Assessing surface and underground cooling methods, coupled to efficient ventilation systems to improve the climatic conditions in deep and hot mines

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mining Engineering

By:

Marcelo Bandeira Teixeira

Dr. Karoly (Charles) Kocsis/Thesis Advisor

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We recommend that the thesis prepared under our supervision by

MARCELO BANDEIRA TEIXEIRA

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Dr. Karoly Kocsis, Advisor

Dr. Carl Nesbitt, Committee Member

Dr. Robert Watters, Graduate School Representative

David W. Zeh, Ph.D., Dean, Graduate School

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Abstract

Exposure to elevated levels of heat and humidity can significantly affect health & safety, and productivity in underground mines. Cold air is primarily achieved by ventilation up to a critical depth from where further cooling must be provided by cooling systems, which can either be located on the surface or underground. Three major strategies that can be applied when it comes to cooling the air: centralized cooling (surface and underground), spot cooling, and micro-cooling. Selecting the most suitable strategy is achieved by assessing the mines’ site-specific characteristics such as auto-compression, geothermal gradient, depth, and others. Evaluation of each heat source contribution to the mines’ heat load profile is crucial to select an optimized cooling system for an underground mine. In order to help with the selection of the most effective cooling method & system a workflow that takes into account the mines’ site-specific characteristics was developed. The workflow can also determine whether ventilation alone would be sufficient to provide adequate work conditions, or a cooling system is needed. Many times, the climatic conditions in the production areas can be improved by simply redesigning the auxiliary ventilation system. Ventilation simulations show that by changing the fan arrangement from forcing to exhausting, appropriate climatic conditions can be achieved in the production area and along the access drift. The through-flow ventilation arrangement was the most attractive auxiliary ventilation system. In addition, the assessment of the thermal flywheel effect was performed at a particular mine site. Renewable-energy based systems such as storing cold energy during winter in glycol tanks and extracting heat from strata by means of organic rankine cycle (ORC) systems are being investigated as future alternatives.
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# Table of Contents

1 Introduction........................................................................................................................... 1

2 Literature Review.................................................................................................................. 2
   2.1 Human Body and Heat Exchange ................................................................................... 2
   2.2 Heat Stress Indices and Thermal Comfort ...................................................................... 3
   2.3 Legislation........................................................................................................................ 6
      2.3.1 South Africa ............................................................................................................. 6
      2.3.2 Australia .................................................................................................................. 7
      2.3.3 Western Australia .................................................................................................... 7
      2.3.4 New South Wales and South Australia ................................................................. 8
      2.3.5 USA ........................................................................................................................ 8
   2.4 Influencing Parameters on Cooling Systems ................................................................. 10
      2.4.1 Geothermal Gradient .............................................................................................. 11
      2.4.2 Surface ambient temperature ................................................................................ 14
      2.4.3 Exogenous to endogenous heat load and refrigeration turndown ratio .................. 18
      2.4.4 Mining Layout and Mining Method ......................................................................... 19
      2.4.5 Volume of Airflow ................................................................................................... 22
      2.4.6 Design Reject Temperature .................................................................................... 25
      2.4.7 Airways: Age, wetness, and size ........................................................................... 26
      2.4.8 Intake Transit Time to Workplace .......................................................................... 28
      2.4.9 Thermal Flywheel Effect ....................................................................................... 29
      2.4.10 Depth ..................................................................................................................... 30
   2.5 Sources of heat – Major environmental parameters ..................................................... 32
      2.5.1 Strata Heat .............................................................................................................. 33
      2.5.2 Auto-compression ................................................................................................. 35
      2.5.3 Machinery and Auxiliary Equipment ..................................................................... 38
      2.5.4 Underground Water .............................................................................................. 41
      2.5.5 Explosives ............................................................................................................. 41
      2.5.6 Backfilling ............................................................................................................. 42
   2.6 Review of cooling systems .............................................................................................. 42
      2.6.1 Ventilation vs. Refrigeration System ...................................................................... 42
      2.6.2 Surface Bulk Air Cooling ....................................................................................... 45
2.6.3 Underground Bulk Air Cooling .................................................................46
2.6.4 Spot Cooling ..........................................................................................47
2.6.5 Micro-Cooling .....................................................................................48
2.6.6 Ice Systems .........................................................................................49
3 Methodology ...............................................................................................51
4 Results and Discussion ................................................................................58
  4.1 Workflow Development ..........................................................................58
  4.2 Redesigning the auxiliary ventilation system .......................................64
  4.3 The Importance of the Thermal Flywheel Effect when Sizing a Cooling System........69
    4.3.1 Ventsim Modeling ..........................................................................70
    4.3.2 Climsim Modeling ..........................................................................72
    4.3.3 Ventsim and Climsim Comparison ................................................73
5 Conclusions and Future Work ....................................................................75
  5.1 Conclusions ..........................................................................................75
  5.2 Future Work ..........................................................................................76
References .....................................................................................................80
List of Tables

Table 1: Threshold Limit Values ........................................................................................................ 9
Table 2: Action Limits .......................................................................................................................... 9
Table 3: WBGT temperature limits based on air velocity and workload ............................................. 9
Table 4: Conditions for an air cooling power of 300 W/m² .................................................................. 23
Table 5: Influence of wetness on strata heat flow ................................................................................ 28
Table 6: Different scenarios for the surface rock parameters ............................................................... 37
Table 7: Critical depth for different conditions ..................................................................................... 38
Table 8: Heat release comparison between a diesel and electric LHD of the same performance .......... 40
Table 9: Simulation Settings .................................................................................................................. 64
Table 10: Thermal Flywheel Parameters for Mine A ............................................................................ 71
Table 11: Input Parameters for Mine A ................................................................................................ 72
Table 12: Results for Mine A - summer: ............................................................................................. 73
Table 13: Results for Mine A - winter .................................................................................................. 73
Table 14: Temperature results comparing Climsim and Ventsim outputs ........................................... 74
List of Figures

Figure 1: Wet-bulb temperature vs. Productivity and accident.........................................................2
Figure 2: Surface rock temperature - 32°C dry-bulb ........................................................................13
Figure 3: Surface rock temperature - 28°C dry-bulb ........................................................................13
Figure 4: Surface rock temperature - 18°C dry-bulb ........................................................................14
Figure 5: Cooling Potential of Ventilation Air as a function of its temperature at the intake ......16
Figure 6: Surface temperature data for Elko, NV – 2017 .................................................................17
Figure 7: Surface ambient temperature variation in Elko and Winnemucca, NV .........................18
Figure 8: Airflow Volume according to the level of mechanization ..................................................24
Figure 9: Design wet-bulb temperature and its impact on cost..........................................................25
Figure 10: Preferred cooling system according to Depth...............................................................30
Figure 11: Heat load profile in different countries – USA, Canada, and USA .................................33
Figure 12: Effect of auto-compression on the heat load .................................................................37
Figure 13: Ventilation/Cooling strategy – Critical Depth.................................................................43
Figure 14: Heat-removal capacity of the air ....................................................................................44
Figure 15: Goldstrike Model – Overview .........................................................................................52
Figure 16: Meikle Cooling System Overview ....................................................................................53
Figure 17: Return water reservoir ....................................................................................................54
Figure 18: Cooling Towers - Natural Heat Exchange ......................................................................54
Figure 19: Condenser Cooling Towers ............................................................................................55
Figure 20: Ventilation shaft - Bulk Air Cooling ...............................................................................56
Figure 21: Bulk Air Cooling Schematic ............................................................................................56
Figure 22: Underground Spot Cooling .............................................................................................57
Figure 23: Workflow - Part I ............................................................................................................61
Figure 24: Workflow - Part II ...........................................................................................................62
Figure 25: Workflow for selecting a cooling strategy ......................................................................63
Figure 26: Series ventilation with forcing fan arrangement (scenario 1) ........................................66
Figure 27: Series ventilation with exhausting fan arrangement (scenario 2) ..................................67
Figure 28: Through-flow ventilation with forcing fan arrangement (scenario 3) ........................67
Figure 29: Thermal Flywheel Modeling Mine A ..............................................................................72
Figure 31: Air-cooled Refrigerant Reservoir Storage .................................................. 77
Figure 32: Air cooled Refrigerant Reservoir Storage - Detailed design ....................... 78
Figure 33: a) Horizontal heat exchanger; b) Vertical heat exchanger .......................... 79
1 Introduction

The increase in consumption of goods has led to the depletion of shallow ore reserves. Consequently, the mines are becoming deeper and, therefore, hotter and more humid. There are two strategies when it comes to managing the heat in underground mines: (1) by providing a ventilation/cooling system or (2) by reducing the contribution of the heat sources. The latter could be achieved, for instance, by reducing the fleet size or other types of machinery. Increasing the ventilation or implementing a cooling system is likely to be the most economical decision considering that any reduction in equipment decreases production, which negatively impacts the mine financially.

Heat in underground mines must be mitigated as the excessive heat impacts the health, safety, workforce morale, productivity and, consequently, the operating cost. Productivity is affected since rest/work regimes have to be implemented to cope with the heat, thus reducing the working time. Approximately, 20% of the work capacity is lost at a Wet Bulb Globe Temperature (WBGT) of 28°C, 30°C and 32°C for heavy, moderate and light labor, respectively. (Kjellstrom, Lemke, Hyatt, & Otto, 2014). The WBGT is the temperature used to determine the thermal load on an individual, calculated by taking into account dry air temperature, humidity, and radiant energy. (Jacklitsch, et al., 2016).

The human body can handle the increase in temperature by several means; however, when the temperature exceeds 34°C the only effective way to cool off the body is by evaporating the sweat from the skin. (Payne & Mitra, 2008). Figure 1 depicts the effect of the wet-bulb ($T_w$) temperature experienced at the mine on productivity and accidents. The definition of wet-bulb temperature is given by D.J Brake (2000) as the “temperature at
which water evaporates into the air (at a particular dry-bulb temperature) once equilibrium between the water and air has occurred.” The wet-bulb temperature ($T_w$) is the most important parameter when dealing with hot climatic conditions for the following reasons: its importance in determining the ability of the air to remove metabolic heat from mine personnel, and its use in calculating the humidity of the air. (McPherson, 2012).

![Figure 1: Wet-bulb temperature vs. Productivity and accident](source)

**Source:** BBE Consulting – 16th North American Mine Ventilation Symposium (2017)

Figure 1 depicts that as the wet-bulb temperature increases the productivity index decreases (blue trend) while the accident frequency index increases (red trend). Understating the human body behavior under heat exposure and assessing the amount of heat experienced by the mine workers are paramount to draw conclusions and actions to mitigate the problem.

## 2 Literature Review

### 2.1 Human Body and Heat Exchange

The human body has certain mechanisms in which the deep body temperature remains at 37°C with 1°C of variation. The heat produced in the human body is present in two forms: environmental heat load and metabolic heat. The exchange of heat between the
body and the environment are in the forms of convection, conduction, and radiation. Besides these, heat is produced by the internal metabolic processes, and it depends primarily on the work rate. The muscular efficiency is in the range of 20-25%, at best. (Gravelling, Morris, & Graves, 1988). Conduction takes place due to the difference in temperature between the two regions in contact. The other two types of heat transfer happen without physical contact, with radiation being a heat transfer from two separate regions through a medium. Thus, a great proportion of the remainder is released to the environment as heat. Depending on the environmental parameters (air temperature, humidity, mean radiant temperature, and barometric pressure) and the skin temperature, heat can be transferred from the environment to the body or vice-versa. While working the body is also producing heat that contributes to the overall heat load. The heat stored by the human body can be determined by subtracting the heat losses by the heat gained. If the value is positive, the body’s temperature increases and heat illnesses may occur. The ability to cope with a hot and humid environment varies from person to person. The individual factors that influence the risk of developing heat illnesses are: body mass, physical fitness, acclimatization, obesity, and consumption of legal and illegal drugs. (Payne & Mitra, 2008).

2.2 Heat Stress Indices and Thermal Comfort

Experiments carried out by Nielsen (1962) have shown that if work is continuously done in a comfortable climate, the core temperature will increase and reach an equilibrium level. The authors state that a new equilibrium level would be reached independently of the environment for air temperatures ranging from 5 to 30°C. (Nielsen & Nielsen, 1962). However, later findings say this temperature range varies inversely with the work rate.
Above the upper limit of the range, the body will face a disequilibrium state, a situation in which heat will be stored in the body, as the core’s temperature rapidly increases. Lind (1963) states that this fact has been the basis for limiting work in a hot environment through the use of heat stress standards. From this point, the body utilizes two mechanisms to lose heat: through augmenting the amount of blood in the blood vessels and sweating.

The human body’s physiological response to the heat stress results in increasing: the body temperature, heart rate, and sweat rate. The heart rate is increased by augmenting the blood flow at peripheral tissues improving the heat transfer from the core to the marginal area. (Wyndham, 1973).

There are three types of heat indices: rational, empirical, and direct. They are based on the heat balance equation, subjective and objective heat strain, and direct measurement of environmental parameters, respectively. The first two types are more complex since they consider the environmental and physiological parameters while the third one, direct indices, takes into consideration solely the environmental ones. According to Fanger (1970), the environment and its thermal comfort are defined by the relation of six parameters, which are subcategorized either under environmental or behavioral factor. The environmental subcategory encompasses ambient temperature, radian mean temperature, humidity, and airflow speed. The metabolic rate and clothing describe the behavioral factor. The cloth factor is important since it insulates the skin from the environment, limiting the heat transfer loss through evaporative cooling. A heat stress index which involves all of these and that may be applied to any environment, sometimes called “universal” index, has been unsuccessfully attempted over the last decades.
The wet-bulb globe temperature (WBGT) is one of the most popular indexes in the world, and it combines the four main climatic parameters: air temperature, air velocity, humidity, and radiant temperature. It is calculated by combining the dry-bulb temperature ($T_d$), wet-bulb temperature ($T_w$), black-bulb temperature ($T_b$), and air temperature ($T_a$) as shown in Equations 1 and 2. (Jacklitsch, et al., 2016).

$$WBGT = (0.7 \ T_w) + (0.2 \ T_b) \quad (1)$$

$$WBGT = (0.7 \ T_w) + (0.1 \ T_a) + (0.2 \ T_b) \quad (2)$$

Equation 1 is applied for indoor or outdoor environments with no solar load while the second equation is used on outdoor environments with solar load.

This index is adopted by a variety of international organizations such as the International Organization for Standardization (ISO – 7243) and the American Conference of Government Industrial Hygienists (ACGIH). The latter uses the WBGT index to establish the threshold limit values (TLVs) to guarantee that the heat exposure will not bring heat-illnesses. One of the disadvantages of using WBGT is that its estimates become poorer as the humidity decreases. (Beshir & Ramsey, 1988, as cited in Ramsey, 1976). The Discomfort Index (DI) is also an indirect index which is easily measured since it does not consider the heat from radiation. Epstein and Moran (2006) carried out a study in which 108 climatic data sets, randomly selected, were used, and a comparison was drawn through linear regression between the WBGT and DI values. A coefficient of determination ($r^2$) of 0.95 was found for the data set. Therefore, the author concluded that Discomfort Index (DI) may be used in conjunction with regulations regarding clothing, work intensity, and acclimation since its application is straightforward. Other heat stress
indices include Effective Temperature (ET), Heat Stress Index (HIS), Wet Globe Temperature (WGT), among others.

Thermal comfort is defined as follows: “the condition of mind which expresses satisfaction with the thermal environment.” (Fanger, 1970). The parameters used to determine if a person is in thermal comfort were derived from a study performed by Fanger (1970): 1 – the human body is in heat balance; 2 – the average skin temperature is within the comfort limits; 3 – sweat rate is in an acceptable range. Therefore, provisions must be taken by the engineering crew, on the planning phase, to successfully achieve a healthy environment regarding heat exposure.

2.3 Legislation

2.3.1 South Africa

One of the most commonly used indices in South Africa is the WBGT. This index is mentioned in Occupational Health and Safety legislation; however, its use is not mandatory in the mining industry. According to the Mine Health and Safety Act No. 29 of 1996 and Regulations temperature limits are described as follows:

Thermal stress:

- Heat:
  
  - >25.0°C wet-bulb and/or
  
  - >32.0°C dry-bulb and/or
  
  - >32.0°C mean radiant temperature

- Cold:
2.3.2 Australia

“OHSA is able to conduct indoor and outdoor environment assessments against heat stress and cold stress indices and then recommendations are provided to ensure compliance with the ACGIH Threshold Limit Values. One index used currently in Western Australia for measuring environmental factors is the Wet Bulb Globe Temperature (WBGT). This is the most universally applied heat stress index. The American Conference of Government Industrial Hygienists (ACGIH) has recommended Threshold Limit Values (TLVs) for differing workloads using this index. Additionally, the ACGIH recommends accommodation to be made for unacclimatized workers and suggests a correction factor for clothing (Appendix D). However, as stated earlier, the degree of activity or workload (metabolic rate) heavily influences body heat load. Therefore, an index that recognizes this work activity may be considered more appropriate. An example of such an index is the Air Cooling Power (ACP) which accounts for the degree of work activity and the clothing worn. ACP calculates the energy balance of metabolic heat production for comparison with the mechanical work done”.

Source: (Department of Industry and Resources, 1997)

2.3.3 Western Australia

“In any workplace in an underground mine, and in any tunnel under a surge stockpile on the surface of a mine, the manager of the mine must ensure that if the
wet-bulb temperature exceeds 25°C, an air velocity of not less than 0.5 m/s is provided, and any appropriate action referred to in Sub-regulation (2) is implemented”.

Source: (Department of Industry and Resources, 1997)

2.3.4 New South Wales and South Australia

“If risks associated with extreme heat exist in an underground mine— implement control measures (including monitoring) to manage heat stress in places in the mine where: (i) persons work or travel, and (ii) the wet-bulb temperature exceeds 27° Celsius”.

Source: (New South Wales Government - NSW Legislation, 2014)

Comparing Australian mines with South African ones, the former are more mechanized and make extensive use of micro-cooling (air-conditioning in the machines’ cabins) than the latter. Therefore, when attempting to apply a regulation from one country to another these differences must be assessed.

2.3.5 USA

Different U.S. organizations and agencies provide guidance and recommendations for working under heat stress conditions. The American Conference of Governmental Industrial Hygienists (ACGIH) states that persons who are more tolerant of working in the heat and are under medical supervision might work in conditions that exceed the Threshold Limit Values (TLV). However, the deep body temperature should never exceed 38°C. The TLV values combine both environmental heat factors, represented by the WBGT, and metabolic heat production. In the case of unacclimatized workers, an Action Limit
guidance is suggested when working in hot environments. (Jacklitsch, et al., 2016). The TLV and the Action Limits is presented in Table 1 and 2, respectively.

Table 1: Threshold Limit Values

<table>
<thead>
<tr>
<th>% Work</th>
<th>Workload</th>
<th>Light</th>
<th>Moderate</th>
<th>Heavy</th>
<th>Very Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 to 100% (Continuous)</td>
<td>31.0°C</td>
<td>28.0°C</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>50 to 75%</td>
<td>31.0°C</td>
<td>29.0°C</td>
<td>27.5°C</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>25 to 50%</td>
<td>32.0°C</td>
<td>30.0°C</td>
<td>29.0°C</td>
<td>28.0°C</td>
<td></td>
</tr>
<tr>
<td>0 to 25%</td>
<td>32.5°C</td>
<td>31.5°C</td>
<td>30.5°C</td>
<td>30.0°C</td>
<td></td>
</tr>
</tbody>
</table>

Source: (American Conference of Governmental Industrial Hygienists (ACGIH), 2017)

Table 2: Action Limits

<table>
<thead>
<tr>
<th>% Work</th>
<th>Workload</th>
<th>Light</th>
<th>Moderate</th>
<th>Heavy</th>
<th>Very Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 to 100% (Continuous)</td>
<td>28.0°C</td>
<td>25.0°C</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>50 to 75%</td>
<td>28.5°C</td>
<td>26.0°C</td>
<td>24.0°C</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>25 to 50%</td>
<td>29.5°C</td>
<td>27.0°C</td>
<td>25.5°C</td>
<td>24.5°C</td>
<td></td>
</tr>
<tr>
<td>0 to 25%</td>
<td>30.0°C</td>
<td>29.0°C</td>
<td>28.0°C</td>
<td>27.0°C</td>
<td></td>
</tr>
</tbody>
</table>

Source: (American Conference of Governmental Industrial Hygienists (ACGIH), 2017)

The Occupational Safety and Health Administration (OSHA) appointed a Standards Advisory Committee on Heat Stress (SACHS) to propose a standard that would minimize the effects of working in hot environmental conditions. The criteria takes into account the increased heat removal when air velocity is increased beyond 1.52 m/s. (Jacklitsch, et al., 2016). The criteria is shown in Table 3.

Table 3: WBGT temperature limits based on air velocity and workload

<table>
<thead>
<tr>
<th>Air Velocity</th>
<th>Workload</th>
<th>Light</th>
<th>Moderate</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 1.52 m/s</td>
<td></td>
<td>30.0°C</td>
<td>27.8°C</td>
<td>26.1°C</td>
</tr>
<tr>
<td>Above 1.52 m/s</td>
<td></td>
<td>32.2°C</td>
<td>30.6°C</td>
<td>28.9°C</td>
</tr>
</tbody>
</table>

Source: Jacklitsch B., et al. (2016)

Also, the National Institute for Occupational Safety and Health (NIOSH) developed the Recommended Alert Limits (RALs) and the Recommended Exposure Limits (RELs).
The former is applied for unacclimatized and the latter for acclimatized worker. In both cases, the worker is considered to be healthy. Equations 3 and 4 show how to calculate RAL and REL, respectively. (Jacklitsch, et al., 2016).

\[
\text{RAL} [\text{°C-WBGT}] = 59.9 - 14.1 \log_{10} M [\text{W}] \tag{3}
\]

\[
\text{REL} [\text{°C-WBGT}] = 56.7 - 11.5 \log_{10} M [\text{W}] \tag{4}
\]

Where M represents the metabolic rate in Watts (W).

### 2.4 Influencing Parameters on Cooling Systems

The parameters listed below represents the major factors that influence on the decision of whether or not a cooling system needs to be implemented, and, if so, where the system should be placed, underground or surface, and the type of the system, bulk or localized. Each of the parameters listed below will be discussed in this section.

- Geothermal Gradient
- Average Surface Ambient Temperature
- Average Rock Surface Temperature
- Surface Elevation
- Exogenous to Endogenous heat loads and refrigeration turndown ratio
- Mining Layout and Mining Method
- Volume of Airflow
- Design Reject Temperature
- Airways: Age, wetness, and size
- Intake transit time to workplace
- Thermal flywheel effect in intake airways
- Depth
2.4.1 Geothermal Gradient

The geothermal gradient is the variation of the virgin rock temperature (VRT) as a function of depth, and it is also a function of the rock thermal properties such as the thermal conductivity of rock. The average value of geothermal flow of heat released from the earth’s core is around 0.06 W/m². (McPherson, 2012). This value is higher on areas with anomalous geothermal activity such as the state of Nevada, USA. For instance, the Goldstrike mine, located in Elko, NV, is relatively close, approximately 26 miles, from a high geothermal zone called Beowawe.

The geothermal gradient impacts the amount of heat flow from the surrounding rock to the airflow. If the airway is dry, the heat flow is proportional to the difference between the virgin rock temperature and the air temperature, increasing the rate of heat flow when the airway is wet. (Payne & Mitra, 2008). Rock temperature at the development end is at a temperature close to the Virgin Rock Temperature (VRT). (McPherson, 2012). As the newly developed airway becomes older, the surface temperature of the rock formations will gradually cool down to within 2°C difference in dry-bulb temperature ($T_d$) for a dry airway, and to within 2°C difference in wet-bulb temperature ($T_w$) in case of extremely wet airways.

The rock temperatures usually increases with depth. In general, up to 50 meters below the surface the rock temperature remain equal to the average air temperature. Between 50 meters and 100 meters, the temperature changes due to the circulating groundwater and the atmospheric variation. After 100 meters, the temperature increases according to its geothermal gradient, which depends both on the thermal properties of the rock such as
conductivity, diffusivity, and also on the tectonic setting. (Maurya, Kailash, Vardhan, Aruna, & Raj, 2015).

It is important to predict the VRT at deeper levels in order to assess the heat which will be transferred from strata to the ventilating air. The evaluation of the strata heat flux may be performed through Equations 5 and 6, for dry and wet airways, respectively. (McPherson, 2012):

\[
q = h \times \frac{G}{B} \times (VRT - \theta_d)
\]

(5)

\[
q = h_c \times \frac{G}{(B - G)} \times (VRT - \theta_{ws})
\]

(6)

Where:

\(q\): Heat flow in W/m²

\(h\): Heat transfer coefficient (W/(m²°C))

\(G\): Dimensionless temperature gradient at the rock surface

\(B\): Biot Number – Dimensionless heat transfer coefficient

\(K\): Thermal conductivity of the rock in W/ (m°C)

\(VRT\): Virgin Rock Temperature in °C

\(\theta_d\): Average dry-bulb temperature in the workplace

Equations 5 and 6 will be further explained in the next chapter. For now, it is important to note the virgin rock temperature is a direct input towards strata heat calculation and the higher initial rock temperatures and geothermal gradient results in higher virgin rock temperatures that, consequently, increases the amount of heat released to the workplace. A sensitivity analysis was carried out to determine the (VRT) as a function of mining depth considering that the surface rock temperature is 32°C, while the geothermal gradient varies by 10°C/km, 20°C/km, 30°C/km, and 40°C/km. Based upon the sensitivity analysis, the VRT trends are presented in Figure 2. The same analysis was
performed using the surface rock temperature as 28°C (See Figure 3) and 19°C (See Figure 4).

Figure 2: Surface rock temperature - 32°C dry-bulb

Figure 3: Surface rock temperature - 28°C dry-bulb
From Figure 2, the VRT can reach 72°C at 1,000 m deep considering a surface rock temperature of 32°C and a geothermal step of 40°C/km. However, for the same depth and geothermal step, the VRT would be only 58°C for a surface rock temperature of 18°C. Therefore, for pre-feasibility/feasibility studies it is important to have an accurate estimation for the average surface temperature over the warmest months to predict VRT and, consequently, strata heat.

2.4.2 Surface Ambient Temperature

The surface ambient temperature (dry-bulb) has a great impact on the cooling capacity since the air flowing through the intake airways will already be basically at the same temperature. It combines with effects of auto-compression resulting in higher air temperatures. An accurate design surface temperature is required in order to properly select the size and type of the cooling equipment. If the design surface temperature is 1°C higher than the actual value, it will affect the surface refrigeration plant over-estimating the plant
capacity about 3 to 4 MW, considering an air volume of 1000 kg/s. (Karsten & Mackay, 2012). The capital and operating cost over the life of the plant will be negatively affected by the over-estimation. This parameter depends on the latitude and altitude of the mines’ location. As the mine is located in a tropical area, the average temperatures encountered throughout the year will be higher than in other regions.

Another factor influencing the temperature of the air is the altitude. As the altitude increases, the air temperature also increases. In a study performed by D.J Brake (2002) comparing major heat sources on Australian and South African’ mines, the yearly average surface ambient temperature for the Australian mine and South African mines was 28°C and 18°C, respectively. This is due to the high altitude difference between the two mines, which is 1,400 m. For high surface ambient temperature such as in Australian mines, it is wise to consider installing a surface cooling system to cool the air since otherwise, the air temperature would increase to unpractical values for a small depth. The wet-bulb temperature also increases with depth; however, it does not depend on the wetness of the shaft. It is proportional to the surface ambient temperature and the pressure at the collar of the shaft.

Figure 5 shows the impact of the surface ambient temperature on the cooling potential of the air. At 1,800 m vertical depth, the surface intake air at 2.5°C WB has 50% more of cooling potential than if it would have been at 10°C WB at the surface.
Figure 5: Cooling Potential of Ventilation Air as a function of its temperature at the intake
Source: (BBE Consulting, 2017)

To assess the impact of the surface ambient temperature in the State of Nevada, particularly on the mining districts, the yearly average temperature of 2016 and relative humidity were retrieved from the US climate data website for the cities of Elko and Winnemucca. In Elko (Winnemucca), the yearly average of dry-bulb temperature and relative humidity is about 8°C and 53%, respectively. In Winnemucca, the dry-bulb temperature and the relative humidity is about 9°C and 49%. The average temperature was drawn based on the data for the year of 2016 while the relative humidity was based on the historical data ranging from 1961 to 1990. Figure 6 shows the daily temperature records measured at the Elko, NV regional airport. (National Weather Service Forecast Office, 2017).
Figure 6: Surface temperature data for Elko, NV – 2017
Source: National Weather Service – United States

Figure 7 shows the average surface dry-bub temperature (Td) of the air during 2016 in the Elko and Winnemucca areas. Although the yearly average surface ambient temperature is relatively low for both areas, in July the average dry-bulb temperature has increased to 21.25°C in Elko and 22.5°C in Winnemucca. This means that during the month of July, the maximum dry-bulb temperature on surface can reach temperatures in the range of 40°C. The lowest average relative humidity for Elko and Winnemucca are 36.60% and 30.5%, respectively. Thus, on a typical day in the hotter months, it may decrease to 20%.
The design of the refrigeration system takes into account the average temperature over the hottest periods of the month. Besides, local arrangements are performed to guarantee the workplaces do not exceed safety limits. Attention has to be taken when analyzing the climatic data as it is based on average values, which could hide a possible heat issue at the workplace. Therefore, on an hourly basis, the temperature may get too hot, and a flexible ventilation/cooling system must be designed to cope with the variations.

Operational experience has shown that in underground development faces in an Australian mine the heat becomes a problem when the average surface temperature exceeds about 21°C wet-bulb. (Moreby, 2002).

2.4.3 Exogenous to Endogenous Heat Load and Refrigeration Turndown Ratio

The total heat load of an underground mine comes from different sources named internal and external (or climatic) heat source. (Brake, 2002) Depending on the prevalence of each respective heat source relative to the total heat, an appropriate cooling system can
be implemented. In cases where the climatic heat contributes greatly to the mines overall heat load, the air will already be at high temperatures before flowing to the workplaces. Therefore, a surface refrigeration plant is required to cool down the air before entering the mine. On the other hand, if the majority of the heat load comes from internal sources such as strata-heat, machinery, auxiliary equipment, backfilling, broken rock, groundwater, and others, the most cost-effective strategy is to utilize localized cooling systems/spot cooling and even micro-cooling. This is also true when the intake travel times are long because more heat will be picked up from strata.

The refrigeration turndown ratio refers to the usage of the cooling system throughout the year. A high ratio means that the system is being used just during the hottest period (summer) while during the winter, spring, and fall the system is shut down. (Brake, 2002). Depending on the weather variation over the year, not just cooling the air during the summer, but also heating it in the winter time.

2.4.4 Mining Layout and Mining Method

The mining method applied at the mine is important to understand and evaluate the possible amount of heat load added by the machinery utilized for developing and extracting the orebody.

Traditionally, the mine design process is not governed by ventilation and refrigeration requirements but based on rock mechanics and hoisting options. Depending on the mining method applied, a satisfactory ventilation/refrigeration may be difficult to achieve. For instance, sub-level stoping method, a common underground method, has difficulty with efficient airflow distribution. Leakages in previously caved areas are responsible for losses
in air volume, affecting the capacity of heat removal of the ventilating air. (Guney & Bell, 1979).

An underground mine may be accessed through a shaft or portal. For deep mines, a shaft is more attractive due to the decreased quantity of rock excavated if compared to a portal. A shaft is used to hoist personnel and broken rock and to transport the intake air. If a shaft is used for hoisting personnel, the minimum air temperature going through the shaft is 10°C wet-bulb; however, if there is a dedicated shaft for the intake air, its temperature can reach a minimum of 6°C wet-bulb. (Ramsden, Branch, & Wilson, 2007).

As the mine spreads out and the workplaces are scattered a greater primary airflow will be required to cope with heat and other pollutants. The intake air may have to travel a long time passing through declines and old voids; hence, maximizing the heat exposure between the air and the rocks, which will cause the ventilating air to reach the active workplaces at a higher wet-bulb temperature than would have been if the route were more direct. (Derrington, 2014).

In a study carried out by Derrington (2014) to analyze the major parameters that influence the need for cooling at the Australian mines, the following parameters analyzed were depth below the surface, rock temperature, surface wet-bulb temperature, and direct or indirect surface intakes. A cooling system may not be necessary form mines where surface temperatures are low. However, if the surface temperature increases above a certain level, a cooling system would be necessary, even at the same mining depth. (Derrington, 2014). Therefore, high surface ambient temperatures or indirect intakes jeopardize the cooling effect of the intake air.
The mine layout depends on the geometry of the orebody. Vein deposits are mined to selective methods such as cut-and-fill, and although the mine may be deep, the development of the extraction is not laterally spread out. Thus, the time for the intake air to travel from the surface to the workplaces is low. Conversely, for massive and tabular deposits the mines are spread out enhancing the opportunity for the air to pick up heat along the way. (Brake, 2002). For this scenario, a spot cooling system is more effective than the surface bulk system. When block caving mining method is applied, large amounts of broken rock is blasted and thus the heat released is also large. A study performed in a copper mine operated using block caving has shown that the potential heat flow from the broken rock would be in the order of 30 MW, representing about 21% of the total need of refrigeration. (Bluhm, Moreby, von Glehn, & Pascoe, 2014).

The mining method applied also influences on the average fissure water flow into the mine and, consequently, the heat load released by the water. In a case study carried out at the Mindola Copper Mine two mining methods were investigated, the down-dip crater retreat, without backfilling, and the up-dip mining method with backfilling. The first method applied resulted in a higher heat load due to the presence of an aquifer on the hanging-wall creating large water influx into the mine. This impact is reduced while using the other method as backfilling reduce the damage on the hanging wall and, therefore, the water influx. (del Castillo, Biffi, Dawborn, & Noort, 2002).
2.4.5 Volume of Airflow

A ventilation system is needed to provide sufficient airflow that will be able to lower temperatures and dilute pollutants generated underground from different sources such as: equipment, blasting fumes, and diesel exhaust fumes. The former may be the critical criteria for determining overall ventilation requirements even for operations experiencing low virgin rock temperature. (Bluhm, von Glehn, & Smith, 2004).

When designing a new ventilation system, the mine operator relies on rules-of-thumb to calculate the amount of airflow required to dilute the pollutants and provide a workable environment for the mine workers. The overall quantity requirements are usually related to the need for removing heat and blasting fumes or to diluting diesel emission. (Bluhm, von Glehn, & Smith, 2004).

The volume of airflow is required to provide a comfortable environment in the sense that the contaminants are removed. Five critical requirements must be taken into account when cooling methods are considered. The requirements are as follows: (Rawlins & Phillips, 2005).

1. The heat released by diesel equipment, which is based on the diesel dilution factor of 0.06 m$^3$/s/kW of diesel rated power at the point of operation to dilute the heat.
2. Amount of air required satisfying the re-entry period after blasting operations
3. Enough air to dilute diesel fumes, diesel particulate matter and any flammable gas present in the underground environment.
4. Minimum air velocity of 0.5 m/s is required to satisfy the cooling requirements of mine workers
5. Comply with the heat load of the mine which are related to mining depth, strata heat, etc.

The capacity of the air to cool the mine workers are measured by air cooling power (ACP), which depends on the air velocity and wet-bulb temperature. ACP, when it comes for planning purposes, relies on site-specific conditions. However, the value will generally fall between 250 W/m² and 290 W/m². (Bluhm, von Glehn, & Smith, 2004).

The use of air-cooling power (ACP) is considered as a pragmatic alternative to the wet-bulb temperature since the effect of instantaneous conditions occurring in a powered loader would result in instantaneous wet-bulb temperatures above the design reject temperature; however, with acceptable air-cooling power due to the air velocity in the haulage drift. (del Castillo, Biffi, Dawborn, & Noort, 2002).

Table 4 shows the impact of the air speed on the wet-bulb temperature for an air cooling power of 300 W/m² at the Mindola Mine, which is compatible with the environmental criteria. (del Castillo, Biffi, Dawborn, & Noort, 2002).

Table 4: Conditions for an air cooling power of 300 W/m²

<table>
<thead>
<tr>
<th>Wet-bulb temperature (°C)</th>
<th>Air speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.0</td>
<td>0.77</td>
</tr>
<tr>
<td>28.5</td>
<td>0.95</td>
</tr>
<tr>
<td>29.0</td>
<td>1.18</td>
</tr>
<tr>
<td>29.5</td>
<td>1.50</td>
</tr>
<tr>
<td>30.0</td>
<td>1.99</td>
</tr>
</tbody>
</table>

Source: (Del Castillo, Biffi, Dawborn, & Noort, 2002)

As a preliminary approach to quantify the primary air quantity data from previous projects or from existing mines that inhabit the same area may be used to observe the ventilation-production ratio. The large gold mines in South Africa have the ventilation-
production ratio ranging from 3 to 8 kg/s per kt/month. (Bluhm, von Glehn, & Smith, 2004).

In mine operations based on diesel machinery, a first approach to determine overall primary ventilation requirements is to use the diesel emission dilution criteria. The rule-of-thumb is to use 0.10 kg/s to 0.15 kg/s per kW diesel rated power on a broad basis. (Bluhm, von Glehn, & Smith, 2004).

A rough estimate for the airflow ratio required in an underground mine may be performed by considering the level of mechanization (kW per kt/month) and the dilution factor (kg/s) for the machinery. Considering the first parameter ranging from 10 – 50 kW per kt/month and a dilution factor of 0.12 kg/s, the airflow quantity curve is drawn and showed in Figure 8. (Bluhm, von Glehn, & Smith, 2004).

![Figure 8: Airflow Volume according to the level of mechanization](image-url)
2.4.6 Design Reject Temperature

There are a large number of studies relating productivity and the frequency of accidents in the mines with the wet-bulb temperature experienced in the workplace, the cost of a refrigeration system is related to the depth, and the designed rejected temperature. (Karsten & Mackay, 2012). The design reject wet-bulb temperature at the majority of the deep mines in South African ranges from 27°C to 28.5°C. (Rawlins & Phillips, 2005).

Figure 9 presents the curves representing the relationship among the depth, designed wet-bulb temperature and the total cost, which includes the refrigeration cost and the cost related to the increase on the number of accidents and the decrease on productivity.

![Figure 9: Design wet-bulb temperature and its impact on cost](image)

*Source: (Karsten & Mackay, 2012)*

It is clear from Figure 9 that there is an inverse relationship between the design reject wet-bulb temperature and the refrigeration cost. As the requirement for refrigeration is
decreased the temperature requirement for the design reject temperature increases. Also, the human-related costs exponentially increase as the rejected temperature goes up.

2.4.7 Airways: Age, Wetness, and Size

The temperature delivered by a shaft is influenced by several factors with the major ones being: the geothermal step, the thermal flywheel effect, which cools the air temperature and, consequently, affecting the heat transfer between the rock wall and intake air, and the evaporation of moisture on the shaft increasing the latent heat and diminishing the sensible temperature. (Bossard, 1993).

Strata heat may have a large contribution to the total heat load. The heat transfer between an airway and the intake air depends on a complex function of the thermal properties of the rock and the air, the effects of moisture on the rock surface, the time since the airway has been opened and the ventilation and inlet air temperature history. (Howes, 1992).

As a comparison, the heat flow for larger and wetter airways with six months since its excavation and experiencing high ventilation rates would be about 2.5 times greater while for smaller and drier airways that have been opened for ten years (considered old airways) having low ventilation rates the heat exchange would be about 2.5 times lower. (Howes, 1992).

Two of the key factors that have to be taken into account to minimize the heat transfer from the wall rock and the intake air are length of the airway, which has to be kept as small as possible and moisture. The latter intensifies the heat transfer by diminishing both the resistance of heat-transfer at the interface and the air dry-bulb temperature. (Hartman, Mutmansky, Ramani, & Wang, 1997).
The wetness of airway influences the heat load on the ventilating air in two ways due to the evaporative cooling effect or condensation heating effect. Firstly, it increases the magnitude of the heat transfer between the rock wall and the ventilating air. Secondly, the variation of the dry-bulb temperature ($T_d$) of the intake air with the depth due to auto-compression is reduced as the level of wetness of the airway increases. Open drains and wet footwalls cause the ventilating chilled air to absorb a large quantity of heat before arriving at the workplace. (Brake, 2002).

This variation regarding the level of wetness, which is measured by the increase on the amount of water vapor presented on the airflow that has evaporated from the airway, may be assessed using an approximation suggested by McPherson (2012), Equation 7:

$$(\Delta T) = 0.00971 \Delta Z - 2.43 \times \Delta X$$

(7)

Where:

- $\Delta T$: Temperature variation ($^\circ$C),
- $\Delta Z$: Change in elevation (m)
- $\Delta X$: The water vapor increase in the air (kg/kg dry air).

The variation of the wet-bulb temperature in-depth due solely to auto-compression does not depend on the wetness of the airway, depending just on the pressure and sigma heat. The sigma heat ($S$) represents the heat energy content of air, and it is defined in terms of Kilojoules of heat associated with each kilogram of dry air. Sigma heat only depend on the wet bulb temperature of the ventilating air for any given barometric pressure. (McPherson, 2012).
In a study conducted at Mount Isa, mining operations were followed for 90 hours, showing the influence of the wetness of an airway on the rock heat flow. The values can be seen in Table 5. (Nixon, Gillies, & Howes, 1992).

Table 5: Influence of wetness on strata heat flow

<table>
<thead>
<tr>
<th>Airway Condition</th>
<th>Rock heat flow (kW)</th>
<th>Water evaporated (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>No equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1 wetness</td>
<td>104</td>
<td>114</td>
</tr>
<tr>
<td>0.2 wetness</td>
<td>124</td>
<td>138</td>
</tr>
<tr>
<td>Full equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1 wetness</td>
<td>38</td>
<td>58</td>
</tr>
<tr>
<td>0.2 wetness</td>
<td>64</td>
<td>86</td>
</tr>
</tbody>
</table>

*Source: (Nixon, Gillies, & Howes, 1992)*

It can be noted from Table 5 that the heat flow from the rock to the ventilating air increases as the wetness increases. The rate of evaporation is directly related to the difference in temperatures of the air and the water, the water surface area, and air velocity. (Hartman, Mutmansky, Ramani, & Wang, 1997).

2.4.8 Intake Transit Time to Workplace

According to D.J. Brake (2001), wind speed in travel ways may not be over 5 m/s as to avoid dust problems. Therefore, the speed restriction places a challenge when the air is directed to workplaces distant from the main shaft as the transit time increases. As a result, the ventilating air will have more opportunity to pick up heat, dust, gases, and other pollutants that would be on the way. The intake transit time is closely related to the shape of the orebody and, therefore, with the mining method applied, which will be further discussed in this chapter. Ventilation software available to the market have the capability
to simulate the transit time a fresh air would take to arrive at the workplace as well as its quality.

2.4.9 Thermal Flywheel Effect

Rock temperatures tend to vary only slightly while the air temperature at the top of the shaft may change from hour to hour according to the surface ambient temperature. Thus, usually, the walls and rock surrounding the downcast releases heat to the ventilating air during the night and absorbs heat during the day, and it continues to happen along the intake airways; however, the effect of surface temperature variation on heat transfer decreases as the air moves towards work environments. (McPherson, 2012).

Thermal flywheel effect is difficult to take into account when modeling the thermal environment because of a large number of parameters interacting among themselves and also the transient characteristic of heat and mass transport processes, which control the strata heat transfer between the surrounding rock and the mine airways. At some depth of the intake shaft heat flow will reverse its direction and the depth at this occurs change by season (summer/winter) or even on a daily basis, depending on three factors: the initial parameters (dry-bulb/wet-bulb temperature and barometric pressure) of the intake air, the rock surface temperature, and the geothermal gradient. (Roghanchi, 2017).

Regarding the way of delivering fresh air (shaft or decline), it is known that the thermal flywheel effect is more prominent along a decline than in a shaft (vertical airway), for a similar quantity of air traveling to the same production level. (Roghanchi, 2017).

The mine may take advantage of this phenomenon while thinking of introducing artificial cooling to the air in the sense that allowing the heat transfer between the surrounding rock and the intake air before introducing cooling will diminish the
refrigeration capacity required to cool the air. The intake air, when driven down the shaft, will emit heat during the day to the surrounding rock and absorb heat during the night as the air temperature will be hotter and cooler during the day and night, respectively, than the surrounding rock and its lining.

2.4.10 Depth

As the mine expands the workplace becomes deeper and further away from the mine’s access such as shaft, portal or adit. Thus, the airflow has to travel greater distances which can greatly impact the effectiveness of a cooling system depending on its location. The efficiency of the surface bulk air coolers decreases as the depth increases since the air picks up heat on its way to the workplaces.

Figure 10 shows a strategy for implementing a cooling system based on the depth of the ore extraction. (Bluhm, von Glehn, & Smith, 2004).

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**Figure 10: Preferred cooling system according to Depth**


For mines whose depths are shallow, a combination of ventilation and refrigeration systems are used to remove the heat underground while those who have operations below the critical depth solely rely on the use of a refrigeration system. (Ramsden, Branch, & Wilson, 2007). The depth where this situation is encountered is the so-called *critical depth*,
which depends on the designed surface air temperature being rejected. The critical depth was defined by D.J Brake (2001) as the depth below the surface where the air exceeds the allowable wet-bulb temperature due to auto-compression with no other heat loads being accounted.

Depth is one of the main constraints regarding heat removal. The options available for reaching a safe and comfortable environment by providing cooling is either by delivering fresh air through ventilation only or using a refrigeration plant to provide a cooling fluid which will absorb the heat present in the environment through air coolers. The guideline presented in Figure 10 is a general indication of what type of system to use to cool the air as the mine gets deeper. The depth at which the transition from one system to the other varies from mine to mine according to the amount of heat encountered in the underground environment.

However, studies have shown that values for the depth may be used as a rule of thumb which suggests that a surface cooling is cost-effective at critical depths up to 1,200 m and virgin rock temperatures up to 50°C. (Hooman, Webber-Youngman, du Plessis, & Marx, 2015).

To find the optimum refrigeration system the designer has to take into consideration all the major factors influencing in the mine. Since each mine has its characteristics, which vary from all other mines, assessing these particularities is paramount on designing the system.
2.5 Sources of heat – Major environmental parameters

This section will describe each of the major heat sources and an evaluation of its impact on the mine environment and how it can affect the selection of a cooling system.

The heat sources are auto-compression, geothermal gradient, machinery, surface temperature, blasting, primary and auxiliary equipment, groundwater, and backfill. The first three are the major sources. To design a ventilation/cooling system, these sources have to be evaluated accurately. To alleviate the heat, a ventilation system is the first option as it is less costly than a refrigeration plant. The amount of airflow delivered in the workplace is increased as the depth increases; however, the mine reaches a point where no increase in the airflow quantity will affect the air cooling power. AMC Consultants (2003) affirm that this takes place when the wet-bulb temperature reaches 32°C. In Australia, the allowable rejected temperature is usually 28°C wet-bulb temperature. From this depth, a refrigeration system must be considered. It is known that wet-bulb temperatures below 29°C are acceptable for acclimatized workforce as they would be able to complete the tasks while being safe from the physiological perspective if unacclimatized mine workers are to be considered, than wet-bulb temperatures below 28°C is considered to be safe. (Whillier & Ramsden, 1975).

Figure 11 depicts the heat source distribution in the USA, Canada, and Australia. Auto-compression represents the major heat source, accounting for more than 50%, at underground mines in Canada and Australia. The scenario is different for the US mines, where major heat contributions come from strata heat and equipment.
Figure 11: Heat load profile in different countries – USA, Canada, and USA
Source: (Roghanchi, 2017), Canada (Kocsis & Hardcastle, 2010), and Australia (D. J Brake, 2002)

2.5.1 Strata Heat

Strata heat is the heat emitted from the surrounding rock to the ventilating air. There are a large number of parameters influencing the heat exchange between the strata and the air, making its determination a difficult task. These parameters include mining method, wetness of airway surfaces, the length and geometry of the opening, virgin rock temperature, depth below the surface, air flow volume, barometric pressure, wet and dry-bulb temperatures, etc. (McPherson, 2012). A variety of methods has been developed to quantify the amount of heat provided by the strata.

Depending on the stage of a mine, different strategies must be used to quantify the strata heat load. McPherson (2012) states that if the objective is to plan further advancements in an existing mine the ventilation engineer could use the empirical approach, based on kW per tonne of mineral production per day, as information would be
available to allow for empirical relationships. For fast approximations, hybrid equations are used. They are often reduced by eliminating parameters that have a limited effect on the results while keeping the ones that strongly influence it. However, if detailed planning is required, a mine climate simulation package should be employed. These packages not only calculate the heat load, but they also predict the impact of the heat on psychrometric conditions such as the dry-bulb, wet-bulb, and relative humidity.

The geothermal gradient impacts the amount of heat flow from the surrounding rock to the airway. If the airway is dry, the heat flow is proportional to the difference between the virgin rock temperature and the air temperature. If the airway is wet the rate of heat flow increases. DJ Brake (2008) states that the rock temperature at the development end is at a temperature close to the Virgin Rock Temperature (VRT). As the newly developed airway becomes older, the rock surface temperature will be within 2°C of the dry-bulb temperature of the air - for a dry airway- and within 2°C wet-bulb temperature of the air in case of the airway is very wet.

This relationship is expressed in Equation 8. (McPherson, 2012).

\[ q = h*G/B*(VRT - \theta_d) \]  

(8)

Determining the parameters h, G, and B is a complex task; however, a simplification may be used for advancing development as a first estimation (to give a sense of scale) through Equation 9, which was presented by Dr. Austin Whillier to calculate heat released after the advancing end of a heading. (McPherson, 2012).

\[ Q = 6 \, k \, (L+4 \, DFA) \, (VRT - \theta_d) \] [W]  

(9)

Where:

K: Thermal conductivity of the rock in W/ (m.°C)
L: Length the heading has already advanced (usually the amount advanced on the previous month)

DFA: Daily face advance in m.

2.5.2 Auto-compression

Auto-compression is the conversion of the potential energy into enthalpy of a fluid when it flows from a higher elevation to a lower one. The amount of heat added to the air can be assessed by the change in elevation according to Equations 9 and 10. (McPherson, 2012).

\[ H_2 - H_1 = (Z_1 - Z_2) \times g \]  
\[ T_2 - T_1 = \frac{(Z_1 - Z_2) \times g}{C_{pm}} \]

Where:

H: Enthalpy [J/kg]
Z: Elevation [m]
T: Temperature [°C]
g: Gravitational acceleration [m/s²]
\( C_{pm} \): Specific heat of the actual air [J/kg°C]

For example, the dry-bulb temperature (Td) lapse rate can be in the range of 9.7°C per 1,000 meters considering a dry shaft and 101.3 kPa of barometric pressure at the collar of the shaft. However, in the majority of cases, the shaft or the airways are not completely dry. Consequently, the rate of increase in the dry-bulb temperature (Td) is eroded by the cooling effect of evaporation (McPherson, 2012). The increased rate in the dry-bulb temperature will be reduced as the humidity on the environment increases. In case of completely wet conditions, the dry-bulb temperature may in fact decrease as the air flows down the shaft.
The temperature difference will increase as the elevation between the two locations becomes larger. For underground mines located in Northern Ontario (Canada) and Australia, auto-compression can account for over 50% of the total heat source. (Carpenter, Roghanchi, & Kocsis, 2015). Thus, profoundly impacting the cooling system. As it can be extracted for the formulas above, the heat added depends on the elevation, gravity, and the specific heat of the air. The latter parameter depends on the air characteristics such as pressure and humidity; however, its variation can be neglected. Thus, the increase in the dry-bulb temperature of the air depends primarily on the elevation. In the case of wet conditions down an intake shaft and along horizontal airways, the dry-bulb temperature ($T_d$) will in fact decrease as a result of evaporation (Payne & Mitra, 2008). The wet-bulb temperature ($T_w$) will increase as the intake air picks up moisture (Whillier & Ramsden, 1975).

The effect of auto-compression and surface air ambient temperature have been analyzed for 3 different scenarios, which are presented in Table 6. The maximum allowable wet-bulb temperatures in the mine’s return air were assumed as 28°C, 27°C, and 26°C. The adiabatic lapse rate on the wet-bulb temperature ($T_w$) was assumed as 4°C per 1,000 meters. The data in Table 6 is related to Elko, NV during the summer (May, June, July, and August) of 2017. The data for dry-bulb and relative humidity were retrieved from the National Weather Service website. The wet-bulb temperature was calculated using a barometric pressure of 30 in of Hg.
Table 6: Different scenarios for the surface rock parameters

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Dry-bulb (°C)</th>
<th>Relative Humidity (RH)</th>
<th>Wet-bulb (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Maximum daily high in summer</td>
<td>32</td>
<td>51%</td>
<td>24</td>
</tr>
<tr>
<td>2: Summer average high</td>
<td>28</td>
<td>43%</td>
<td>19</td>
</tr>
<tr>
<td>3: Summer Monthly average</td>
<td>18</td>
<td>43%</td>
<td>11</td>
</tr>
</tbody>
</table>

Figure 12: Effect of auto-compression on the heat load

Figure 12 shows that the critical depth where a cooling system is required assuming that the wet-bulb temperature (Tw) in a mine’s return airway cannot exceed 28°C is 1,700 meters for Scenario 1, 2,250 meters for Scenario 2, and over 3,000 meters for Scenario 3. Furthermore, if the allowed wet-bulb temperature in the mine’s return airways is lowered to 27°C, the critical depth where a cooling system is required is 1,500 meters for Scenario
1, 2,000 meters for Scenario 2, and over 3,000 meters for Scenario 3. These parameters and values are also provided in Table 7.

Table 7: Critical depth for different conditions

<table>
<thead>
<tr>
<th>Reject design Temperature (°C)</th>
<th>Surface ambient temperature (wet-bulb - °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenario 1</td>
</tr>
<tr>
<td>26</td>
<td>500 m</td>
</tr>
<tr>
<td>27</td>
<td>750 m</td>
</tr>
<tr>
<td>28</td>
<td>1,000 m</td>
</tr>
</tbody>
</table>

Auto-compression becomes more dramatic when the depth increases. For deep mines the strategy that may be adopted is to install an underground refrigeration system. Most likely the cooling system must be implemented before reaching the critical depth as other heat sources will be experienced at the mine.

2.5.3 Machinery and Auxiliary Equipment

The equipment utilized in an underground environment is either powered by electricity or by diesel. The electrical power used to drive fans and other machinery are a major source of heat underground. The level of mechanization dictates the contribution to the total heat load in the underground mine and also the selection of the cooling system. Chilled service water is broadly used in South Africa, and it is effective in cooling the environment since the mines are labor-intensive. However, in mechanized mines such as in Australia, there is low usage of service water mainly because the drilling process. Hand-held drills are responsible for the majority of the use of service water and are performed using equipment which has an air-conditioned cabin (micro-cooling). (Brake & Fulker, 2000). The mining industry at Nevada’s precious metal mines in North America are highly mechanized. (Roghanchi & Kocsis, 2017).
According to Whillier and Ramsden (1975), the rise in dry-bulb temperature of the airflow passing through the fan is proportional to increase in pressure. The author says that a fan producing a rise in the pressure of 1 KPa will affect the air temperature by increasing 1.1°C.

In addition to that are the diesel-powered vehicles such as jumbos, trucks, and LHD’s which are widely used in the underground environment. The calorific value for diesel is about 45 MJ/ kg of diesel fuel burned, considering a density value as 0.8 kg/liter. The efficiency of a diesel engine at peak power is considered to be as 33%, the rest of it, approximately, two-thirds are released to the environment as heat. (McPherson, 2012). A diesel equipment produces at a full load about 3 kW of heat per rated kW and on average about 1.5 kW per rated kW idle. (Bluhm, von Glehn, & Smith, 2004). For example, a machine with an engine power of 250 kW would produce on average about 375 kW of heat. Therefore, they represent a considerable source of heat and must be accounted for.

Besides trackless machineries such as LHDs and loaders, hoist, pumps, refrigeration complex, conveyor, and crusher generate heat at a considerable rate. (Guney & Bell, 1979). The level of mechanization may be summarized as ranging from 10 kW (rated diesel) per kt/month to high values of 50 kW (rated diesel) per kt/month. (Bluhm, von Glehn, & Smith, 2004). The basic information needed for mining design purposes is the type and amount of diesel machinery, multi-blast requirements, contaminant removal, and air velocity. (Rawlins & Phillips, 2005). To assess the heat from the utilization of diesel loaders and trucks, the fuel consumption is first measured. The calorific value (sensible and latent heat) for diesel is about 45 MJ/ kg of diesel fuel burned, considering a density value as 0.845 kg/liter. (Nixon, Gillies, & Howes, 1992).
Electrical equipment has a higher efficiency than diesel machinery resulting in less heat released to the environment. This higher efficiency is achieved because the electric motor requires less input power than diesel’s motors for the same performance due to torque characteristics of the former, and the input energy is used for the equipment to perform work against gravity. (Millar, Trapani, & Romero, 2016). The most important electrical contributors to heat in an underground mine are:

- Ventilation system fans-10% end heat
- Pumps-10% end heat
- Bolters and drill jumbos-7 kW heat load in average mine
- Lighting-100% end heat

A comparison between a diesel and electric LHD has been performed in a case study in Northern Ontario. The results are show in Table 8. (Millar, Trapani, & Romero, 2016).

<table>
<thead>
<tr>
<th></th>
<th>Diesel LHD</th>
<th>Electric LHD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine output</td>
<td>243</td>
<td>177</td>
</tr>
<tr>
<td>Thermal efficiency (%)</td>
<td>37</td>
<td>95</td>
</tr>
<tr>
<td>Heat dissipated from the prime mover (kW)</td>
<td>516</td>
<td>9</td>
</tr>
<tr>
<td>Drive train losses (kW)</td>
<td>97.2</td>
<td>97.2</td>
</tr>
<tr>
<td>Total heat dissipation (kW)</td>
<td>614</td>
<td>107</td>
</tr>
</tbody>
</table>

Source: Millar, Trapani, & Romero, 2016

It can be noted from Table 8 that the electrical LHD has a high thermal efficiency two times more than the diesel LHD whereas the total heat dissipation is about six times less. The heat released by the diesel machine occurs in the form of latent and sensible heat while for the electrical one it occurs just in the form of sensible heat. (Maurya, Kailash, Vardhan, Aruna, & Raj, 2015). For one liter of diesel fuel consumed the equipment generates approximately 1.1 liters of water added from combustion. (McPherson, 2012).
The heat transfer rate occurs at a high rate at the opening being advanced. Eventually, after the rock has been exposed to the ambient surface rock temperature tends to be within 1-3°F (0.6-1.7°C), stabilizing the heat transfer. But in highly mechanized mines the openings are rapidly advanced and so the heat transfer at the working place, where large numbers of mine workers are concentrated. (Hartman, Mutmansky, Ramani, & Wang, 1997).

2.5.4 Underground Water

Underground water is also an important contributor to the heat of the environment due to the ease at which heat can be transferred from the water to the air.

Underground water is delivered to the mine through the fissures presented in the surrounding rock (natural water). It is considered a heat source when its temperature is the same as the virgin rock temperature. As soon as the influx water is exposed to the intake air, it quickly loses heat to the ambient until reaching the air wet-bulb-temperature. Service water is another source of underground water, and it is mainly used for dust suppression.

The contact between the strata water and the ventilating air should be avoided and the water influx water should be drained and directed to pipes for transporting to the surface. Whillier and Ramsden (1975) suggests that the data regarding the amount of water flow should be based on the tons of fissure water per tons of rock broken. Knowing this ratio, the heat load provided by the water may be estimated.

2.5.5 Explosives

In order to provide broken rock for mining, the face has to be drilled and blasted. Blasting is accomplished by explosives in case the ore is considered hard rock. This process immediately releases heat to the workplace and its amount varies depending on the
explosive used. For instance, the heat released while using ANFO is about 3600 KJ/kg. The available energy stored on the explosives will ultimately be disposed as heat. (Nixon, Gillies, & Howes, 1992).

By assessing the amount of explosive used on a daily basis, the heat load on the ventilating air may be estimated. A large amount of heat is carried away with the blasting fumes by the return air within one or two hours after blasting, depending on the degree of fragmentation and the quality of the ventilation in the area. However, part of it will remain in the workplace on the broken rock, around 50%. Some of the heat produced in the blasting stage will leave the workplace along with the blasting fumes, and other parts of the heat will remain in the broken rock. The heat released to the workplace depends on ventilation arrangements, rock fragmentation and mining cycle (residence time of broken rock). (Nixon, Gillies, & Howes, 1992).

2.5.6 Backfilling

Cement releases through an exothermic reaction approximately 250 kJ/kg as it cures. Considering 10% of cement backfill the heat released from the backfill is 25 kJ/kg. (Millar, Trapani, & Romero, 2016). For some mines in the western United States, such as the mines in Nevada, this is a major source of heat since the cut-and-fill method, usually applied, and requires the production of a cement fill.

2.6 Review of Cooling Systems

2.6.1 Ventilation vs. Refrigeration System

The steps in a sensitivity analysis study aims to offer the best cooling strategy encompass the use of a ventilation software to simulate the total heat load and the effect of
the cooling system. After that, a cost study is carried out to identify the capital and operational cost.

As the mine increases in depth, a greater volume of airflow is required to be delivered to the workplace, “flooding” the environment with air. However, at a certain depth, known as critical depth, no effect will be reached just by delivering more fresh air. At this point, a refrigeration system should be used. This factor depends both on the surface ambient temperature since it is the starting temperature of the air and on the designed rejected air temperature. When a refrigeration system is applied, the air flow should be reduced instead to the lowest amount possible to avoid greater costs to cool the air. (Brake, 2001). This procedure is depicted in Figure 13.

![Figure 13: Ventilation/Cooling strategy – Critical Depth](image)

Source: D.J Brake (2001)

The capacity of the ventilating air to remove heat from the underground workings depends on two parameters: the wet-bulb temperature at the working level and the design reject temperature for the air, which is limited to 28°C. (Whillier & Ramsden, 1975). Figure
Figure 14 shows the heat-removal capacity of the air as a function of the design reject temperature and depth. This graphic is used to predict the quantity of air required to remove the heat from the mine workings.

There are four major refrigeration systems: surface bulk air cooling (BAC), underground BAC, spot cooling and micro-cooling (air-conditioned cabins and cooling vests). These major systems may be combined to satisfy the need for cooling air at the workplace. Some questions that arise is the stage of selecting a refrigeration system are: (Brake, 2001).

- Where will the refrigeration plant be allocated (Surface or underground)?
- How the system could be combined (surface bulk air cooling, ice plants, underground air coolers fed through chilled water provided by the surface)?
- How much will be the contribution of each form?

Source: Whillier and Ramsden (1975)
The cheapest refrigeration strategy is to adopt the micro-cooling system since it has a high positional efficiency by cooling the air immediate surrounding to the mine worker. However, its application is compromised by the high mobility of the workforce. Eventually, the mine operator will have to perform an activity outside the cabin, especially in non-highly mechanized mines in which drilling for rock bolting, for instance, is still hand-made. The cooling vests have the disadvantage of diminishing the worker’s flexibility due to the apparatus carried with the vest and also the productivity.

The cooling power provided by the refrigeration plant may be reduced if some actions are implemented such as the use of an energy recovery system, transition from diesel equipment to electrical, and through seals and doors which guarantee the chilled airflow is being directed to the zones in need.

2.6.2 Surface Bulk Air Cooling

Surface bulk air cooling technology uses chilled water to exchange heat with the air. It can take place in a direct or indirect heat exchanger. The chilled water is provided by either a surface or underground refrigeration machinery. For deep gold mines, the water is chilled underground due to positional efficiency issues. However, for other mines, such as the platinum mines in South Africa the machinery are located on the surface, and the water is distributed by insulated pipes. (Mackay, Bluhm, & Van Rensburg, 2010).

Surface bulk air cooling is the first option to be considerate due to its economic and practical application. Compared to underground refrigeration and cooling systems they are often cheaper and more straightforward when it comes to installation, operation, and maintenance. (Wilson, Bluhm, Funnel, & Smit, 2003).
It is accomplished by delivering fresh air from the surface and chilled water for the places that only need it. When the surface BAC becomes uneconomical, other options such as the use of surface-chilled service water may be investigated. The surface bulk air cooling has a low positional efficiency when compared to other methods of refrigeration since the air is cooled relatively far from the delivery point. This system is negatively affected by the heat added due to auto-compression and by the strata heat, from the surrounding rock in case of a high geothermal gradient, until a certain depth where it is impractical to keep cooling the air on surface. (Mackay, Bluhm, & Van Rensburg, 2010).

An ultra-cold surface BAC system may be used for deeper depths if the air or water is cooled at lower temperatures such as close to zero. However, a dedicated shaft must be provided as the shaft used for hoisting and transporting personnel may not be below 10°C. Even this system will reach a depth at which it will not be cost effective. (Ramsden, Branch, & Wilson, 2007).

2.6.3 Underground Bulk Air Cooling

An underground cooling system can be introduced by several techniques: (a) as chilled service water, (b) secondary air cooling, (c) tertiary air cooling, and (d) as controlled recirculation within established mine districts. (Mackay, Bluhm, & Van Rensburg, 2010). A primary underground BAC system is usually installed not far from the bottom of the intake shaft. If the distance between the underground to the work areas is significant, a secondary stage, or even tertiary stage cooling system is considered. In respect to secondary air cooling, the components and methods to cool the mine air are selected according to site-specific characteristics. One option is to use the direct-contact spray heat exchangers, while the other option is to use closed-circuit cooling-coil heat exchanger banks. According to
Mackay, Bluhm, & Van Rensburg (2010) a controlled recirculation system may be used to increase airflow within hot areas. The former is thermally more efficient. However, it has disadvantages on pumping. The Tertiary or in-stope air cooling is generated through tertiary air coolers where the water is used as a coolant fluid. After this, the water is discharged and drained. (Mackay, Bluhm, & Van Rensburg, 2010).

Underground BAC may use underground or surface refrigeration plants. The former is more efficient as the refrigerant liquid does not pick up as much heat as if it would have to descend from the surface. The difficulty of accessing the equipment for maintenance is a disadvantage of the underground refrigeration plant. Another one is fouling due to the lower quality of the water used underground. However, the main disadvantage is the amount of heat that can be rejected in the return airway. The temperature of the return airway must comply with legislation.

Chilled service water may be delivered to the workplace through a well-insulated piping system containing water refrigerated to 0°C (the lowest possible temperature before freezing). It is a very effective way of delivering cooling because of its high positional efficiency. To minimize the cost of sending chilled water underground refrigeration machines are built underground. Locating them underground bring problems such as size constraints, higher maintenance costs, and higher condensing temperatures. (Mackay, Bluhm, & Van Rensburg, 2010).

2.6.4 Spot Cooling

Spot cooling also known as decentralized cooling is used when heat issues are encountered in areas away from the main airways. This system consists of an evaporator that is installed inside the auxiliary duct and a condenser installed outside the duct.
(McPherson, 2012). A high positional efficiency and mobility can be achieved, as the system is close to the production stopes. The main disadvantage includes limited cooling capacity due to size constraints, and the ability of the system to reject heat into the mine’s return airways. (Brake D. J., 2001).

In conjunction with the cooling system, an effort must be made to avoid leakages and to use systems to recover energy aiming to reduce operational costs (power cost). The downcast pipes carrying chilled water or air are insulated to prevent cooling losses. Turbine generator systems and hydro-lift systems (or three-pipe feeder systems) are examples of systems designed to recover energy. (Mackay, Bluhm, & Van Rensburg, 2010).

To find the best, economically and safely meeting the requirements, refrigeration system the designer has to take into consideration all the major factors influencing in the mine. Since each mine has its characteristics which vary from all other mines assessing these particularities is paramount in designing the system.

2.6.5 Micro-Cooling

The cheapest refrigeration strategy is to adopt the micro-cooling system since it has a high positional efficiency by cooling the air immediate surrounding to the mine worker. However, its application is compromised by the high mobility of the workforce. Eventually, the mine operator will have to perform an activity outside the cabin, especially in non-highly mechanized mines in which drilling for rock bolting, for instance, is still hand-made. The cooling vests have the advantage of diminishing the worker’s flexibility due to the apparatus carried with the vest and also the productivity. (Brake D. J., 2001).

Cooling vests can be classified either as active or passive. The ones regarded as passive do not need any mechanical or electrical apparatus to be utilized. The types of
passive vests are phase-change garment (PCG), and cooling garment. Meanwhile the active vests need some equipment to function, and it can be subdivided into four types: air-cooled garments (ACG), liquid-cooled garments (LCG), vests based on gas expansion and the hybrid cooling garments. (Al Sayed, Vinches, & Halle, 2016).

The air-cooled garments exchange heat through evaporating the sweat produced by the body. Its efficiency severely drops in environments with high humidity. A study performed by McLellan et al. (1999) found out that the air-cooled garment was able to increase the tolerance time by 150% in heavy work, and 80% in light work for a working place with 40°C and 30% RH, a hot and dry environment. Again, as the relative humidity increases, lower gains in productivity is achieved. (Al Sayed, Vinches, & Halle, 2016).

Liquid-cooled garments work by circulating a chilled fluid, usually water, within tubes placed in the garment. The flow of the fluid is provided by a small pump, which is driven by battery. To achieve higher efficiencies the mass flow and the coolant temperature must be controlled. A higher contact between the body surface and the garment and a minimum temperature of 100°C, which is related to the wearer’s comfort, improves the garment’s efficiency. (Al Sayed, Vinches, & Halle, 2016).

2.6.6 Ice Systems

This system reaches an economic limit where the cost of pumping water to the surface becomes excessive. Therefore, ice-making plants are considered to distribute ice to underground distribution systems. The ice is blended with water to form ice slurry, and it is then moved underground by gravity. The advantage of this process is that the heat added by auto-compression is used as latent heat to melt the ice, and, therefore, the slurry gets underground still cold ready to be used in the BAC or spot coolers. For comparison, since
water is pumped underground it also picks up heat due to auto-compression, which represents a rise in the temperature of 2.34°C per 1,000 m of pipe - data found in a pilot study for the Vaal Reefs mine - while for the ice slurry it would remain practically constant since the heat would be used to change the phase of the slurry (latent heat). (Bellas & Tassou, 2005).

However, according to McPherson (2012), the major disadvantage of this system is the significant increase in capital and operating cost. Thus, it is used as a last resort in the mines. In a study carried out in an ultra-deep platinum mine in Australia, the author states that providing ice from ice makers located at the surface to be sent underground is more attractive than other options as the depth gets closer to 3,000 m. (Mackay, Bluhm, & Van Rensburg, 2010).

Recently, a cooling system based on ice generation has been compared to traditional systems that used chilled water to cool the ventilating air. Three particular topics must be addressed when it comes to ice systems: components and characteristics of large systems, ice making equipment, and methods for conveying it and the cost and power requirement associated with it. (Bluhm, Biffi, & Wilson, 2000).

In the case of extreme depths, an ice system becomes more effective as less pumping is required if compared to a typical chilled water system the ice system requires 70 to 60% less flow from the surface. (Bluhm, Biffi, & Wilson, 2000). Ice is made on the surface and then conveyed underground to a series of melting dams. From these dams, chilled water will be distributed to the air coolers. The number of dams underground depends on the depth of the mine with one being placed at the bottom of the main shaft and another on the lowest mining working area. The ice is melted by running warm water, returning from the
working areas, through the dams. Therefore, having a double benefit as the ice is melted and the service water is cooled down.

A detailed comparison was carried out aiming to compare chilled water and ice systems for different depths at the Witwatersrand mine. The conclusion from this study is that the power needs for ice system are about 10% to 15% lower than chilled water system while capital investment is about 5% lower, considering the depth of 3,000 meters. (Bluhm, Biffi, & Wilson, 2000).

3 Methodology

The workflow developed in this thesis utilized Barrick Goldstrike’s case study, which is located in Northern Eureka County near Elko, NV. The Goldstrike mine is owned and operated by Barrick Mining Corporation. The objective of the case study was to gain in-depth insight into specific site-specific characteristics and concepts that were later used to develop the workflow. The collected data includes climatic and ventilation parameters measured underground, coupled to discussions with the senior ventilation engineer in respect to the cooling system components including: (1) bulk air cooling, (2) refrigeration plant, (3) cooling towers, (4) storage reservoir, and (5) spot cooling units. In addition, the updated ventilation model developed in Ventsim™ was provided, analyzed, and discussed.

The mine currently has five intakes (Betze portal #1, Betze portal #2, Banshee, Meikle production shaft, and Rodeo shaft) and four exhausts (NP portal, Meikle borehole, Meikle service shaft, and Rodeo exhaust raise). The amount of air being exhausted is around 2,630,000 cubic feet per minute (CFM) as the last model update on October 2nd, 2018. Figure 15 depicts the Goldstrike model.
The objective of this case study is to analyze and understand the underground cooling systems being utilized at the Goldstrike mine and how it takes into account the site-specific characteristics. The Goldstrike cooling system takes advantage of the characteristic of its location such as low relative humidity, which facilitates the heat exchange between air and water. Therefore, natural heat exchange takes place between air and water on the first two steps of the cooling system.

The bulk air cooling system at Goldstrike uses water as a coolant, chilled by refrigeration machines located at the surface, to bring the downcast ventilating air to about 2 °C-3°C. As the shafts are dedicated only for ventilation purposes it opens the possibility of further decreasing the air temperature in the future. The different stages and processes of the cooling system can be seen on the plant layout shown in Figure 16.
Figure 16: Meikle Cooling System Overview

Return hot water coming from the Rodeo Bulk Air Cooling (BAC) and also from the underground workings is storage in a tank located at the surface. At this water reservoir, the first cooling process takes place when water and the atmospheric air exchange heat overnight. This heat exchange comes at limited cost as the heat is naturally transferred. The return water tank is shown in Figure 17. After this process, the water is directed to a Pre-cooling Tower, in which the water will be further cooled. At the cooling tower, the water will again undergo natural heat exchange with the atmospheric air. The cooling towers take advantage of the low relative humidity of the environment, which makes the heat transfer more effective. The unit can be seen in Figure 18.
After the pre-cooling towers, the water is sent to the refrigeration plant, which is the last step to cool water down to 2-3°C. Ammonia is used as the coolant in the process and
after running through the evaporator, where heat exchange occurs between the water and ammonia, the coolant is sent to the condenser cooling tower before going again to the refrigeration cycle. Chilled water is then sent to the bulk air cooling (BAC) system on surface and underground for localized mobile coolers. The condenser cooling tower is depicted in Figure 19.

![Figure 19: Condenser Cooling Towers](image)

Chilled water (2-3°C) is sprayed inside the bulk air cooling tower, while the intake air is forced up the towers by two fans on each side of the shaft, heat is removed from the intake air as water droplets collect at the bottom of the towers. During winter, warm water is sprayed to heat the mine’s intake air. The operation is controlled by a switchover that is automatically activated when surface temperature is below 0°C (33°F). Figure 20 and Figure 21 show the ventilation shaft and the schematic of the bulk air cooling, respectively.
In the spot cooling system at Goldstrike, air is forced by a 100 hp fan through the heat exchangers that use chilled water as the refrigerant. The air is then directed to the working areas, and the water from the exchangers is returned to the surface by a 12-inch
pipe. The water is stored in the return water tank to cool off overnight. The spot cooling unit can be seen in Figure 22.

![Figure 22: Underground Spot Cooling](image)

Underground spot cooling becomes necessary when chilled air coming from the surface arrives at the working areas at high temperatures as it picks up heat along the air. Therefore, a spot cooling is required to cool the air further to drop the temperature to acceptable level. Units can be installed in the production workings and dead-end development heading as needed.

As the Goldstrike mine deepens, a different approach might be needed to reduce the ventilating air temperature. The effectiveness of the cooling strategy depends on the size and position of the air coolers equipment. An alternative for future workings would be to install secondary bulk air coolers, using spray chambers with chilled water from the surface, on main crosscuts at the extremely hot locations. Another alternative to the actual cooling system would be to install an ice storage facility that uses glycol as refrigerant. Ice
is produced overnight when the energy cost is lower, and it is, then, used throughout the day. However, this should be considered as a last resort since both the high capital cost and high energy consumption of generating ice.

This case study helped to assess and understand different methods of cooling and how the system can benefit from site-specific characteristics such as low relative humidity during summer (e.g. 10%) and significantly lower temperature during night-time, in order to select the most effective cooling scenario.

4 Results and Discussion

4.1 Workflow Development

The main goal of the thesis was to develop a workflow, which can help the mine operators assess and select the most cost effective method & system for cooling the work areas. The workflow takes into consideration site-specific characteristics such as VRT, surface temperature, mining equipment, mining method, backfilling, etc. This flowchart represents an improvement, since so far the mining industry relied on the mining depth alone when selecting the most effective cooling method/ system able to provide adequate work conditions in the production workings and throughout the mines. In addition, the proposed workflow can determine whether ventilation alone would be sufficient to provide adequate work conditions. It is important to note that the workflow provides a first phase assistance to select an efficient cooling system; however, a detailed analysis must be performed to reach a final decision.

At first, a design reject temperature must be defined (e.g. \( T_w = 29 ^\circ\text{C} \)). Then, the heat generated by auto-compression is calculated, and the temperature at the working level is
determined and compared to the designed reject temperature. When considering the auto-compression effects only, if the temperature at the workplace is equal or higher than the designed reject temperature, the flowchart shows that the mine has reached the critical depth. In case the mine has not reached the critical depth yet, the workplace temperature must still be assessed and compared to the design reject temperature. The reason why the workplace temperature must be assessed is that the conditions at the workplace may not be in compliance with recommendations/ regulations due to other heat sources that might be present such as mining equipment, auxiliary equipment, strata heat, oxidization, etc. If the workplace temperature is higher than the reject designed temperature, the ventilation capacity must be increased. This can be achieved by either adding a surface fan to the existing infrastructure or by sinking a new ventilation shaft. As a result, the airflow velocity and, consequently, the air volume will be increased providing more cooling capacity underground. On the other hand, if the workplace temperature is lower than the design reject temperature, no action is needed since the workplace is in compliance regarding heat exposure. (See Workflow – Part I in Figure 26).

When assessing the workplace temperatures, the mine operator must keep in mind that the standard deviation of the workplace temperature can be in the range of 2 °C wet-bulb ($T_w$), for a well-designed and maintained ventilation system. (Brake, 2001). If temperature distribution in the work areas is assumed to be normal, then 66% of the workplace temperatures are within one standard deviation of the average workplace temperature, 95% of the workplace temperatures will be within two standard deviations ($T_w = 4 °C$), and 99% will be within three standard deviations ($T_w = 6 °C$). For example, if the average wet-bulb temperature in a stope is $T_w = 27 °C$, then 99% of wet-bulb
temperatures in other stopes and throughout the mine will be between $T_w = 21^\circ C$ and $T_w = 33^\circ C$.

In case the mine has reached the critical depth, a cooling system must be implemented to reduce both dry-bulb and wet-bulb temperatures. To select an efficient cooling system, using this workflow, the primary and secondary heat sources are assessed. For readability purposes, the workflow was split in two parts, I and II, which are present in Figure 26 and 27, respectively. The workflow as a whole is shown in Figure 28.

As an example, assuming that the primary and the secondary heat sources at a hypothetical mine are auto-compression and mechanization, respectively, the suggested primary cooling systems include surface bulk air cooling (ultra-cold), underground primary bulk air cooling (BAC), ice systems, and spot cooling as the secondary cooling method. The difference between the BAC (conventional) and BAC (ultra-cold) is that for the ultra-cold bulk air cooling system a dedicated intake shaft must be used to delivery ultra-cold air underground.
Figure 23: Workflow - Part I
Figure 25: Workflow for selecting a cooling strategy
4.2 Redesigning the Auxiliary Ventilation System

An alternative to mitigate the heat in underground mines is to redesign the auxiliary ventilation system. To assess the impact of various auxiliary ventilation delivery systems, a ventilation model was developed using Ventsim™. The mining method used to extract high-grade ore reserves from a steeply dipping ore body is cut-and-fill (C&F), as the ore reserves are hosted in poor rock formations.

For the auxiliary ventilation system, three airflow delivery methods were considered: (1) Series ventilation with fans in forcing arrangement, (2) Series ventilation with fans in an exhausting arrangement, and (3) Through-flow ventilation with fans in an exhausting arrangement. The air volume requirements in the production stopes were determined according to the diesel exhaust dilution criteria of 0.065 m$^3$/s/kW (100 cfm/bhp). Since the objective was to redesign an auxiliary ventilation system, the simulations were performed at a particular production area as opposed to the entire mine. However, if the goal were to analyze the primary ventilation system, then the whole mine would be considered.

The mine airways (haulage drift, access drift, and production areas) were designed in an arched style, having 5m x 5m dimensions (height and width). Table 9 shows the parameters utilized by Ventsim™ in the simulations.

Table 9: Simulation Settings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow - Allowable Error</td>
<td>0.010 m$^3$/s</td>
</tr>
<tr>
<td>Temperature Accuracy</td>
<td>0.10°C</td>
</tr>
<tr>
<td>Rock Thermal Conductivity</td>
<td>2.00 W/m.°C</td>
</tr>
<tr>
<td>Rock Thermal Diffusivity</td>
<td>0.938 x 10$^{-6}$ m$^2$/s</td>
</tr>
<tr>
<td>Geothermal Gradient</td>
<td>2.5°C/100m</td>
</tr>
<tr>
<td>Surface Barometric Pressure</td>
<td>101.3 kPa</td>
</tr>
<tr>
<td>Surface Temperature - Dry Bulb</td>
<td>30°C</td>
</tr>
<tr>
<td>Surface Temperature - Wet Bulb</td>
<td>20°C</td>
</tr>
</tbody>
</table>
Table 9 shows that the temperature accuracy is 0.10°C. For example, if the temperature at a certain location is calculated as 25°C, based on model output accuracy, the wet-bulb temperature could be in the range of 24.90°C to 25.10°C.

Two 200 hp LHDs are used to transport the fragmented ore from two stopes into two remuck bays located in the access drift that connects the haulage drift with the production stopes. From the remuck bays, the ore is transported along the access drift, then along the haulage drift to an ore pass by a 350 hp haul truck. The efficiency of the LHDs was considered as 35%.

For scenario 1, the auxiliary ventilation system consists of two 1.2m diameter fabric ducts installed along the access drift and throughout the production stopes. Along each duct, a 150 hp auxiliary fan is installed in the haulage drift. Besides, a 50 hp auxiliary fan is installed in the ventilation duct serving the production stope. Along each duct 23 m$^3$/s is delivered to each production stope. The air volume requirements have been determined according to the diesel exhaust dilution criteria. Additional 25% air volume was allocated along the haulage drift to avoid airflow recirculation at the fresh air pickup location. The dry-bulb temperature ($T_d$) and the wet-bulb temperature ($T_w$) of the fresh air entering the auxiliary ducts is 30°C and 22°C, respectively (See Figure 27).

For scenario 2, the auxiliary ventilation system consists of two 1.2m diameter steel ducts installed along the access drift and throughout the production stopes. In this case, the fresh air is delivered along the access drift, and contaminated air from the production stopes is drawn into the ducts and directed along the access drift, and the haulage drift into the mine’s exhaust system. It should be mentioned that in this case, the heat added by the
auxiliary fans is not transferred to the mine air in the production stopes, as it is directed into the mine’s exhaust system via the haulage drift (see Figure 28). For scenario 3, the contaminated air from the production stopes is directed to the level above and into the mine’s exhaust system along two 2.0m diameter ventilation raises (see Figure 29).

Ventilation simulations show that in case of series ventilation with fans in forcing arrangement (scenario 1), due to the heat added by the mining equipment and the auxiliary fans, the highest wet-bulb temperature occurs in the access drift within the vicinity of the remuck bays. At this location, the wet-bulb temperature is 29.4°C, which is just above the allowed threshold limit value (TLV) of 29.0°C (see Figure 27). In case of series ventilation with fans in exhausting arrangement (scenario 2), the wet-bulb temperature at the remuck bays decreases from 29.4°C to 23.5°C, which is well below the threshold limit value of 29°C. With through-flow ventilation (scenario 3), the wet-bulb temperature of the ventilating air at the remuck bays is 23.4°C, which is again well below the TLV of 29°C.

Figure 26: Series ventilation with forcing fan arrangement (scenario 1)
Ventilation simulations show that by changing the fan arrangement from forcing to exhausting, appropriate climatic conditions can be achieved in the production area and along the access drift, as the sensible and latent heat generated by the fans and mining equipment is not transferred to the ventilating air. In addition, for health and safety
purposes, the through-flow ventilation arrangement is the most attractive scenario, as besides heat, diesel particulate matter (DPM) generated by the LHDs and the haul truck is directed to the level above and into the mine’s exhaust system along the 2.0 m diameter ventilation raises.

For mining zones where the temperature conditions are extremely high, a solution would be to use remote mining, in which the operators are on the surface performing the job. Leeville mine, operated by Newmont Mining Corporation, is already applying remote mining by using loaders that are remotely operated on the surface. At this point, the system has a capacity of three (3) working stations, and in each station, an operator could run two loaders.

An exercise using the workflow was performed on the three (3) auxiliary ventilation scenarios previously described. For this exercise, the selected design criteria was the wet-bulb temperature with the threshold limit value (TLV) of 29°C. For scenario 1 (series ventilation with fans in forcing arrangement system), the wet-bulb temperature at the access drift is 29.4°C (±0.10°C). Therefore, according to the workflow, a cooling system must be implemented since the temperature at the access drift is higher than the design reject temperature of \( T_w = 29°C \). This is mainly due to the heat added by the mining equipment (LHDs and haul truck) and the auxiliary fans. Thus, it can be assumed that the primary heat source is due to mechanization, and the secondary heat source is due to the auxiliary fans. The workflow recommends placement of a bulk air cooling system (conventional) at the surface plus a spot cooling unit in the production area.

For scenario 2 (series ventilation with fan in exhausting arrangement system), the wet-bulb temperature at the access drift is 23.5°C, which is well below the TLV. According
to the workflow, the working area is in compliance with the recommendations regarding heat exposure. This is also the case for scenario 3 (throw-flow ventilation with forcing fan arrangement) as the wet bulb temperature at access drift is 23.4°C.

4.3 The Importance of the Thermal Flywheel Effect when Sizing a Cooling System

The thermal flywheel effect and the thermal damping effect are important elements in mine ventilation and underground environment control, which can significantly affect the climatic conditions in deep underground mines. When air descends an intake shaft, its lining and the surrounding strata will emit heat during the night when the incoming air is cool and, on the contrary, absorb heat during the day if the air temperature becomes greater than that of the strata temperature. The depth of the intake shaft where heat flow reverses varies by season (to some extent even daily), firstly due to the initial starting conditions of the air ($T_d$, $T_w$, $BP$), and secondly, due to the rock surface temperature and its geothermal gradient. The change of the phase angle of the periodic, harmonic and temperature variation is known to be the thermal flywheel effect (TFE). For example, during summer, as heat from the intake air is transferred to the cooler strata, the temperature at the bottom of the intake shaft can be approximately 8 °C to 10 °C lower of what a climatic simulator with no ability to account for the thermal flywheel effect would predict. This difference in the dry-bulb temperature of the mine air could lead to a significant overdesign in the capacity of the cooling system, which in some cases would show the project as unfeasible.

The effect of surface temperatures and auto-compression play a major role in the design of mine comfort, ventilation and refrigeration strategies. A comparison of two ventilation software packages, Ventsim and Climsim, were conducted for mine A. The goal
of this software comparison was to display the effects of the thermal flywheel in an underground mine. Ventsim has the capability to predict the thermal flywheel effect and the thermal damping effect, while Climsim does not. The Ventsim model used for simulation and analysis is the most current model for MINE A. Therefore, the model displays validated parameters for ventilation and climatic simulations.

4.3.1 Ventsim Modeling

To model the thermal flywheel and thermal damping effect in Ventsim, the annual flywheel heat selection mode was used. Table 10 shows the parameters used for the thermal flywheel calculation. Many of the parameters used were predetermined when the model was provided for our use. The modeling work was completed for one of the mine’s intake production shaft. The values for ‘automatic variance,’ ‘dry bulb maximum’, ‘dry bulb minimum’, ‘wet bulb maximum’, and ‘wet bulb minimum’ are not used in the calculation for annual flywheel, as they are only used for daily flywheel calculations. The selection of ‘summer dry bulb’ and ‘summer wet bulb’ were selected based on the average temperature for the summer (June, July and August) taken from The National Weather Service Forecast Office. The warmest month from the data showed the warmest month as August, which is why it was selected. The selection of ‘winter dry bulb’ and ‘winter wet bulb’ were selected based on the average temperature for the winter (December, January and February) also taken from The National Weather Service Forecast Office.
Table 10: Thermal Flywheel Parameters for Mine A

<table>
<thead>
<tr>
<th>Thermal Flywheel</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>[RESET]</td>
<td>No</td>
</tr>
<tr>
<td>Automatic Variance</td>
<td>30.00 °F</td>
</tr>
<tr>
<td>Copy Standard Heat</td>
<td>No</td>
</tr>
<tr>
<td>Diurnal Cycle Time Hours</td>
<td>24</td>
</tr>
<tr>
<td>Dry Bulb Maximum</td>
<td>80.0 °F</td>
</tr>
<tr>
<td>Dry Bulb Minimum</td>
<td>50.0 °F</td>
</tr>
<tr>
<td>Summer Dry Bulb</td>
<td>71.0 °F</td>
</tr>
<tr>
<td>Summer Wet Bulb</td>
<td>53.6 °F</td>
</tr>
<tr>
<td>Warmest Month</td>
<td>August</td>
</tr>
<tr>
<td>Wet Bulb Maximum</td>
<td>77.0 °F</td>
</tr>
<tr>
<td>Wet Bulb Minimum</td>
<td>40.6 °F</td>
</tr>
<tr>
<td>Winter Dry Bulb</td>
<td>30.8 °F</td>
</tr>
<tr>
<td>Winter Wet Bulb</td>
<td>27.6 °F</td>
</tr>
</tbody>
</table>

Figure 29 shows the results of the thermal flywheel modeling. The solid red and blue lines shown in Figure 29 are the Airway Dry Bulb Temperature and Airway Wet Bulb Temperatures, respectively. The dashed red and blue lines are the Atmospheric Dry Bulb and the Atmospheric Wet Bulb, respectively. Through the model output data, the effects of thermal damping (decrease in amplitude) are present but the effect of the thermal flywheel (phase shift) is not present. This indicates that thermal flywheel is basically equal to thermal damping at relatively shallow depths such as in this case. The vertical length of the shaft is approximately 539 meters.
4.3.2 Climsim Modeling

In order to show the importance of analyzing the thermal flywheel effect, Ventsim and Climsim were utilized for comparing the climatic data (dry-bulb and wet-bulb temperatures) at the top and bottom of the shaft. Again, Climsim does not have the capability to show the effects of thermal flywheel or thermal damping. Two seasons were considered for the comparison of the thermal flywheel effect, namely summer and winter seasons. Table 11 shows parameter inputs of the Climsim modeling for MINE A.

Table 11: Input Parameters for MINE A

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (kPa)</td>
<td>101.60</td>
</tr>
<tr>
<td>Quantity (m$^3$/s)</td>
<td>261.00</td>
</tr>
<tr>
<td>Length (m)</td>
<td>539.00</td>
</tr>
<tr>
<td>Area (m$^2$)</td>
<td>23.60</td>
</tr>
<tr>
<td>Perimeter (m)</td>
<td>17.24</td>
</tr>
<tr>
<td>Friction (kg/m$^3$)</td>
<td>0.0417</td>
</tr>
<tr>
<td>Wetness</td>
<td>0.50</td>
</tr>
<tr>
<td>VRT In (°C)</td>
<td>10.00</td>
</tr>
<tr>
<td>Geothermal Step (m/°C)</td>
<td>16.00</td>
</tr>
<tr>
<td>Conductivity (W/m.°C)</td>
<td>4.00</td>
</tr>
<tr>
<td>Diffusivity (m$^2$/s x 10$^{-6}$)</td>
<td>1.75</td>
</tr>
</tbody>
</table>
Tables 12 and 13 show the results of the Climsim modeling. During summer, the dry-bulb and wet-bulb temperature at the bottom of the intake shaft are 33.81 °C and 29.10 °C, respectively. While during winter, the dry-bulb and wet-bulb temperature at the bottom of the shaft are 31.44 °C and 28.10 °C, respectively.

Table 12: Results for MINE A - Summer:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Top</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry-Bulb (°C)</td>
<td>21.70</td>
<td>33.81</td>
</tr>
<tr>
<td>Wet-Bulb (°C)</td>
<td>12.00</td>
<td>29.10</td>
</tr>
<tr>
<td>Humidity (%)</td>
<td>29.23</td>
<td>70.25</td>
</tr>
<tr>
<td>Enthalpy (kJ/kg)</td>
<td>33.70</td>
<td>91.60</td>
</tr>
<tr>
<td>Sigma Heat (KJ/kg)</td>
<td>33.47</td>
<td>88.86</td>
</tr>
<tr>
<td>VRT (°C)</td>
<td>10.00</td>
<td>43.70</td>
</tr>
<tr>
<td>Strata - Latent heat (kW)</td>
<td>0.00</td>
<td>13,429.79</td>
</tr>
<tr>
<td>Strata - Sensible heat (kW)</td>
<td>0.00</td>
<td>2,234.90</td>
</tr>
</tbody>
</table>

Table 13: Results for MINE A - Winter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Top</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry-Bulb (°C)</td>
<td>0.00</td>
<td>31.44</td>
</tr>
<tr>
<td>Wet-Bulb (°C)</td>
<td>0.00</td>
<td>28.10</td>
</tr>
<tr>
<td>Humidity (%)</td>
<td>100.00</td>
<td>77.49</td>
</tr>
<tr>
<td>Enthalpy (kJ/kg)</td>
<td>9.41</td>
<td>87.08</td>
</tr>
<tr>
<td>Sigma Heat (KJ/kg)</td>
<td>9.41</td>
<td>84.53</td>
</tr>
<tr>
<td>VRT (°C)</td>
<td>10.00</td>
<td>43.70</td>
</tr>
<tr>
<td>Strata - Latent heat (kW)</td>
<td>0.00</td>
<td>14,623.03</td>
</tr>
<tr>
<td>Strata - Sensible heat (kW)</td>
<td>0.00</td>
<td>9,030.96</td>
</tr>
</tbody>
</table>

4.3.3 Ventsim and Climsim Comparison

The results for the modeling in Climsim and Ventsim are shown in Table 14. The values are comparing the wet and dry-bulb temperatures at the top and bottom of the shaft based on model simulation results.
Table 14 shows that the values predicted by Climsim are significantly different from the Ventsim values, which is attributed to the effects of the thermal flywheel effect. During summer, the difference between the dry-bulb temperature at bottom of the shaft and the dry-bulb temperature at the top of the shaft predicted by Climsim is approximately 12°C, while Ventsim estimated a difference of approximately -4.6°C. The negative value means that the temperature at the bottom will be lower than the ambient temperature at the top of the shaft, as heat is transferred to strata. During winter, the difference between the temperature at the bottom of the shaft and the dry-bulb temperature of surface predicted by Climsim is approximately 31.44°C, while Ventsim estimated a difference of only 5.50°C.

This large discrepancy between Ventsim and Climsim results is due to the thermal flywheel effect. During summer, the temperature of the ventilating air has high values due to both the high surface temperature and to the heat added by auto-compression. Because of the difference in the air temperature and strata, heat flows from the ventilating air to the strata and, consequently, the temperature of the ventilating air decreases as it downcasts the shaft. In the winter, heat stored in the strata is released back into the ventilating air since the temperature of the strata is higher than the temperature of the ventilating air. Thus, the temperature of the ventilating air increases as it flows down the shaft. However, at certain
depth, due to the geothermal gradient the temperature of the strata becomes higher than the temperature of the ventilating air. As a result, heat will flow from the ventilating air to the strata. Contrary to Ventsim, Climsim does not consider the change, at a certain depth, in the direction of the heat flux.

If the mine’s cooling system design were based on Climsim climatic parameters, the cooling system would be significantly overdesigned resulting in large capital and operating costs. Therefore, the thermal flywheel effect must be taken into account when designing and sizing a cooling system.

5 Conclusions and Future Work

5.1 Conclusions

As the mine deepens, a different approach might be needed to reduce the ventilating air temperature, therefore, coping with heat in underground mines. The conclusions that can be drawn for the work presented are summarized as follow:

- Exposure to elevated levels heat and humidity, can significantly affect health & safety, and productivity in underground mines.
- Developed a workflow, which can be used by the mine operators to select the most effective cooling method & system based not solely on depth, but on the mines’ site-specific characteristics. The workflow can also determine whether ventilation alone would be sufficient to provide adequate work conditions, or a cooling system is needed.
- Many times, the climatic conditions in the production areas can be improved by simply redesigning the auxiliary ventilation system - Very cost effective. For health and safety purposes, the through-flow ventilation arrangement is the most attractive
scenario, as heat and diesel particulate matter (DPM) generated by the LHDs and the haul truck is directed to the level above and into the mine’s exhaust system along the return air raises (RAR).

- Selecting surface bulk air cooling vs. U/G bulk air cooling depends on the depth of the mine and the distance of production stopes from the intake shaft
- Selecting localized air cooling vs. bulk air cooling depends on the level of mechanization, type of mining equipment (e.g. diesels), and strata heat.
- Selecting ultra-chilled water as cooling agent can be effective, while environmental friendly.
- It is important to take into account the thermal flywheel effect when designing and sizing cooling and refrigeration systems for underground mines in order to avoid additional capital and operating costs.

5.2 Future Work

Research focusing on renewable energy systems has being performed to reduce the overall cost of a mechanical cooling system.

The first alternative to be analyzed is a novel system designed to store coolth during the winter months and be used when needed. To achieve this goal a concrete storage reservoir using propylene glycol as the cooling storage liquid refrigerant would be excavated in bedrock. As cold ambient air circulates around galvanized steel tanks at the reservoir coolth is stored and as the seasons change the tanks will be insulated to preserve cooling potential. The location of the reservoir and its design can be seen in figure 24. As the temperature of the air increases, during summer time, the air would reduce its
temperature by circulating through the reservoir and exchanging heat with the coolant, propylene glycol. (Fox & Kocsis, 2019).

![Figure 30: Air-cooled Refrigerant Reservoir Storage](source)

Source: Fox & Kocsis (2019)

Usually, fresh air is supplied through a decline tunnel, named as plenum, which intersects the shaft at about 50-70 meters below the shaft collar. The location of the reservoir regarding the plenum is shown in Figure 25.
Ground Source Heat Pumps (GSHP) is being analyzed to supplement energy to the existing cooling/heating systems. Geothermal systems are also being investigated as the main energy source for cooling underground mines, in case of substantial sources of geothermal energy is present. The advantages of these systems are that they are renewable and, therefore, it mitigates carbon emissions. The implementation of these systems is advantageous in locations with anomalous geothermal energy such as the state of Nevada.

Geothermal temperatures are divided into high (>220°C) and low (<220°C) temperatures. The former could be applied for commercial production of electricity while the latter does not have the same capability. However, since the low-temperature reservoir is able to recover heat having temperatures as low as 70°C, which makes it attractive as temperature as high as 220°C is not likely to happen. The way that a temperature-reservoir can harness heat is through the employment of a binary cycle plant, which used either an
organic (Organic Rankine Cycle (ORC) or an ammonia-water mixture (Kalina cycle). Although the ORC cycle has low efficiency, it can be applied at a mine site to supplement electricity for spot cooling units and/or for a battery charging station for any battery-powered equipment present at the mine.

The usage of GSHP is due to the relatively constant temperature of the ground at depths below the frost line. During summer, the ground temperature is cooler than the air and in winter, the opposite happens, the ground is warmer than the air. Therefore, the ground works as a heat source or a sink depending on the season. Its application is established for residencies, and it has not been considered in the mining industry. One type of GSHP that could be applied is the Ground-coupled heat pumps (GCHP), which uses the ground as heat source or sink. The heat exchanger in this type can be as a refrigerant-to-water heat or as direct-expansion (DX). The former will have a water or antifreeze solution pumped through vertical, horizontal, or coiled pipes placed on the ground. The latter uses a refrigerant in direct-expansion. (Sarbu & Sebarchievici, 2014, as cited in Scalise, Teixeira, Kocsis, & Robertson, 2019). Figure 26 shows horizontal and vertical GCHP.

![Figure 32: a) Horizontal heat exchanger; b) Vertical heat exchanger](image-url)
References


