impact of being employed in the identified workings. The costs can also be reduced further with the implementation of a cooling system management program, utilizing the system only when required. This has both the benefit of cost reduction and worker engagement in the system. Putting controls into the system that engage the workforce has the benefits of knowing that the workers are not putting themselves into potentially harmful conditions and increases worker participation surrounding heat stress.
Chapter 8

Conclusions and Future Work

The goal of this thesis was to develop heat management solutions to the heat stress conditions within the mine environment. The study area heat stress concerns have developed over recent years as the pumping infrastructure has grown, providing more sources of heat to an expanding underground area. Through the development of heat monitoring equipment and research that can be applied to the potash environment, the author has developed monitoring and management approaches to the growing heat stress concerns. The methods developed have ranged from the identification of heat sources within the mine environment to management measures of airflow temperature and therefore heat stress reduction. The techniques range from passive to mechanical in nature, with feasible actions.

8.1 Achievements and Contributions

Through the process of this study there have been a number of improvements made to the worker education and mine planning strategies, which have been applied to other locations across the mine for the purpose of educating and reducing potential heat stress conditions for the workers.

8.1.1 Engineering Achievements

Since the commencement of this thesis an additional pumping location was established within the mine, with hot conditions in mind, based on the principles developed within this study. The identification, ventilation and heat control methods described within this thesis were applied successfully to the location, with the same instrumentation and monitoring processes used.
8.1.2 Operational Achievements

The applications of the engineering achievements briefly described in Chapter 8.1.1 have been successfully implemented without disruptions to the operations within other areas of the Esterhazy potash mine. This achievement and ongoing management has contributed to the high level of performance within the brine pumping location now and for years to come.

8.2 Limitations

During the development of this thesis, heat modeling software was acquired with the intent of modeling the study area for further analysis. The software programs that were obtained are currently used for ventilation modeling, planning, and strategizing long term work, but were found to be ineffective for heat modeling. The same limitations that affect the software programs can also have similar effects on determination of the heat loads found within the mine environment, as they relate to the wetness of the excavation and age of the excavations. Excavations that are unusually wet may have a greater influence on the sensible heat, as energy is contained within latent heat. The age of rock may perhaps also have a greater influence on the rock’s ability to conduct heat.

The real time data compiled within the study area was collected on a detailed basis (every 10 minutes for environmental monitoring), which allowed for an enormous amount of data to be obtained, with fluctuations within. The nature of the activities taking place within the study area, such as power outages, drilling, bolting, and welding, can be represented by the outliers in the data. Within the trended data there are obscure outliers, and these were ignored for the purposes of this study as they do not accurately represent the day to day conditions.

Throughout the data collection process, there were interruptions that occurred with the data logging and sensory equipment. This can be observed in Appendix A as breaks in data points and
variations to the start and stop times as equipment calibrations took place. This excluded data that had been compromised during the equipment setup to ensure accuracy. Particularly Zone 4 data had a significant break in data as a result of power fluctuations which occurred from June 29, 2015 to August 11, 2015.

8.3 Future Work

8.3.1 Effect of Heat on Rock

The advancements in heat management that have taken place since 2013 have had some success on the heat redistribution through the recirculation circuit developed to passively remove heat through the rock strata. Since the inception of this method, the ground stability has rapidly declined immediately downstream of Circuit A Zone 8. Some initial analysis of the mineral composition of the rock strata has shown some dissimilarity to the rest of the study area rock, which may have resulted in the advanced rock creep. This relationship should be further studied to develop any limitations of using the passive heat removal method.

8.3.2 Software Development

The current software programs available on the market are excellent tools for showing the modeled environment, but have limited predictive capabilities that are required as a heat management tool. Further research and development of modeling capabilities would be a huge asset in assessing various strategies to combat heat stress conditions within the mine environment.

8.3.3 Regulations and Labour Relations

The Mines Regulations, 2003 and The Occupational Health and Safety, 1996 are limited when describing the environmental heat stress conditions that may be found within the mine. Defined parameters of heat stress for the mine environment would be an asset in ensuring worker safety through a governing body and should be considered for future work. Additionally, engagement of
the Health and Safety Committees within the mining community in respect to heat stress may also lead to an increase in worker education regarding working in hot environments.
References


Centre for Disease Control, (http://www.cdc.gov/niosh/topics/heatstress/heatrelillness.html)


Siemens AG, Three Phase Distribution Transformers 50 to 2500 KVA, 2015, pp 3-11 www.siemens.com


The Occupational Health and Safety Regulations, 1996, Thermal Conditions, 4 Oct 96 cO-1.1 Reg 1 s70.

The Mines Regulations, 2003, Part XIV, Air Quality and Ventilation Underground at a Mine, being Chapter 0-0.1 Reg 2, effective July 16, 2003


Appendix A
Environmental Monitor Data

Figure A-1 Shaft Supply Air Enthalpy

Figure A-2 Shaft Supply Wet Bulb Globe Temperature
Figure A-3 Zone 12 Enthalpy

Figure A-4 Zone 12 Wet Bulb Globe Temperature
Figure A-5 Zone 4 Enthalpy

Figure A-6 Zone 4 Wet Bulb Globe Temperature
Figure A-7 Zone 5 Beginning Enthalpy

Figure A-8 Zone 5 Beginning Wet Bulb Globe Temperature
Figure A-9 Zone 5 End Enthalpy

Figure A-10 Zone 5 End Wet Bulb Globe Temperature
Figure A-11 Zone 6 (Heat Flux and Probe Location) Enthalpy

Figure A-12 Zone 6 (Heat Flux and Probe Location) Wet Bulb Globe Temperature
Figure A-13 Zone 6 End Enthalpy

Figure A-14 Zone 6 End Wet Bulb Globe Temperature
Figure A-15 Zone 8 Beginning Enthalpy

Figure A-16 Zone 8 Beginning Wet Bulb Globe Temperature
Figure A-17 Zone 2 Beginning Enthalpy

Figure A-18 Zone 2 Beginning Wet Bulb Globe Temperature
Figure A-19 Zone 3 Beginning Enthalpy

Figure A-20 Zone 3 Beginning Wet Bulb Globe Temperature
Figure A-21 Zone 3 End Enthalpy

Figure A-22 Zone 3 End Wet Bulb Globe Temperature
Figure A-23 Zone 9 End Enthalpy

Figure A-24 Zone 9 End Wet Bulb Globe Temperature
Figure A-25 Zone 1 Enthalpy

Figure A-26 Zone 1 Wet Bulb Globe Temperature
Figure A-27 Zone 13 Beginning Enthalpy

Figure A-28 Zone 13 Beginning Wet Bulb Globe Temperature
Figure A-29 Zone 14 End Enthalpy

Figure A-30 Zone 14 End Wet Bulb Globe Temperature
Appendix B
Heat Flux Plate Data

Figure B-1 Zone 6 Back Heat Energy Transfer

Figure B-2 Zone 6 Wall Heat Energy Transfer
Figure B-3 Zone 8 Back Heat Energy Transfer

Figure B-4 Zone 8 Wall Heat Transfer
Figure B-5 Zone 14 Back Heat Transfer

Figure B-6 Zone 14 Wall Heat Transfer
Appendix C
Virgin Rock Probe Data

Figure C-1 Zone 6 Salt Strata Probe Dry Bulb Temperatures with Depth (Vertical)

Figure C-2 Zone 6 Potash Strata Dry Bulb Temperature with Depth (Horizontal)
## Appendix D

### Equipment Heat Losses

#### Table D- 1 Electrical Cable Heat Losses

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