University of Nevada, Reno

Managing and Controlling the Thermal Environment in Underground Metal Mines

A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Geo-Engineering

By

Pedram Roghanchi

Karoly (Charles) Kocsis/Dissertation Advisor

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We recommend that the dissertation
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PEDRAM ROGHANCHI

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Dr. Karoly (Charles) Kocsis, Advisor

Dr. Danny Taylor, Committee Member

Dr. Javad Sattarvand, Committee Member

Dr. Behrooz Abbasi, Committee Member

Dr. Ronald Breitmeyer, Committee Member

Dr. Hanif Livani, Graduate School Representative

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

August, 2017

Abstract

The main aim of this research work was to discuss the methods of identifying and control heat in underground mine environments. The research contains three main sections as follow:

1. Selecting an appropriate heat stress index for underground mining application

Methods: The aim of this research study was to discuss the challenges in identifying and selecting an appropriate heat stress index for thermal planning and management purposes in underground mines. A method was proposed coupled to a defined strategy for selecting and recommending heat stress indices to be used in underground metal mines in the US and worldwide based on a thermal comfort model.

Results: The performance of current heat stress indices used in underground mines varies based on the climatic conditions and the level of activities. Therefore, by carefully selecting or establishing an appropriate heat stress index is of paramount importance to ensure the safety, health and increasing productivity of the underground workers.

Conclusions: This method presents an important tool to assess and select the most appropriate index for certain climatic conditions in order to protect the underground workers from heat related illnesses. Although complex, the method presents results that are easy to interpret and understand than any of the currently available evaluation methods.

2. Best practices in use of continuous climatic monitoring systems for assessment of underground mine climatic condition:

Methods: Major heat sources in an underground metal mine in Nevada was quantified using over one year of climatic data collection in both primary and auxiliary ventilation systems.

Furthermore, auxiliary ventilation systems were examined in a development heading and a production area at our partner mine. Climatic models were developed and validated to simulate the climatic conditions based on intake airflow conditions and the heat load along the ducting system. Considerations were also given to the fact that arsenic concentrations may be present at the face. Different scenarios were studied to design and optimize the auxiliary ventilation systems in order to minimize the heat generated by multiple auxiliary fans and minimize arsenic concentration in the production workings.

Results: The results show that the heat generated by different major heat sources can change throughout the mine as a function of surface temperature. Furthermore, current auxiliary ventilation design cannot maintain the comfort limits of the underground workers. In some cases, some type of cooling system must be utilized to retain the thermal comfort in production workings.

Conclusions: In many instances, by simply adjusting or upgrading the auxiliary ventilation system in a problem area of a mine will effectively dilute the pollutants that are generated during production operations and provide adequate climatic conditions to the mine workers. This can be achieved through various methods such as: (1) extending the auxiliary duct towards the face, (2) installing an additional auxiliary fan to overcome the added pressure losses in the system, (3) changing the size of the fan, (4) switching from an "exhausting" arrangement to a "forcing" arrangement, and (5) installing an "overlap" auxiliary ventilation system.

3. Quantifying the thermal damping effect in underground vertical openings using artificial neural network:

Method: A nonlinear autoregressive time series with external input (NARX) algorithm was used as a novel method to predict the dry-bulb temperature (Td) at the bottom of the shaft as a function of surface air temperature. Furthermore, an attempt was made to quantify typical "damping coefficient" for both production and ventilation shafts through simple linear regression models.

Results: The performance of the model was examined using climatic data collected at two underground mines during summer and winter. Analyses demonstrated that the artificial neural network (ANN) model could accurately predict the temperature at the bottom of a shaft. Comparisons between the collected climatic data and the regression-based predictions show that a simple linear regression model provides an acceptable prediction of the T_d at the bottom of intake shafts. The same approach can be used to predict the thermal damping effect on the wet-bulb temperature (Tw) at the bottom of production and ventilation shafts.

Conclusions: A comparison between collected data and the climatic modeling demonstrates that the ventilation or climatic modeling software packages do not have the ability take into account the "thermal damping effect (TDE)" (also known as thermal flywheel effect) when modeling the thermal environment in deep and hot underground mines. The major difficulty in incorporating TDE comes from a large number of variables interacting with each other plus the time-dependent heat and mass transport processes that control the flow of strata heat into/from the mine airways.

Dedication

This thesis is dedicated to my parents, who gave me the greatest support throughout my life and education.

Acknowledgement

I would like to express my sincerest gratitude to those who have helped me to complete my degree. I would like to thank Dr. Karoly (Charles) Kocsis, my Ph.D. advisor for offering research work and his invaluable guidance, encouragement, valuable suggestions and support through these years.

I would like to thank the committee members, Dr. Karoly (Charles) Kocsis, Dr. Danny Taylor, Dr. javad Sattarvand, Dr. Behrooz Abbasi, Dr. Ronald Breitmeyer, Dr. Robert Watters, and Dr. Hanif Livani for their support in completing this work.

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Chapter 1 Introduction

1.1. Background

Mining in the USA remains one of the most hazardous industries, despite significant reductions in fatal injuries over the last century *(Coleman & Kerkering, 2007; Saleh et al., 2011; Jacklitsch et al., 2016)*. Occupational health hazards within the mining industry include physical (e.g. traumatic injuries, hearing loss), chemical (e.g. silica, diesel particular matter), biological, ergonomics, as well as psychological hazards *(Donoghue, 2004; Saleh et al., 2011)*. The effects of some of these hazards can be diagnosed immediately, while many will have long term effects on the health, safety, and the life quality of the mine workers (e.g. black-lung, and silicosis) *(Donoghue, 2004; NIOSH, 2000)*.

As the increasingly mechanized underground mines in the US become deeper, the issue of heat becomes a significant problem. Hot and humid environments can seriously affect the performance, overall productivity and most importantly the ability of the underground workforce to perform work in a safe manner. Assessment of the thermal environment is becoming more important due to significant effects of excessive heat on safety and health of the underground miners. These effects on individuals can be from thermal discomfort to heat-related illnesses such as thermal stress, heat cramps, heat rash, and heat stroke *(Brake & Bates, 2002; Sheer et al., 2001)*. The main sources of heat in underground metal mines include auto-compression as air descends through vertical openings, strata heat (geothermic gradient), machinery, mine water influx, explosive detonations, friction between falling rock, human metabolism, pipelines and oxidation *(Brake & Bates, 2002; Kocsis & Hardcastle, 2010; Carpenter et al., 2015)*. In deep and hot mines, the removal of

this heat is a top priority for the mine operators as mine workers are at risk for heat-related illnesses and injuries *(Donoghue, 2004)*. It is imperative that the underground mine climatic conditions remain safe for human presence, as mine workers actively work in this environment. The hot and humid environment also has a negative impact on the efficiency of the underground workforce which may result in production decline *(Xiaojie et al., 2011)*.

1.2. Significance of Heat Problems in Underground Mines

There is well established mechanism which controls the temperature of a human body to maintain thermal equilibrium when exposed to heat stresses. However, if the heat stress exceeds a certain level, this mechanism is no longer able to fully remove the metabolic heat. In situations when the human body is unable to effectively promote heat transfer to the ambient surroundings, the risk of heat stress related illnesses and injuries can drastically increase *(Donoghue, 2004; Xiang et al., 2014; Roghanchi et al., 2015)*.

The magnitude of heat which is stored in the human body is given by the metabolic heat minus the algebraic sum of the heat flows between the human body and its immediate environment. Considering steady states, the heat storage (S) is often considered as zero in order to assure comfort for a worker. The thermal interaction of the human body with the environment can be written, as follows *(ISO 7933, 2005)*:

$$S = M - (C + R + B + E + K + W) \ (W/m^2) \qquad\qquad Eq. \ 1.1$$

The human body is basically a biological "heat engine" of low mechanical efficiency. Within the human body, through chemical reactions, nutrients combine with oxygen to produce: (1) metabolic heat, and (2) mechanical work. The mechanical work output is seldom more than 20% of the total metabolic energy even for vigorous activities, and it is

taken into account when work is performed against gravity. The metabolic energy, which

is proportional to the oxygen consumption can be defined as:

Metabolic energy = Metabolic heat + Work performed against gravity

If the human body is to remain in thermal equilibrium, then the metabolic heat (M) must

be transferred to the surrounding environment at the same rate. Heat transfer from the

human body to the ambient surroundings can occur through a combination of various

heat transfer processes such as: (1) respiratory heat exchange, (2) convection, (3)

radiation, and Evaporation. At "thermal equilibrium", the rate of heat storage is basically

zero *(Shapiro & Epstein, 1984; King, 2004; Epstein & Moran, 2006)*. Physical fitness,

hydration state, gender, anthropometric data, age, history of heat illnesses,

acclimatization, drug use, alcohol consumption, hypertension, and body size are some of

the important parameters that affect the individual response to heat exposure *(ACGIH,*

2014; Jacklitsch et al., 2016). Table 1.1 shows different comfort sensations based on the

total heat stored in the human body.

Table 1.1. Five thermal effect zones associated with thermal comfort and sensation *(Fanger, 1970)*

Thermal Sensation	Zone of Thermal Effect	Comfort Sensation	Total Heat Storage (S)
Very hot	(1) In-compensable heat zone	Very uncomfortable	$S \gg 0$
Hot	(2) Sweat evaporation compensable zone	Uncomfortable	$S \approx 0$
Warm		Slightly uncomfortable	
Slightly warm	(3) Vasomotor compensable zone	Comfortable	$S = 0$
Neutral			
Slightly cool			
Cool	(4) Shivering compensable zone	Slightly uncomfortable	$S \approx 0$
Cold		Uncomfortable	
Very Cold	(5) In-compensable cold zone	Very uncomfortable	$S \ll 0$

Physical fitness, hydration state, gender, anthropometric data, age, history of heat illness, acclimatization, drug use (prescription and narcotic), alcohol consumption, hypertension, and body size are of the relevant parameters that affect the individual response to heat exposure *(NIOSH, 2000; ACGIH, 2014)*.

1.3. Objectives

The main goals of this research work were as follow:

1. *Assessment of the presence of issues as well as safety and health concerns in deep and hot mines in the US*

> <u>Task 1.</u> Literature review of heat issues in underground mines, identifying the problem areas, and methods of control heat in underground environment

2. *Challenges in identifying appropriate heat stress indices to be used in underground mine*

> <u>Task 1.</u> Understanding human thermal balance and comfort limit
>
> <u>Task 2.</u> Comparison between heat stress indices based on Pierce Two-node model
>
> <u>Task 3.</u> Development of new selection criteria for mine planning phase and operation phase
>
> <u>Task 4.</u> Recommend heat stress indices for thermal comfort assessment of underground workers based on various metabolic rate

3. *Optimizing auxiliary ventilation system to improve the climatic condition in development and production workings*

> <u>Task 1.</u> Best practices for design and use of climatic monitoring systems in hot US mines
>
> <u>Task 2.</u> Identifying the optimum airflow velocity for thermal comfort
>
> <u>Task 3.</u> Application of mean skin temperature as a heat stress index

Task 4. Case studies in optimizing auxiliary ventilation system to reduce heat load in developments and production workings

4. Identifying and quantifying the thermal damping effect in underground vertical openings

Task 1. Identifying the thermal damping effect based on over a year of data collection at two underground gold mines in Nevada

Task 2. Quantifying the thermal damping effect using artificial neural network model

Task 3. Developing the thermal damping coefficients for production and ventilation shafts

1.4. Dissertation structure

This dissertation is organized in seven chapters as follow:

Chapter 1. Introduction

Chapter 2. Controlling Heat Induced Health and Safety Problems in Underground Mines: This chapter aimed to discuss major heat-related issues and provide an overview of various mine ventilation and cooling systems, which can be employed to overcome high levels of heat and humidity in underground mines. In this chapter, the effects of heat exposure on the health, safety, and productivity of the mine workers are also highlighted.

Chapter 3. Challenges in Selecting an Appropriate Heat Stress Index to Protect the Workers in Hot and Humid Underground Mines: This chapter discussed the challenges in identifying and selecting an appropriate heat stress index for thermal planning and management purposes in underground mines. A method is proposed coupled to a defined strategy for selecting and recommending heat stress indices to be used in underground metal mines in the US and worldwide based on a thermal comfort model.

Chapter 4. Evaluation of the Atmospheric and Underground Environmental Conditions by Means of Continuous Climatic Monitoring Systems – Lessons Learned: This chapter aimed to highlight the lessons learned from the climatic monitoring programs, which were conducted over two years at two underground metal mines in Nevada. The monitoring program for both primary and auxiliary ventilation systems was discussed. The practices and challenges in using continuous climatic monitoring systems in deep and hot metal mines were highlighted.

Chapter 5 & 6. Improving the climatic conditions in development and production workings of hot underground mines by re-designing the auxiliary ventilation system - Case study # 1 & # 2: In these chapters, auxiliary ventilation systems in a development and a production area were re-designed to minimize the heat load at these locations. Different scenarios were studied to find the optimum ventilation system along with a cooling system to maintain the thermal comfort at the development and production areas.

Chapter 7. Quantifying the Thermal Damping Effect in Underground Vertical Shafts using the Nonlinear Autoregressive with External Input (NARX) Algorithm: The objective of this chapter was to quantify the thermal damping effect in vertical underground airways. A nonlinear autoregressive time series with external input (NARX) algorithm was used as a novel method to predict the dry-bulb temperature (T_d) at the bottom of the shaft as a function of surface air temperature. The performance of the model was examined using climatic data collected at two underground mines during summer and winter.

Chapter 8. Conclusions and future works.

Chapter 2 - Controlling Heat Induced Health and Safety Problems in Underground Mines

2.1. Introduction

Among the mining hazards, exposure to heat and humidity can significantly affect the safety, health, and the productivity of the mine workers particularly in deep and hot underground mines *(Roghanchi et al., 2015)*. Short-term acute heat exposures can cause a rise in the core temperature of the human body, which can result in a heat-related illness or a combination of heat-related illnesses. Adverse long-term chronic heat exposures can generate serious occupational heat-related illnesses such as cardiovascular diseases, mental health problems, and chronic kidney diseases. High core body temperatures coupled with dehydration can also generate negative behavioral effects such as physical fatigue, irritability, lethargy, impaired judgment, loss of dexterity, and loss of concentration *(Zhang, 2003; Zhang et al., 2010; Xiang et al., 2014)*.

2.3. Heat Sources in Underground Mines

The rising demand for minerals has driven the underground mines to extract ore reserves from increasingly deeper levels, and also steered the mines to increase the level of mechanization year after year. As a result, the underground mine environment has become more extreme, as temperature and humidity levels continued to rise due to an increase in the size and number of diesel engine powered mining equipment and other sources of heat. The major heat sources in underground mines are: (1) strata heat (geothermal gradient), (2) auto-compression, and (3) mining equipment.

2.3.1. Strata heat

The main difficulty in quantifying the heat that is transferred from the strata (or vice versa) to the mine air is the large number of ventilation, geological and mine design variables, which are often interacting with each other to control the flow of heat from strata. These parameters include the length and geometry of the mine openings, the depth below surface, wetness of the mine openings, roughness of the airways, volume of air, the virgin rock temperature, inlet air parameters, the thermal properties of the rock formations, etc. When cool air passes through a horizontal airway, its temperature usually increases. This is caused by the natural geothermal heat being conducted through the rock formations towards the airway, then passing through the boundary layers of the mine air close to the rock surface. The envelope of the rock immediately surrounding the newly driven airway will rapidly cool at first, and there will accordingly be a relative high rate of initial heat release into the mine air. This will decline in time and as the rock surface gradually cools approaching an equilibrium state when its temperature equals that of the air *(McPherson, 2009)*.

Despite the fact that the air temperature along the main airways rises and falls as a function of the surface climate, the temperature in the main returns can remain relatively constant. This is because cool air will promote heat flow from the rock formations. As the temperature of the air approaches the natural temperature of the rock, such heat transfer will gradually diminish. Furthermore, when the ventilating air leaves a highly mechanized production area, its temperature can be greater than the local strata temperature. In this case, heat will be transferred from the ventilating air into the rock formations. The air will

start cooling until an equilibrium state is again formed, when the temperature of the mine air equals that of the strata.

2.3.2. Auto-compression

When air descends through a vertical opening (e.g. shaft) some of its potential energy is converted into enthalpy, which produces an increase in pressure, internal energy and as a result, temperature *(Danko, 2013)*. The rise in air temperature as air descends a vertical airway is independent of any frictional effects. The heat added from strata to the ventilating air can be positive or negative, but the increase in temperature due to an elevation difference is certain for any vertical airway. The effects of auto-compression are also independent of the amount of air. In deep mines, as a result of auto-compression, the intake air leaving the bottom of the shaft may already be at temperatures that necessitates some form of cooling *(kocsis and Hardcastle, 2010)*. Despite the fact that there may be a significant rise in air temperature along intake airways, the most noticeable increases may occur in the production workings. This is because, firstly, the newly exposed and warm surface of the broken ore/rock will transfer its heat to the ventilating air and, secondly, the diesel engine powered mining equipment that is concentrated in the production area can generate a considerable amount of heat *(Roghanchi et al., 2017)*.

2.3.3. Mining equipment

Increasing mechanization made the mining equipment to join the strata and auto-compression as an added major source of heat in underground mines. Production equipment and service vehicles as well as well as transformers and fans are all devices that convert an input power, via a useful effect into heat. For any given mining equipment, the total heat produced is simply the rate at which power is supplied, less any work done

against gravity *(Danko, 2013)*. The internal combustion engines of diesel equipment have an overall efficiency of only one-third of that achieved by electrical units. Hence, diesels will produce approximately three times as much heat as electrical equipment for the same mechanical work output. One-third of this heat is generated by the diesel equipment radiator and its body, one-third appears as heat in the exhaust gases. The remaining heat is generated by the frictional processes as the machine performs its tasks *(Sunkpal, 2015)*. A significant difference between diesel and electrical equipment is that diesels produce part of their heat output in the form of latent heat. Each liter of diesel fuel is consumed produces approximately 1.1 liter of water in the exhaust gases *(Sunkpal, 2015)*. This may be multiplied several times due to the evaporation of water from the cooling systems and where water is employed in emission control systems.

2.4. The Effect of Heat Exposure on the Underground Worker's State of Health, Safety, and Productivity

Performing work in a hot and humid environment can alter the thermoregulation process of a mine worker, which can induce a heat related illness or a combination of heat related illnesses. Table 1.2 summarizes the heat related illnesses, causes, symptoms, as well as the required treatment to re-establish thermal balance. Heat stroke and heat exhaustion are two of the most frequent illnesses that are caused by work performed in a sub-standard environment. Heat stroke is a serious illnesses, which carries a high risk of fatality if the worker is not immediately treated and the climatic conditions are not corrected. Heat exhaustion, which preludes heat stroke, is caused when the thermoregulation system of a mine worker is unable to transfer the metabolic heat generated through various activities to the ambient surroundings at the rate at which is produced. To prevent these conditions,

the wet-bulb temperature of the working area is recommended to be reduced to below 29°C in order to reduce the risk of heat exhaustion and heat stroke *(Donoghue, 2004)*.

Brake and Bates *(2002)* provide a list and highlight the major factors that can influence heat stress levels among the mine workers in hot and humid environments in order to decrease the risk of heat exhaustion as well as heat stroke. Among these factors, cardiovascular fitness is absolutely essential in promoting good circulation by which oxygen from the lungs is delivered to the vital organs. Acclimatization, hydration, the level of activity (e.g. metabolic rate), and the type of clothing worn are also important factors to promote and manage heat exchange between the mine workers and the ambient surroundings.

The consequences of exposure to heat and humidity has an accumulating growth effect on the health and safety of mine workers. The longer the workers are exposed to heat, the more their core body temperature tends to increase away from an acquired comfort level *(Handcock, 1999)*. In this state, heat storage in the body accumulates over time and the heat stress level increases. This can make heat a silent and dangerous health hazard, as its effects are often not exposed until life threatening health conditions develop. The ability of the human body to adjust to changing climatic conditions is the cause of this imminent danger. In this case, an immediate effect can be physical fatigue, impaired judgment, and disinterest in the assigned tasks. In the case of vigorous physical work, the rise of body temperature is much more rapid and begins at a much lower heat load level, which will cause the workers to encounter the dangerous effects of heat within shorter exposure times. Figure 2.1 shows the effects of heat stress as a function of exposure time.

Another noticeable effect of high temperature and humidity conditions is reluctance and/or inability of a mine worker to perform active muscular work. This often begins as a mere inertness, supplemented by sleepiness. This effect may initially be resisted and passed off as a genuine condition of fatigue, which can ultimately lead into heat exhaustion and heat stroke *(Haldane, 1905)*. Several studies have shown that a worker is much less efficient in a warm and humid climate, due to the fact that in such conditions the natural tendency of its nervous system is to become less active and for muscular work to diminish *(Britain & Samuel, 1907)*.
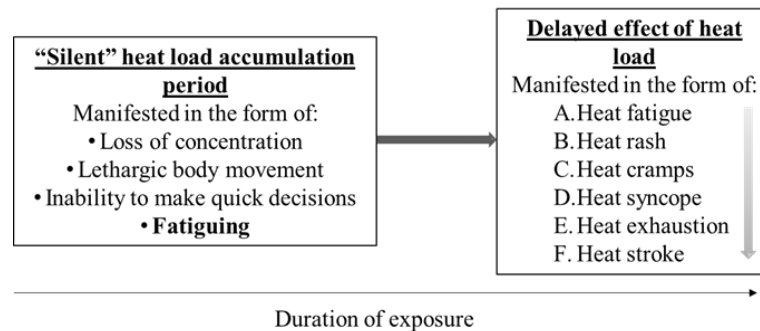
Figure 2.1. Illustration of the effects of heat stress over time

2.5. Assessing the thermal comfort in deep underground mines

An evaluation of "*thermal comfort*" must start with the recognition that comfort is basically a state of mind *(Fanger, 1970)*. The estimation of comfort requires a scientific model to establish a correlation between one or more climatic factors and determine the resulting comfort sensation that would be experienced by an individual in a specific environment. As various individuals has shown unreliable results during different thermoregulation tests, such an association is rather difficult to be determined experimentally. Consequently, most-

Table 2.1. Heat-related illnesses in underground mines *(Brake & Bates, 2002; Donoghue 2004; Jacklitsch et al., 2016)*

Heat Illness	Cause	Symptoms	Treatment
Heat rash	An individual develops heat rash when his/her pores become obstructed and sweat cannot escape. The cause of heat rash is often friction on the surface of the skin.	The rash may appear as blisters or red lumps. Heat rash may cause itchiness. It is usually developed in the parts of the body that rub together such as neck, upper chest, and in elbow creases.	Heat rash usually goes away on its own. Lightweight clothing may help to decrease the itchiness.
Heat syncope	Refers to a fainting episode that occurs when an individual in a hot and humid environment doesn't have adequate blood flow to the brain, causing the person to lose consciousness. This can occur when an individual is standing in a hot environment for a long period time without any movement	Dizziness, lightheadedness, weakness, loss of consciousness, pale or sweaty skin, weak pulse.	The affected individual shall sit or lie down in a cool place. Elevating the legs above the level of the heart may help to promote blood flow to the heart. Rehydration with water or a sport beverage helps to alleviate the symptoms.
Heat cramps	Heat cramps are painful, brief muscle cramps. Muscles may spasm or jerk involuntarily. The mechanism of heat cramps is unknown, but they can be caused by dehydration or lack of adequate electrolytes in the diet.	Heat cramps and symptoms are painful muscle spasms usually involving the legs, chest or the abdomen.	Heat cramps usually go away on their own. Resting in a cool place and drinking cold water or sport drinks helps to control the severity of the symptom.
Heat exhaustion	Heat exhaustion is a condition whose symptoms may include heavy sweating and a rapid pulse, a clear result that the human body is being overheated.	Heavy sweating, paleness, muscle cramps, tiredness, weakness, dizziness, headache, nausea, vomiting, and fainting.	Activity must stop immediately. Heat exhaustion can be self-treated. Decreasing the body temperature is crucial to treat the heat exhaustion. Resting in a cool place and drinking cold fluids may help. Prompt medical attention is necessary if the symptoms do not go away within an hour.
Heat stroke	Heat stroke is the most serious heat related illness, which occurs when the core temperature of the human body rises above 40˚C. At this temperature the thermoregulation functions of the human body can be seriously damaged. It can also generate irreversible damage to the brain and other vital internal organs.	Confusion, altered mental status, slurred speech, loss of consciousness, profuse sweating, and seizures.	Heat stroke is a very serious illness, which carries a high risk of fatality within the underground environment when the worker is not quickly treated and the climatic conditions are not immediately corrected.

thermal models are developed to take into account behavioral responses from a large number of individuals that are exposed to various climatic conditions.

Thermal comfort models can be categorized into "*physiological*" and "*psychological*" models *(Cheng et al., 2011)*. A physiological thermal model involves the self-regulatory function of the human body to varied thermal environments. These self-regulatory processes include vasoconstriction, shivering, vasodilation, sweating, etc. Physiological thermal models range from the simplest "*one-node*" models to the complex "*three-dimensional*" finite element models. Examples of "*one-node*" thermal models are: the one-node model *(Givoni & Goldman, 1971)*, the two-node model *(Gagge et al., 1971)*, the two-node model with transient response *(Jones, 1992; Fiala et al., 1999)*. A psychological thermal model can predict both local and whole-body thermal sensations. Examples of psychological thermal models are: the whole-body thermal state model (Dear et al., 1993), transient models, non-uniform models, uniform models *(Arens et al., 2006; Zhang et al., 2010)*, the transient thermal sensation model *(Fiala et al., 2010)*, etc.

The International Standards Organization (ISO) has formed an integrated series of international standards to assess the human response to various thermal environments. For example, for a hot and humid environment a three-tier approach can be applied, which involves: (1) a simple thermal index such as WBGT, that can be used for monitoring and control *(Parson, 2006)*, (2) a rational index such as SW_{req}, which involves an assessment of the heat exchange process between a worker and the environment *(ISO 7933, 2005)*, and (3) a standard for physiological measurement, which can be used to establish a monitoring system for the workers *(Parson, 2006)*. This method of evaluation and interpretation calculates the thermal balance of the human body from the parameters of the thermal

environment such as: t_a, t_r, P_a,v_a which are estimated according to ISO 7726. The physical characteristics of the workers exposed to these conditions such as the metabolic rate (M) is estimated on the basis of ISO 8996 *(2004)*. Furthermore, the thermal characteristics of the workers clothing are estimated on the basis of ISO 9920 *(2009)*.

In this study, a "*thermal model*" was developed to assess the effect of the net heat load and humidity on the health and safety of the mine workers coupled with climatic and physiological parameters such as airflow, temperature, humidity, work intensity, and clothing. Simulations performed on the thermal model mirrored the stress conditions which can be experienced by a mine worker as a function of ambient conditions, clothing, and various metabolic rates. Many heat stress publications *(ISO 7933, 2005; ISO 8996, 2004; NIOSH, 2010; Jacklitsch et al., 2016)* use the fundamental principle which implies that an increase in work rate should be compensated by a reduction in environmental heat load *(Graveling et al., 1988)*. The limit setting criteria for this thermal model was also derived from this principle.

The metabolic rate, the level of humidity, the dry-bulb temperature and the type of clothing are all key parameters which can confirm thermal equilibrium, or determine the net heat that will be stored in the human body. Metabolic rates of 200 W/m^2, 250 W/m^2, and 300 W/m^2 were considered for this study, which represent light, moderate, and vigorous levels of activity. Input parameters can also characterize physical work which involves sustained hand-and-arm movement, arm-and-trunk work, and intense arm-and-trunk work, ISO 8996 *(2004)*. Throughout the climatic and thermoregulation simulations the airflow velocity, and type of clothing was kept constant at 1.5 m/s, and a coefficient of heat transfer of 0.6. The air temperatures used in the thermal model ranged from 20˚C through to 36˚C, since these

are normally observed values in many underground mines. The output results of the model which are maximum evaporation rate, required evaporation rate and required sweat rate are interpreted base on the state of acclimatization of the subject. There is an alarm and a danger criteria for the predicted sweat rate and the duration of exposure. Two stress criteria of a) maximum skin wetness (w_{max}), b) max sweat rate (SW_{max}) and a criteria of strain max water loss in the form of maximum tolerable exposure time (TLV) form the basis for the interpretation of the values. When the predicted values are below the maximum values sufficient sweat can be evaporated to maintain thermal equilibrium. The environmental conditions been considered for this analysis are severe and will involve excessive water loss from the body of the subjects. A comprehensive analysis of the development and implementation of this model is found in *(Sunkpal, 2015)*.

The output results generated from the model runs, which include the maximum evaporation rate, the required evaporation rate, and the required sweat rate have been determined according to a non-acclimatized mine worker. A distress signal was also imbedded in the thermal model based upon a risk criteria, which took into account the predicted sweat rate, the skin wetness, and the work duration (e.g. duration of exposure) of the mine worker. Three stress criteria such as: (a) the maximum sweat rate (SW_{max}), (b) duration of exposure, and (c) maximum skin wetness (w_{max}), established the basis for work comfort, data analysis and interpretation. It was assumed that when the predicted values were below the maximum permissible stress values, sufficient sweat was evaporated from the skin and/or the clothing surface of a mine worker in order to maintain thermal equilibrium. The output results generated by means of climatic and thermoregulation simulations are presented in Figure 1.2 (a, b, c), Figure 1.3 (a, b, c), and Figure 1.4 (a, b, c).
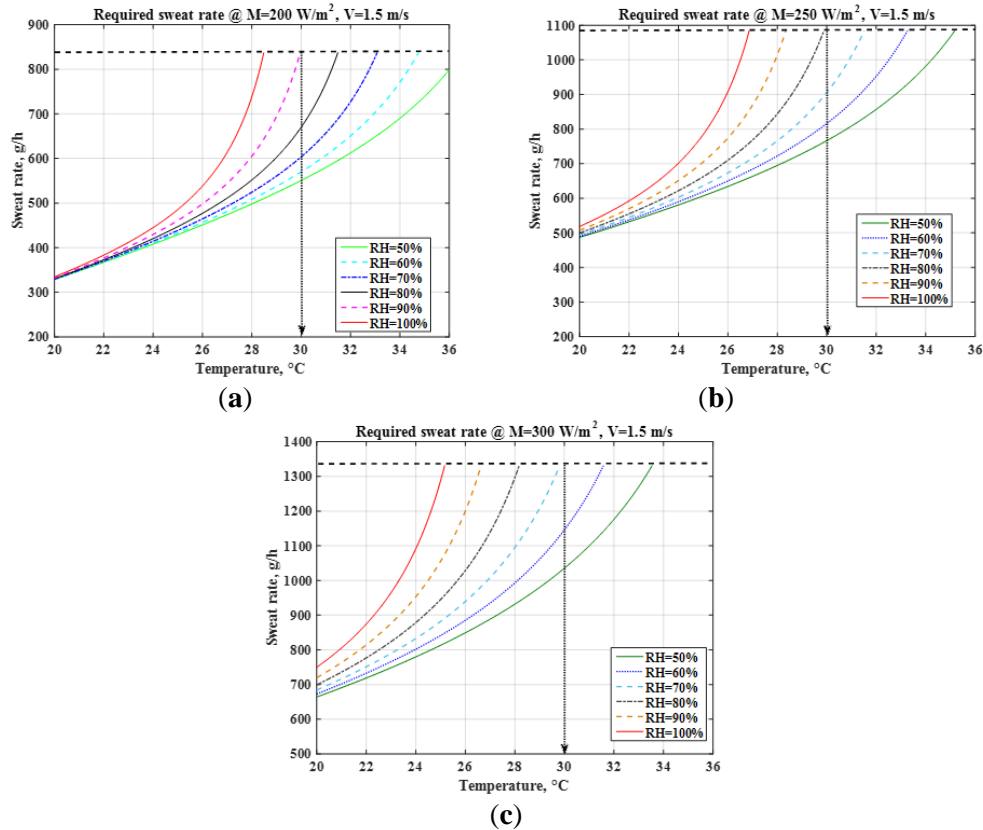
Figure 2.2 (a, b, c). Maximum allowable levels of relative humidity (RH) as a function of temperature (t) and maximum sweat rate (SW_{max}) for: (a) M = 200 W/m²; (b) M = 250 W/m²; and (c) M = 300 W/m²

Figure 1.2 (a, b, c) shows the maximum levels of RH, which are permitted in a production area of an underground operation for temperatures ranging from 20°C through to 36°C. The RH levels are also a function of the limiting sweat rates (SW_{max}) produced by a mine worker, which performs manual work at increasing levels that correspond to metabolic rates of 200 W/m², 250 W/m², and 300 W/m². The maximum sweat rate produced by an un-acclimatized mine worker (SW_{max}) varies from 840 (grams/hour) to 1,080 (grams/hour), and 1,330 (grams/hour) for metabolic rates of 200 W/m², 250 W/m², and 300 W/m², respectively.

The thermal model considers that fresh air is delivered to the production area at a constant velocity of 1.5 m/s, and the clothing worn by the mine worker has a coefficient of heat

transfer of 0.6. Figure 2(a) shows that for a low level activity, which corresponds to a metabolic rate $M_l = 200$ W/m^2, and for ambient temperature $t = 30°C$, the maximum allowable RH in the production area is 90%. Figure 2(b) shows that for the same climatic conditions but for a medium level of activity, which corresponds to a metabolic rate $M_m = 250$ W/m^2, the RH in the production area should not exceed 80%. Figure 2(c) shows that for the same climatic conditions, but for a metabolic rate $M_v = 300$ W/m^2, the RH in the production area should not exceed 68%.
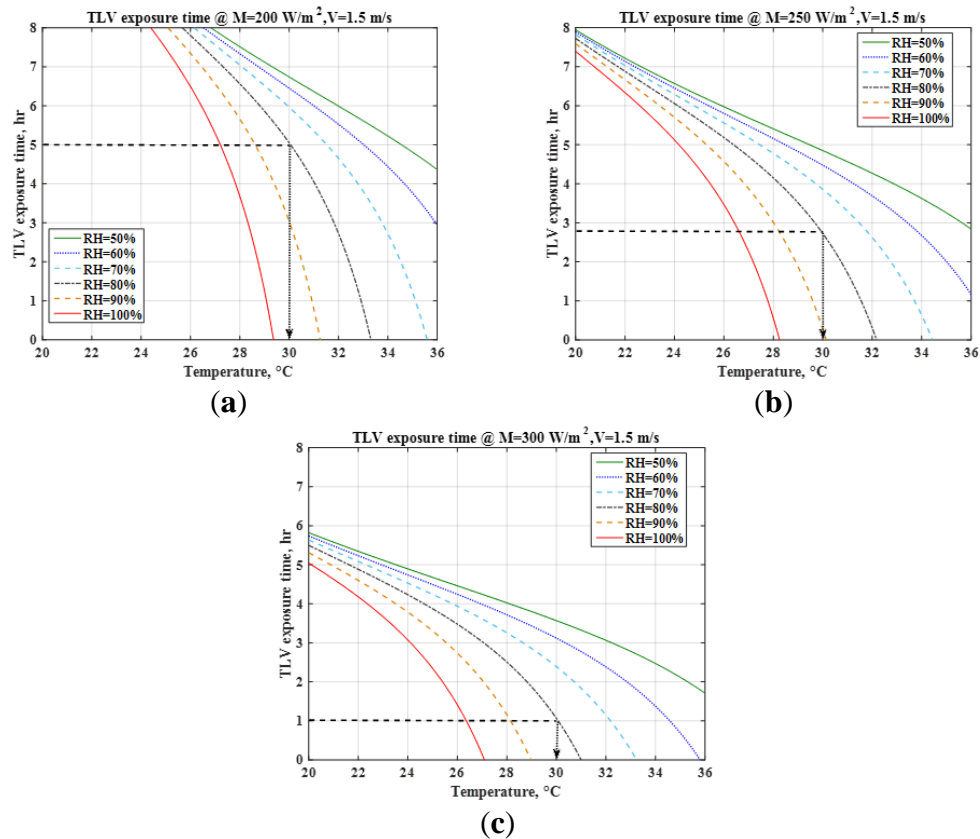
Figure 2.3 (a, b, c). Maximum exposure limits (e.g. work duration) as a function of temperature (t), and relative humidity (RH) for: (a) M = 200 W/m^2; (b) M = 250 W/m^2; and (c) M = 300 W/m^2

Figure 1.4 (a, b, c) shows the maximum allowable exposure times (e.g. work duration) of a mine worker in the production area, who performs manual work at levels that correspond to metabolic rates of 200 W/m^2, 250 W/m^2, and 300 W/m^2. The maximum allowable

exposure times are also a function of the dry-bulb temperature, which varies from 20˚C through to 36˚C, as well as RH, which varies from 50% through to 100%. The maximum allowable exposure time was determined by means of simulation techniques performed on the thermal model, which considers that fresh air is delivered to the production area at a constant velocity of 1.5 m/s, and the type of clothing of the mine worker has a heat transfer coefficient of 0.6. Figure 3(a) shows that for a low level of activity, which corresponds to a metabolic rate of $M_l = 200$ W/m², for an ambient temperature t = 30˚C, and for RH = 80%, the maximum allowable exposure time of a mine worker is 5.0 hours. The allowable exposure time reflects continuous manual work performed at a constant metabolic rate. Furthermore, for the same ambient conditions, if the metabolic rate of the mine worker increases to 250 W/m² and 300 W/m², the maximum allowable exposure time needs to decrease to 2.8 hours, and 1 hour, respectively. Based on the above mentioned ambient conditions and work duration limits, a mine worker will have the ability to maintain thermal equilibrium. If the temperature and/or the RH in the production area further increases, the permitted work duration needs to decrease according to the graphs shown in Figure 3 (a. b, c).

Figure 4 (a, b, c) shows the maximum levels of RH, which are permitted in the production area for temperatures that vary from 20˚C through to 36˚C. In this case the RH levels are a function of the maximum skin wetness (w_{max}) of an un-acclimatized mine worker, which performs manual work at levels that correspond to metabolic rates of 200 W/m², 250 W/m², and 300 W/m². The skin wetness (w), which can vary from zero to a maximum value of 0.85 was determined according to research work published by Fanger in 1970. The thermal

model also considers that fresh air is delivered to the production area at a constant velocity of 1.5 m/s, and the clothing worn by the mine worker has a heat transfer coefficient of 0.6.

Figure 4(a) shows that for manual activity, which corresponds to a metabolic rate $M_l = 200$ W/m^2, and for an ambient temperature t = 30˚C, the maximum allowable RH in the production area is 87%. Figure 4(b) shows that for the same climatic conditions but for a higher level of activity which corresponds to a metabolic rate $M_m = 250$ W/m^2, the RH in the production area should not exceed 74%. Furthermore, Figure 4(c) shows that for the same climatic conditions, but for a metabolic rate $M_v = 300$ W/m^2, the RH in the production area should not exceed 63%.

(a)   (b)

(c)
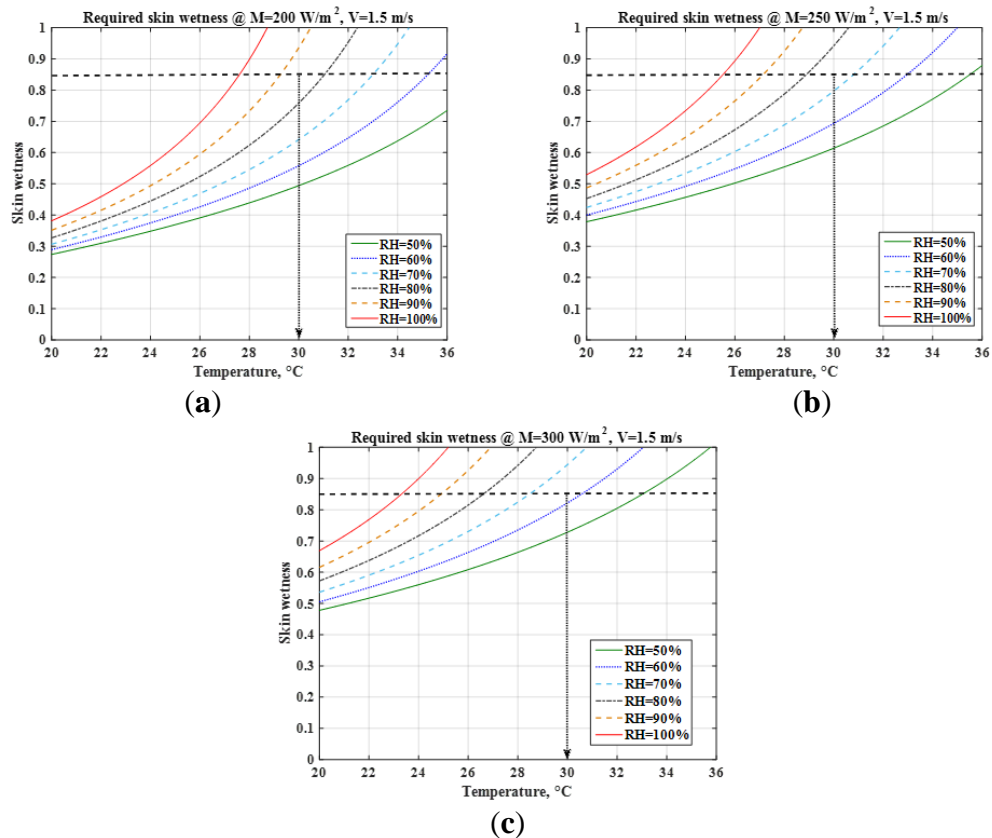
Figure 2.4 (a, b, c). Maximum allowable levels of relative humidity (RH), as a function of temperature (t) and maximum skin wetness ($w_{max} = 1$) for: (a) M = 200 W/m^2; (b) M = 250 W/m^2; and (c) M = 300 W/m^2

The above results determined by means of simulation techniques, which are presented in Figure 1.2 (a, b, c), Figure 1.3 (a, b, c) and Figure 1.4 (a, b, c) show that the climatic parameters of an underground environment as well as the thermoregulation parameters of a mine worker took into account the limiting physiological parameters such as the maximum sweat rate (SW_{max}), the maximum skin wetness (w_{max}) and the maximum exposure time (hours). The simulation results emphasize the fact that an accurate thermal model has the ability to either quantify the maximum allowable climatic parameters in an underground work area such as temperature (t) and relative humidity (RH), or for a given work environment and predetermined metabolic rates (M) to determine the maximum exposure times (e.g. work duration) for the mine workers. The allowable exposure time represent the maximum time a worker can continue to perform tasks in order to maintain thermal equilibrium.

2.6. Method of Controlling Heat

Deciding between different heat mitigation techniques can drastically change the operating cost of an underground mine. Considering the list of energy demanding activities, ventilation is identified as one of the top contributors. Ventilation costs make up to 40% of the total electricity usage, and up to 60% of underground operating costs *(Karacan, 2007; Kurnia et al., 2014)*. Because every mine is unique, it is essential to monitor the climatic conditions in the mine to understand where the heat is coming from, in order to identify and design the most appropriate method of cooling. In the majority of cases the airflow itself is sufficient to remove the heat that is produced during the mining processes. In deep metal mines, the heat removal, which is usually the dominant environmental problem, may necessitate the use of some level of refrigeration.

2.6.1. Acclimatization

Several studies have summarized the parameters which are important to the thermoregulation process of the human body, such as physical fitness, acclimatization, hydration state, hypertension, gender, and age. Furthermore, other parameters may include factors such as previous heat-related illnesses, difficulty to acclimatize or re-acclimatize to the heat and humid conditions, hypertension, body size, drug use, and alcohol use *(Havenith, 1985; Kenny et al., 2009).* A properly designed and applied heat acclimatization program will increase the ability of the mine personnel to work in hot and humid environments, while decreasing the risk of heat-related illnesses. For a healthy worker, acclimatization to a hot and humid environment can be usually attained in 7 to 14 days *(DOD 1980, 2003; NEHC, 2007; ACGIH, 2014).*

2.6.2. Identifying and applying a heat stress index

Heat stress indices have several safety and health applications in the mining industry. Among these applications setting exposure limits or threshold limit values, is probably the most important application of a heat stress index *(Lee, 1985).* A heat stress index integrates personal, physiological, and thermal parameters into a single number for a "*quantitative*" assessment of exposing mine workers to heat stress *(McPherson, 1962; Graveling, 1988; Epstein & Moran, 2006).* Heat stress indices can be grouped into: (1) rational indices, which are based on calculations involving the heat balance equation; (2) empirical indices, based on objective and subjective heat strain assessments; and (3) direct indices, which involve direct measurements of environmental parameters such as dry-bulb temperature, wet-bulb temperature, wet-bulb-globe temperature, relative humidity, airflow velocity, etc. *(Graveling, 1988; Brake & Bates, 2002; Epstein & Moran, 2006).*

A heat stress index, which is anticipated to be used for a specific work area, should satisfy the following criteria before being established as a standard for industrial use *(Webber et al., 2003)*: (a) be applicable to and accurate within the range of conditions for which it will be used, (b) take cognizance of all relevant parameters of heat stress, (c) be applicable through simple measurements and calculations, (d) apply valid weighting to all factors considered, in direct relation to their contribution to total physiological strain, (e) provide a practical foundation in order to develop regulatory standards.

2.6.3. Re-designing the ventilation system

Designing or re-designing the primary and/or the auxiliary ventilation systems to provide adequate air volumes to the production workings should be explored before any level of refrigeration is considered. For example, under certain conditions and based upon the mining method employed, a localized "*exhausting*" auxiliary ventilation system can be re-designed into a "*forcing*" system. The higher velocity airstream emerging from a forcing duct can provide cooler air at the face of a dead-end development heading, having also taken into account the heat generated by the auxiliary fan. Another advantage of a forcing auxiliary ventilation system is that flexible fabric ducts can be used due to positive pressure along the ducting system. The main disadvantage of a forcing auxiliary systems is that pollutants added to the ventilating air at the face will affect the entire length of the drift, as the return air passes back along it.

The advantages of both forcing and exhausting auxiliary ventilation systems can be combined when an "*overlap*" system is used. A push-pull overlap ventilation system can provide adequate airflow velocities at the face of a production stope, while the contaminated air is immediately directed into the ducting system. The problem with an

overlap auxiliary system is that it requires a relatively large cross-sectional area where two ducting systems can be installed. For this study, the use of an overlap ventilation system wasn't feasible due to small cross-sectional areas in the production and development workings. An efficient ventilation system which has the ability to deliver appropriate air volumes to the production workings can be an effective method to control heat and humidity in underground mines.

2.6.4. Cooling systems and strategies

The main objective of mine ventilation system is to provide comfort to the mine workers and machinery by supplying an adequate amount of fresh air to remove the pollutants generated during development and production operations. However, the ability of ventilation systems to provide acceptable climatic conditions can decrease as a function of mining depth, the geothermal gradient and the level of mechanization. In deep and hot mines, the removal of heat is a top priority for the mine operators, as mine workers can be exposed to heat-related illnesses and injuries. Despite the fact that many underground mines in the US may not have a history of severe heat problems mine-wide, there might be localized areas (e.g. production workings, development headings) where the temperature and humidity values are continually exceeding the allowable limits. Selecting the most suitable method of cooling depends on the magnitude of heat which needs to be removed, the makeup of the combined heat load (e.g. auto-compression, strata, mining equipment, blasting), the employed extraction method(s), the location of problem areas, and economic considerations.

Table 2.2. Current cooling strategies and application to the mining industry *(Ramsden et al., 2007; Mackay et al., 2010; Kamyar et al., 2016; Al Sayed, 2016).*

Cooling Method	Strategy	Details
Micro-climate cooling systems	These cooling systems serve the purpose of cooling the area directly around the worker. Examples of this include air-conditioned cabs and cooling garments.	(a) located where the miners work and travel, (b) maximum positional efficiency, (c) low capital investment, (d) mobile, (e) workers are not always in air conditioned cabs, (f) current cooling garments are not optimal for use in underground mines.
Spot cooling systems	These small, mobile units are placed in problem areas to mitigate heat or to supplement the central cooling system when necessary.	(a) located in areas away from main airways, (b) low cooling capacity, (c) high positional efficiency, (d) low capital investment, (e) mobile, (f) must reject heat into a return airway.
Surface bulk cooling systems	The intake shaft draws air through a spray chamber known as bulk air cooler (BAC) to chill the air. A dedicated fridge shaft may be used entirely for ultra-cold air.	(a) located on the surface, (b) largest cooling capacity, (c) lowest positional efficiency, (d) can dissipate heat directly to the atmosphere, (e) limited by the depth of the mine
Underground bulk cooling systems	Utilize a BAC or cooling-coil coolers to chill the main intake air. Secondary underground BACs may be set up along the main intake.	(a) located underground in main airways, (b) large cooling capacity, (c) low positional efficiency, (d) limited by space underground, (e) must reject heat into a return airway or through return waterlines to the surface

2.7. Discussions

In many instances, by simply adjusting or upgrading the auxiliary ventilation system in a problem area of a mine will effectively dilute the pollutants that are generated during production operations and provide adequate climatic conditions to the mine workers. This can be achieved through various methods such as: (1) extending the auxiliary duct towards the face, (2) installing an additional auxiliary fan to overcome the added pressure losses in the system, (3) changing the size of the fan, (4) switching from an "exhausting" arrangement to a "forcing" arrangement, and (5) installing an "overlap" auxiliary ventilation system. If the required air volumes in the active areas are more than the primary ventilation system is able to provide, other measures may need to be considered in order to increase airflow delivery. This may include the installation of a ventilation-on-demand

(VOD) control system, adding booster fans to improve airflow distribution in localized areas, and/or upgrading the surface fans.

In hot and humid underground mines, the heat index used for comfort evaluation must be carefully selected. This heat index shall provide protection for the mine workers as much as possible. The primary objective in selecting a heat stress index is simplicity. It is more likely that the environmental engineers and the mine personnel will accept and employ a thermal index which has been presented in a format that can be well understood and easily applied. On the other hand, a simple thermal index may limit its relevance to a very specific case or a localized area. However, the necessity to apply numerous modifications to simple indices in order to adjust them for various work conditions, can negate the apparent advantage of a thermal index to be directly used to protect the mine workers.

When miners are working directly in the hot mine environment, they must stay hydrated, take breaks, and wear the proper attire. It is important to stay hydrated as dehydration not only reduces work output but also puts the mine worker at risk for heat related injuries *(Brake, 2001)*. If a mine worker is performing moderate work for less than two hours during a shift, it is recommended that they drink 1 cup (6 ounces) of water every 15 to 20 minutes. If a mine worker is performing strenuous work and/or is performing moderate work for more than 2 hours then they should take breaks and drink hydrating fluids containing electrolytes throughout the shift *(Jacklitsch et al., 2016)*. Short, intermittent breaks are recommended over a single, long break during a shift as work-rest cycles are better for reducing fatigue. If at all possible, these breaks should be conducted in a cooler area.

There are a number of available cooling systems and strategies, which vary as a function of cooling capability, cost, mobility, and efficiency. No cooling system is necessarily better

than another, as the various mine specific conditions may require a cooling method, which is unique to a particular operation. The majority of the most widespread cooling methods as well as some less common cooling systems are basically applicable to the hot and humid underground mines in USA. How these systems are applied will vary on a case by case basis for each mine based on a variety of factors such as: the combined heat load of the mine, geographic location, mining depth, employed mining method(s), material handling system, level of mechanization, diesel equipment fleet, and economic constraints. An underground mine's cooling strategy should be planned and designed by taking into account that an underground operation is a "dynamic" system, as the mine continually deepens and new adjacent orebodies are being developed. Cooling units can be upgraded and different combinations of cooling systems can be utilized. This is important not only for the safety and health of the U.S. mine workers, but also for the sustainability of the U.S. mining industry.

Clothing and personal protective equipment (PPE) can significantly reduce the heat exchange processes, as they insulate the human body and reduce the available skin surface area much needed to promote evaporative cooling. Other industries have begun using cooling garments which utilize air cooling, water circulation, and gas expansion systems in an effort to cool the workers. However, recent research has concluded that the currently available cooling garments aren't yet fully compatible to be used in hot and humid underground mines. For this reason, whenever possible mine workers should avoid wearing multiple layers and should wear clothing made of materials which promote heat exchange and moisture transfer between the human body and the ambient surroundings. While mine workers should follow these practices, the environmental engineers are responsible to

establish safe policies and protocols to be followed in order to prevent heat-related injuries

in underground mines.

Chapter 3 Selecting an Appropriate Heat Stress Index to Protect the Workers in Hot and Humid Underground Mines

3.1. Introduction

Hot and humid environments can negatively impact the performance, overall productivity and most importantly the ability of the underground workforce to perform work in a safe manner *(Brakes & Bates, 2002)*. Evaluations of the underground thermal environment are becoming more important due to the proliferations of health and safety problems related to adverse climatic conditions in underground miners *(Carpenter et al., 2015)*. These health and safety problems are normally in the form of thermal discomfort, heat-related illnesses such as thermal stress, heat cramps, heat rash, heat stroke, etc. *(Donoghue, 2004)*.

A heat stress index integrates personal, physiological, and thermal environment parameters into a single number for a "*quantitative*" assessment of exposing mine workers to heat stress *(McPherson, 1962; Graveling et al., 1988)*. Heat stress indices can be grouped into: (1) rational indices, which are based on calculations involving the heat balance equation; (2) empirical indices, based on objective and subjective strain assessments; and (3) direct indices, which involve direct measurements of environmental parameters such as dry-bulb temperature, wet-bulb temperature, relative humidity and airflow velocity *(Brake and Bate, 2002; Epstein & Moran, 2006; Jacklitsch et al., 2016)*.

Since 1905 over 160 heat stress indices have been proposed for various thermal environments *(Freitas & Grigorieva, 2015)*. Figure 3.1 shows the cumulative number of heat stress indices that were proposed from 1905 to 2012. The graph reveals two important facts about heat stress indices. Firstly, there has been no single index that can be used as a

"universal index" (mentioned by Belding, 1970; Gagge & Nishi, 1976; Brake & Bates, 2002; Epstein & Moran, 2006). A universal index would be an index that includes a range of comfort limits based on different metabolic rates. Secondly, a large number of heat stress indices may bring confusion in choosing the appropriate one for a specific industry or work environment. The large number of available heat stress indices and the lack of a defined procedure to determine which index to be used for a particular climate has rendered comfort and environmental engineers to rely on guesswork in choosing an index for work climate evaluation. Many of the underground mines in the US and world-wide can select an index while they are unaware of its limitations (Observation of the authors from several underground gold mines in Nevada). This is partly occurring due to the fact that measuring and collecting a large amount of physical and human-related parameters and subjecting them to complex climatic modeling is not simple and practical.
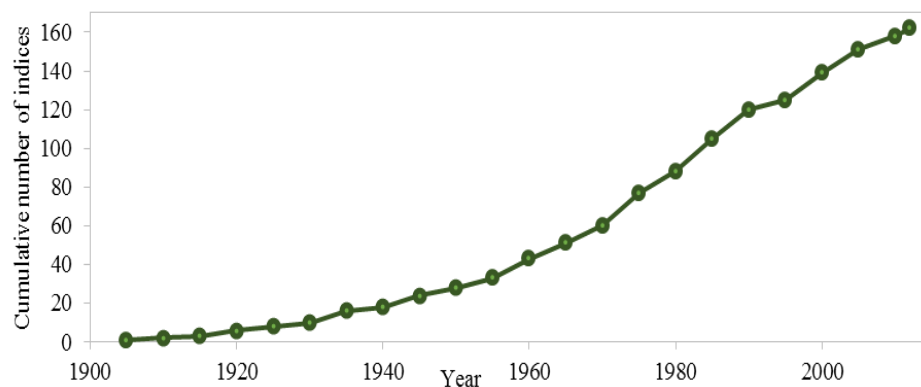
Figure 3.1. Cumulative number of heat stress indices from 1905 to 2012

It has been agreed that an ideal heat index is needed to accurately assess the climatic conditions on a regular basis and protect the workers in hot and humid conditions. Furthermore, this index would need to be user friendly and computationally straightforward for the environmental practitioners *(Jacklitsch et al., 2016).* This research

study posed the question of which index can be recommended for a particular climate and work condition? In this paper, a method is used to compare a thermal comfort model with some of the most widely used heat indices in underground mines. The method is applied to predict the "*comfort zone*" and to recommend an index based on its performance as close as possible to the "*comfort zone*". The comparative analysis uses comfort data including air temperature, airflow velocity, humidity, and estimated physiological parameters such as clothing and activity rates.

3.2. Thermal Comfort

Humans are comfortable within a very small range of core body temperatures. Biochemical processes in the human body will not function if the temperature becomes too low or too high. At high temperatures, enzymes lose their activity and at low temperatures there is inadequate energy to continue metabolic processes *(Niash, 2015)*. Humans can tolerate extreme core temperatures below 35°C or above 41°C for only brief periods of time *(Niosh, 2015)*. There are mechanisms by which the body can regulate its core temperature both at rest and during activity, and in both hot and cold or humid environments, along with health risks that are associated with physical activity in the aforesaid environments *(King, 2004)*. Through its intricate temperature regulation, the human body is able to reach a state of thermal equilibrium with the surrounding environment when the variation of internal energy, at the body core level is equal to zero *(Fanger, 1970)*.

Assessment of "*thermal comfort*" must start with the appreciation that comfort is a state of mind. It is extremely difficult to classify the many factors which affect thermal comfort. The interaction between the physical demand imposed upon an individual, his/her physiological status and his/her psychological attitudes must be considered in interaction

with social customs, tangible perceptions and the likes *(Goldman, 1970)*. Since thermal comfort is rather subjective and restrictive, it is better to define a comfort zone within which most workers will be comfortable. This necessitates the need to define a "*zone*" in which most of the workers will consider comfortable, the so called "*comfort zone*". This comfort zone will be ascribed using the climatic and physiological parameters of the mine environment and some existing thermal comfort models.

3.2.1. Thermal Comfort Zone:

Thermal comfort is the condition of mind which expresses satisfaction with the thermal environment *(ASHRAE, 2007, 2009)*. Based on ASHRAE definition, the "*thermal comfort zone*" is the condition that satisfies 80% of sedentary persons within the environment. According to Fanger *(1970)*, three parameters need to be satisfied for a person to be considered in the thermal comfort zone. These parameters are: (1) the worker's sweat rate needs to be within comfort limits; (2) the worker is in heat balance; (3) the worker's mean skin temperature is within comfort limits. There are six main factors (air temperature, relative humidity, radiant temperature, air velocity, metabolic rate, and clothing) affecting the thermal comfort, which can be perceived as both environmental and personal *(Fanger, 1970; Brake & Bates, 2002; Donoghue, 2004)*. These are briefly described, as follows:

3.2.1.1. Air Temperature: is defined as the temperature of the ambient air surrounding the occupant that defines the net heat flow between the human body and its environment. Temperature is the most significant component to the experience of comfort in an environment. When the surrounding dry and wet bulb temperatures are high, this process becomes more difficult and we may overheat or feel warm. When surrounding

temperatures are low, the rate of heat loss becomes more rapid, and we may feel uncomfortably cold *(Boduch and Fincher, 2010)*.

3.2.1.2. Mean Radiant Temperature: can be defined as the temperature of a uniform enclosure whereby a small black sphere at the test point would have the same radiation transfer as it does with the real environment *(Boduch and Fincher, 2010)*. In practice, heat transfer from radiation is assumed to be negligible in underground mines. Therefore, mean radiant temperature is considered to be equal to ambient air temperature.

3.2.1.3. Airflow Velocity: is the average speed (with respect to location and time) of the air to which the body is exposed. Airflow velocity distribution is a key factor influencing heat and mass transfer. Airflow velocity affects both convective and evaporative heat transfer coefficients, and thus influences thermal comfort conditions *(McIntyre, 1978)*. The reaction of a person to air movement is likely to be a complicated phenomenon as it depends on the climatic parameters including temperature, humidity, clothing worn, metabolic rate, and resulting skin temperature *(McIntyre, 1978)*. The designed airflow velocities along working faces of underground mines tend to range from 0.3 and 4.0 m/s *(McPherson, 1984; Mousset-Jones, 1986)*.

3.2.1.4. Relative Humidity: is the ratio between the actual amount of water vapor in the air and the maximum amount of water vapor that the air can hold at that air temperature. While temperature is the most important factor in generating a phenomenological sense of thermal comfort, relative humidity plays a critical role in conjunction with the dry-bulb and wet-bulb temperatures to provide a sense of comfort/discomfort. High levels of relative humidity can work against the evaporative cooling effects of sweating and leave the body prone to over-heating. When relative humidity gets too high, discomfort develops, either

due to the feeling of the moisture itself *(ASHRAE, 2005)* which is unable to evaporate from the skin, or due to increased friction between skin and clothing with skin moisture *(ASHRAE, 2005)*.

3.2.1.5. Worker's Clothing: which is usually described as the thermal resistance or insulation level between the human body and its environment, with the clothing insulation typically quantified in terms of its "Clo" values (1 Clo = 0.155 m^2/W insulation value).

3.2.1.6. Worker's Metabolic Rate: is the energy released per unit time by the oxidation processes in the human body and is dependent on the amount of muscular activity. Metabolic rate varies according to the intensity of activity performed. Metabolic rate is also proportional to the body weight, body surface area, health, sex, age, amount of clothing, and surrounding thermal and atmospheric conditions *(Auliciems & Szokolay, 2007)*.

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the interrelationship between these factors determines the climatic conditions acceptable to a majority of the occupants within a working environment *(ASHRAE, 2005)*. ASHRAE's definition of comfort zone is rather complex, however it can be altered through some estimations to a zone which strictly depends on comfort parameters.

3.3. Heat Stress Indices

The idea of the thermal index goes back to 18th century *(McPherson, 1962)*. Without considering the dry-bulb temperature, perhaps the first published heat stress index was the wet-bulb temperature proposed by Haldane *(1905)*. Since then a large number of heat stress indices have been proposed. Many of the earlier indices only included four environmental

factors, such as: Effective Temperature (ET), Equivalent Temperature (E_{eq}), Operative Temperature (OpT), and Wet-bulb Globe Temperature (WBGT). Later, new indices took into account clothing and the metabolic rate as behavioral parameters. Heat stress indices have been employed in different engineering applications. Presently, no one single index has gained universal acceptance. Belding *(1970)* and Gagge and Nishi *(1976)* pointed that having a unique valid system for rating heat stress is not possible since the interaction between the climatic parameters is complicated. Many of the current indices were developed for a specific use. Each heat stress index has special advantages that makes it more suitable for a particular work environment. Despite extensive research work (see Table 3.1), it is currently not possible to quantitatively compare the available heat indices using a valid method. Therefore, it is the user's responsibility to examine each index and select the one that best suits the defined thermal climate and protects the mine workers.

Table 3.1. A literature review on heat stress indices comparison methods

Comparison Method	Author(s)
Experiment Acclimatized and/or un-acclimatized men and/or women Range of work and/or resting conditions Wide range of climatic conditions Different environmental and behavioral parameters	MacPherson (1960) Klemm & Hall (1972) Ljunberg et al. (1979) Pulket et al. (1980) Morris & Graveling (1986) Mairiaux & Malchaire (1995)
Comparison between Direct Indices Summary of indices and their correlation to thermal comfort	Epstein & Moran (2006)
Comparison between Temperature - Humidity Indices Comparison between rational methods and temperature-humidity indices	Alfano et al. (2011)
Data Analysis Large or small climatic databases as input parameters of climatic condition Assumed data	Beshir & Ramsey (1988) Blazejczyk et al. (2012)
Rational Method Concept of limiting metabolic rate Energy balance equation	Brake & Bates (2002) Zuhairy & Sayigh (1993)

Heat stress indices have several safety and health applications in the mining industry and other businesses. Among these applications the following are mentioned:

- *Setting exposure limits or threshold limit values:* Perhaps, the most important application of a heat stress index is to define the maximum exposure time or safety limits *(Lee, 1958).*

- *Defining the comfort limits:* Another important application of a heat stress index is to define the comfort zone, which is applicable in the interest area (e.g. office, work area).

- *Determining the optimum control measures:* Heat stress indices can be used to evaluate and select the measures and available options of controlling heat such as air movement, air conditioning, work/break protocols, etc.

- *Past exposures evaluation:* Heat stress indices can be also used to assess past exposures to heat in underground mines. For this purpose, more comprehensive indices can give better results.

- *Evaluation of safe work:* An index can be a good indication of the limits of safe work. Particularly, in sport, military and mining industry settings, use of an appropriate index can help prevent heat and cold related illnesses.

- *Climate zone classifications:* Heat stress indices can be used to determine climate zones. These classifications are important to assure a safe and comfortable work environment.

There are some general limitations that should be taken into account for many of the heat stress indices, as follows:

- Many of the indices do not include a wide range of climatic conditions. These indices may be precise for a climatic condition (e.g. warm environment), but inappropriate for others. A good example is the scale of the "*Equivalent Temperature Index*", which does not extend beyond 24 $^\circ$C. Therefore, an engineer may have to consider and work with more than one heat stress index if the work environment changes.

- Inbuilt errors exist in some of these indices. Several indices (e.g. direct indices) are developed based on algebraic or statistical models. There is some degree of error when these mathematical methods are applied. An example is the error of the "*effective temperature index*" scale in wind speed at high temperature *(Alfano et al., 2011)*.

- Important factors such as acclimatization cannot be included *(McPherson, 1962; Budd, 2008)*. For a given level of heat stress, heat strain experienced by an acclimatized individual is different from an un-acclimatized person. Many of the indices do not distinguish between acclimatized and un-acclimatized subjects in their application.

- Brake & Bates *(2002)* states that most heat stress indices were developed for externally paced work. Increasing degree of mechanization of heavy tasks and new regulations result in informed workers that support self-pacing in thermally stressed climates.

- Averaging methods are not always physiologically valid. Many of the indices are developed based on thermal stress of the workers and averaging of large experimental data. Though, the reaction of the individuals to heat load can be modified by age, gender, etc. Furthermore, the response of a group of self-paced and acclimatized workers to heat will largely differ from a group of un-acclimatized and less experienced workers.

- The validity and reliability of many indices are questionable. For example, the Discomfort Index (DI) was developed as a simplified version of WBGT *(Alfano, 2011)*. In the WBGT index, globe temperature (GT) measures the combined effect of radiant heat, air temperature, and air speed. The DI does not take into account the air speed by replacing GT with ambient temperature, which may cause significant errors in evaluating some climatic conditions.

- The primary purpose of evaluating the climatic conditions is to assess the work environment and re-design the control system (e.g. ventilation, cooling, work/break protocols) in order to meet safety, health and comfort indicators for the mine workers *(McPherson, 1962)*. None of the indices can take into account all the comfort determining factors and their interrelation. Consequently, the work environment should be assessed regularly irrespective of how comprehensive is the index.

3.4. Comparison between the Heat Stress Indices based on Pierce Two-Node Model

The National Institute for Occupational Safety and Health (NIOSH) published a revised recommendation standard in 2016 titled: "*Occupational Exposure to Heat and Hot Environments*", and proposed a selection criteria along with heat stress indices to be used in hot and humid environments. It recommends several heat stress indices including direct indices (e.g. dry-bulb temperature and wet-bulb temperature), rational indices (e.g. operative temperature, skin wetness, and Belding-Hatch heat stress index), and empirical indices (e.g. the effective temperature, wet-bulb globe temperature, wet-globe temperature, and universal thermal climate index) *(Jacklitsch et al., 2016)*.

It is not practical to review and compare all the available indices based on the above mentioned methods. Generally, we know that to measure and collect a large number of physiological and human-related factors is not simple and practical in the underground mines. To investigate the validity of a heat index for use under realistic underground mining conditions, a climatic model based on the mine climate data, including air temperature, relative humidity, airflow velocity, and the physiological parameters of the miners in the form of metabolic rate and clothing was developed and proposed for mine climate assessments. The radiant temperature was assumed to be equal to the air temperature in the algorithm of the model since the radiation heat transfer is negligible compared to convective and conductive heat transfers.

For this research study, the Pierce Two-Node model was selected, as its algorithm was straightforward and easy to understand as a computer application for thermal comfort assessments, specifically, for mining engineering applications. Other models of thermal comfort *(e.g. Fanger, 1970)* are also worth considering.

The Pierce Two-Node model was developed at the John B. Pierce Foundation at Yale University. The model has been continually expanding since its first publication in 1970 *(Gagge et al., 1971)*. The most recent version of the model appeared in the 1986 ASHRAE Transactions *(Gagge et al., 1976)*. In the Pierce Two-Node model solution, the human body is modeled as two concentric cylinders, where the inner cylinder represents the core of the human body, and the thin outer cylinder represents the skin shell *(Doherty & Arens, 1988)*. The skin and core temperatures were calculated as a function of time by solving the heat balance at the core and skin nodes.

The rate of heat stored by the body (S) is given as the rate of metabolic heat production (M) minus the heat energy lost to the environment through the skin and respiratory tract, and the mechanical energy lost due to work as shown in equation 3.1:

$$M - W - Q_{sk} - F \pm C \pm R = S \ (W/m^2) \qquad \text{Eq. 3.1}$$

A simple expanded version of equation 3.1 is presented in equation 3.2, as follows:

$$M[(1 - \eta) - 0.0173(P_{sat} - P_a) - 0.0014(34 - t_a)] - 16.7(0.06 + 0.94W_{rsw})h_c(P_{sk} - P_a)F_{pcl} - h(t_{sk} - t_a)F_{cl} = \Delta s$$
Eq. 2.2

$$t_{skin} = 30 + 0.138\,t_a + 0.254\,P_a - 0.57V_a + 0.0128\,M - 0.553\,Rcl \qquad \text{Eq. 3.3}$$

$$F_{pcl} = 1/(1 + 0.344\,I_{cl}) \qquad \text{Eq. 3.4}$$

$$h_c = 0.608P^{0.6}v_a{}^{0.6} \qquad \text{Eq. 3.5}$$

$$h_r = 4.61(1 + (t_a + t_{sk})/546)^3 \qquad \text{Eq. 3.7}$$

$$h = h_c + h_r \qquad \text{Eq. 3.8}$$

$$F_{cl} = 1/(1 + 0.155h_c I_{cl}) \qquad \text{Eq. 3.9}$$

3.5. Results

Several heat stress indices mostly used for work comfort evaluation in mines were studied. The only exclusion criteria applied in selecting an index was that the index equation be unambiguously stated in the publication and that the required inputs are among our measured and estimated ventilation and climatic parameters such as relative humidity, air temperature, airflow velocity, barometric pressure, metabolic rate and clothing. Indices with input parameters which formed variants of the measured parameters were also

considered. Heat stress indices, mostly applied in underground mines, were calculated using the publications listed in Table 3.2.

Table 3.2. Heat index algorithms that have been used in this study.

No.	Index Formula	Reference
1	$Discomfort\ Index\ (DI) = 0.4 \times tw + 0.4 \times ta + 8.3$	*Thom (1959)*
2	$Discomfort\ Index\ (DI) = 0.5 \times tw + 0.5 \times ta$	*Sohar et al. (1962)*
3	$Modified\ Discomfort\ Index\ (MDI) = 0.75 \times tw + 0.3 \times ta$	*Moran et al. (1999)*
4	$Discomfort\ Index\ (DI)$ $= ta - (0.55 - 0.0055 * RH) \times (ta - 14.5)$	*Kyle W.J., (1994)*
5	$Thermohygrometric\ Index\ (THI)$ $= 0.55 \times tw + 0.2 \times t_{dew} + 5.3$	*Schoen (2005)*
6	$Humidex = ta + (5/9) \times (e - 10)$	*Masterson and Richardson (1979)*
7	$Wet\ bulb\ globe\ temperature\ (WBGT) = 0.7 \times tw + 0.3 \times ta$	*Yaglou and Minard (1957)*
8	$Effective\ Temperature\ (ET)$ $= ta - 0.4 \times (ta - 10) \times \left(1 - \left(\frac{RH}{100}\right)\right)$	*Houghton & Yaglou (1923)*
9	$New\ Effective\ Temperature\ (NET) = \frac{37-(37-ta)}{(0.68-0.0014 \times RH)} + \left(1/\left(1.76 \times 1.4 \times v^{0.75} - 0.29 \times ta \times (1 - 0.01 \times RH)\right)\right)$	*Gagge et al. (1971)*
10	$Thermal\ Strain\ Index\ (TSI) = \frac{1}{3} \times tw + 3/4 \times ta - 2 \times v^{0.5}$	*Lee (1956, 1958)*

The method evaluated each heat stress index to determine whether it conforms to the ascribed comfort zone in the Pierce Two-Node model. The modeling results of several cases for varying activity rates of 100, 150, 200, 250, 300 (W/m^2), and airflow velocity from 0.1 m/s to 1.5 m/s, relative humidity from 0% to 100%, skin wetness of 0.5 to 1, efficiency of 5% to 15%, and air temperature from 0˚C to 50˚C were studied. A non-acclimated worker is assumed to wear coverall and the underground environment was assumed to be a uniform environment ($T_a = T_r$). Based on this criteria, an "*appropriate*" index or set of indices were selected to be used in the prevailing mine climate and

physiological conditions (see Table 3.3). Any heat index algorithm can be used with any preferred activity and airflow velocity rate, in order to be assessed for acceptability.

Table 3.3. Recommended heat stress indices for comfort assessment based on various metabolic rates

Metabolic rate (W/m^2)	Appropriate heat stress index
100	ET, NET, TSI, WBGT, Humidex, THI, DI (1962), DI (1959), DI (1990), DI (1959), THI, DI (1968), DI (1998), DI (1963)
150	NET (RH<80), TSI (30<RH<70), ET, WBGT, Humidex, THI (RH>50), DI (1959), DI (1998), DI (1963), DI (1959) (RH<60)
200	Humidex, DI (1959), NET (RH<50), TSI (20<RH<40), ET (RH<50), WBGT (RH<80), THI (RH<50),
250	Humidex, DI (1959), NET (RH < 50), TSI (20 < RH <40), ET (RH < 50), WBGT (RH < 70), DI (1959)
300	Humidex (RH < 50), DI (1963) (RH < 50), DI (1959)

Figure 3.2 and 3.3 give visual valuations of how each particular heat stress index is performing relative to the generated comfort zone and provide a clear indication on the ability of the index to protect the mine workers. Contour plots depicted in Figures 3.2 demonstrate that, in uniform environments ($T_a = T_r$), with airflow velocity of 1.5 m/s and for an activity rate of 200 W/m^2, the "*discomfort*" index, in general deviates from the comfort zone. Furthermore, the "*effective temperature*" index does not perform very well relative to the comfort zone. However, the "*humidex*" heat index tends to perform quite well especially at higher humidity rates, which are typical of deep and hot underground mines. In terms of index performance relative to the comfort zone under these climatic and physiological conditions, The result of the simulation shows that the "*wet bulb globe temperature*" (WBGT) index seems to perform better than the other three indices and will therefore be an ideal candidate to be selected for assessing the comfort of the mine workers at metabolic rate of 200 W/m^2. Furthermore, the graphs show that the heat stress indices tend to be noisier relative to the comfort zone compared to the results obtained in the first

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case. This obviously reflects the heavy impact of an increased metabolic rate (e.g. work intensity) on the comfort of mine workers. At the metabolic rate of 250 W/m^2, however, all of the above indices failed to predict the comfort zone, particularly at high relative humidity, which is the case in most of underground operations (Figure 3.3).
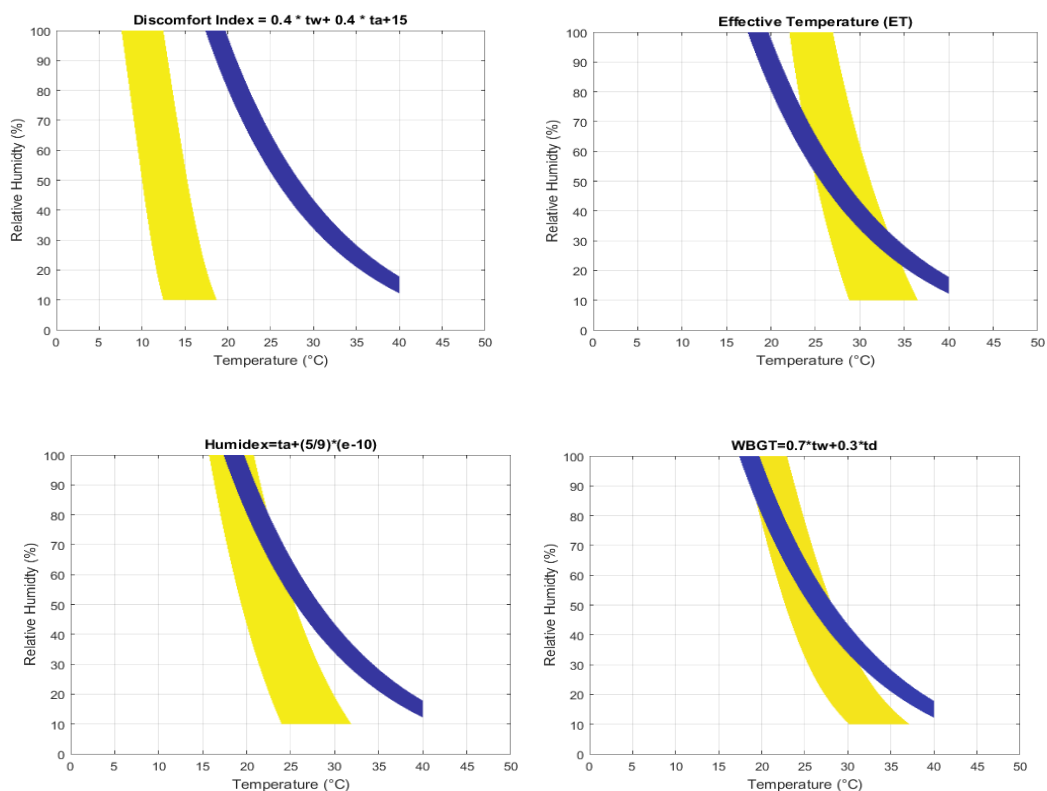
Figure 3.2. Convergence between selected heat stress indices (yellow) and comfort zone (blue), (M=200 W/m^2, V=1.5 m/s, W_{rse} = 0.7, Clothing: coverall).
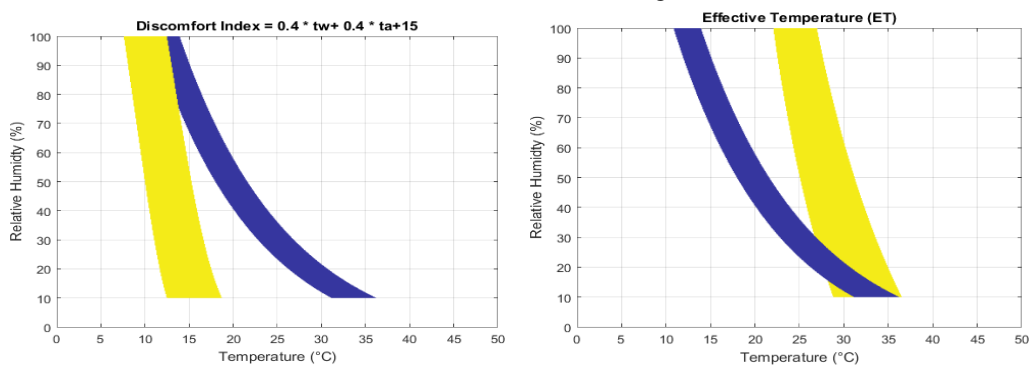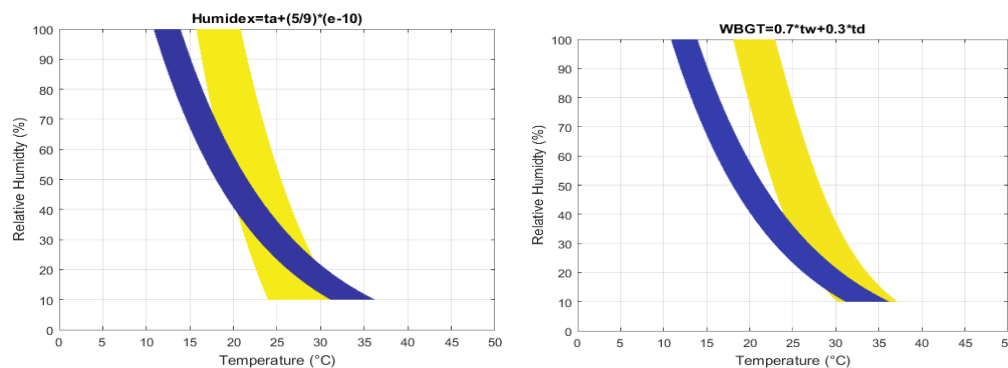
Figure 3.3. Convergence between selected heat stress indices (yellow) and comfort zone (blue), (M=250 W/m^2, V=1.5 m/s, W$_{rse}$ = 0.7, Clothing: coverall).

3.6. Recommended Selection Criteria

The problem with NIOSH *(Jacklitsch et al., 2016)* selection criteria is that no existing index meets all the requirements proposed by NIOSH. On the one hand, direct and empirical indices have relatively simple measurement and calculation procedures. They however, as shown in this study, do not incorporate the physiological comfort parameters for evaluating total strain. This is because many of these indices are developed using statistical and simple mathematical methods and are not based on the energy balance equation. Conversely, rational indices may be more comprehensive and accurate compared to other types of indices. However, the measurement and calculation procedures are complex and difficult to comprehend. Consequently, many of the underground mines in the US and world-wide may select an index while they are unaware of its limitations.

In extreme hot and humid conditions often faced by mine workers, the heat index used for comfort evaluation must be carefully selected. It should provide protection for the mine workers as much as possible. In order to optimize this selection process, it is recommended that index selection be classified based on two phases of mining, namely: *(a) Planning and Design Phase; and (b) Operational Phase*. This is essential since a well assessed

thermal condition in the planning and design phase will minimize the burden of managing heat stress in the operational phase. Furthermore, through this approach a more complex and complete analysis can be carried out in the planning and design phase as opposed to the operational phase, where it is essential that the index to be specifically selected for the local conditions and should not be complicated. In view of this premise the following factors are suggested to be considered when selecting an index based on the two discussed phases:

(a) Planning and Design Phase

- The index should be applicable for the purposes of underground mine climatic guidelines;

- The accuracy of the heat stress index must be proven by means of previous applications, or use;

- The purpose of using a heat stress index is to evaluate comfort limits, safe work limits, and/or to determine the optimum control method;

- All major factors contributing to the heat load during mining activities should be included in the work comfort assessment;

- The included factors should have a valid weight in relation to the total heat strain;

- Interpretation of the results should be straight-forward.

(b) Operational Phase

- The index should be applicable for the purposes of underground mine climatic guidelines;

- The purpose of using a heat stress index is to set exposure limits or threshold limit values under a wide range of environmental conditions;

- All the contributing factor should be measurable or reasonably assumed;

- The measurements, measuring instruments and protocols, and interpretation of the collected data and results should not interfere with worker's performance;

- Measurements and calculations should be simple;

- Interpretation of the index should be straight-forward.

3.7. Discussion

Which heat index is the most appropriate? The relationship between the comfort zone and the heat indices is simple and easy to comprehend. An almost superimposed relationship defines an "ideal" index for the conditions that describe the comfort zone and index. The primary appeal of heat indices should be *simplicity (McPherson, 1992)*. It is more likely that mine ventilation engineers and the mining crew in general will approve a thermal index due, in part, to the fact that the index can be presented in a format that they can understand and apply. That is, if the index is simple. Unfortunately, simple outputs also limit the appropriateness of the value to a specific or special case. The necessity of using numerous modifications to simple indices in order to adjust for various conditions, to a large extent, negates the apparent advantage of indices *(Roghanchi & Kocsis, 2017)*.

The comfort model used measured and estimated comfort parameters and compared output data generated from model runs with the measured ventilation and climatic parameters such as airflow velocity and activity rates. The computer algorithm for this model is based on the numerical solution of the heat balance equation and the heat transfer coefficients

recommended by the Pierce Two-Node model. Furthermore, the environment engineers are provided a tool to assess, identify and recommend a simple but appropriate index to be applied underground through the use of this simulation method described in this paper. The model run results depicted various responses of heat indices to different climate and physiological conditions. The results can be used to propose various suitable heat indices for work comfort evaluation. The method though complicated, provides an avenue for simple indices to be evaluated based on a comprehensive set of comfort parameters instead of their conventional reliance on the climate and mostly on two parameters only, the air temperature and humidity.

In conclusion, although there are many heat stress indices, there has never been a well-defined method or process to select an appropriate index for a particular underground climate. This has limited mine environmental engineers to select a heat stress index/indices based largely on intuition and guesswork. This method presents an important tool to assess and select the most appropriate index for certain climatic conditions in order to protect the underground workers from heat related illnesses. Although complex, the method presents results that are easy to interpret and understand than any of the currently available evaluation methods. It also gives the added advantage that simple indices can be assessed based on physiological comfort parameters. However, more research work is needed to further enhance the method and validate the climatic model to accurately assess the climatic conditions and select the most appropriate and safe index that will protect the mine workers.

Chapter 4 Evaluation of the Atmospheric and Underground Environmental Conditions by Means of Continuous Climatic Monitoring Systems – Lessons Learned

4.1. Measurement of heat stress in underground mines

Heat stress is the net heat load to which a workers is exposed from the combined contributions of environmental and physiological parameters which results in heat storage in the body *(Jacklitsch et al., 2016)*. Heat stress may be assessed by measuring the climatic and physical factors of the environment and then evaluating their effects on the human body via an appropriate heat stress index.

Metabolism in humans is accompanied by heat generation, with the core body temperature remaining a constant at about 36.9°C (37 ± 1°C) and in contact with surrounding climate temperature; mine workers have sensations expressed as either warm or cold. When workers are subjected to ambient temperatures greater than the threshold limits, it causes physiological effects expressed in the following forms: loss of attentiveness to other people's activities, taking regular rests or breaks, a longing to hurriedly complete the task, irritability, reduced concentration and reduction in sensitivity *(Navarro Torres & Raghu, 2011)*.

In underground mines, there are many sources of heat which cause the increase of temperature of air during its travel through mine airways. The mines intake air temperature gradually increases due to the depth and the length of air travel through the underground opening. One of the main sources of heat in underground mines is the strata temperature. Other sources of heat to the air in the underground atmosphere are air auto-compression,

machinery emission, explosive detonation, human metabolism and mine water thermal influx. The detail definition of major heat sources was presented in Chapter 2 (Section 2.3).

Heat is usually the dominant environmental problem in deep metal mines. Classifying and analyzing the heat sources in a mine allow for calculation of the total heat load. Stationary and moving heat sources are also necessary in understanding and modeling the heat and humidity transport. The potential heat sources in an underground mine are:

Table 4.1. Heat sources in underground mines

Heat Sources	Level of Significance	Nevada's Precious metal mines
Auto-compression	Low to high	Moderate
Strata heat	Low to very high	High (geothermal activity)
Underground water	Low to moderate	Low
Machinery	Low to very high	High (highly mechanized mine)
Human metabolism	Negligible to low	Negligible (highly mechanized)
Oxidation	Negligible to low	Negligible
Blasting	Negligible to low	Negligible
Rock movement	Low to moderate	Negligible
Pipelines	Negligible to moderate	Negligible

To understand and model heat and humidity transport, all major heat sources in an underground mine need to be identified and quantified. There can be a considerable difference in the spectrum of the heat and mine power source distributions between different mines due to many factors such as depth, mechanization, power sources, geothermal activity and rock thermal properties.

4.2. Measurement of Important Environmental Parameters in Underground Mines

4.2.1. Air Temperature

Ambient air temperature (air temperature/ dry-bulb temperature) defined as the temperature of the ambient air surrounding the worker that defines the net heat flow between the human body and its environment. The air temperature is the most significant component to the feel of comfort in a work environment. When the surrounding dry is high, this process becomes more difficult and a worker may overheat or feel warm. When the surrounding temperature is low, the rate of heat loss becomes more rapid, and the worker may feel uncomfortably cold *(Boduch and Fincher, 2010)*.

Several types of instrument are available to measure the ambient temperature whether as a single or continuous measurements. These instrument are equipped with different types of thermometer available including liquid-in-glass thermometers, thermocouples, and resistance thermometer. Regardless of the instrument type, following considerations should be taken to account:

1. The thermometer must be within the range of the temperature to be measured.

2. The thermometer must be stabilized before taking any measurements. Particularly, if the instrument is stored in a case or pocket.

3. The measurement must be taken in contact or close to the area of thermal interest.

4. Radiant condition must be considered. Measurement must be taken away from fans, compressors, pumps, mine vehicles, mine equipment, or any other heat source where the surface temperature is different from the air temperature.

5. It is recommended to take several measurements at a same location in several time steps in order to avoid any unusual temperature reading due to release of some gasses from the rib or back, oxidation, idling of equipment close to the unit, groundwater and more.

4.1.2. Relative humidity

Humidity, amount of water vapor within a given space, is usually measured as relative humidity, the ratio between the actual amount of water vapor in the air and the maximum amount of water vapor that the air can hold at that air temperature and barometric pressure. While temperature is the most important factor in generating a phenomenological sense of thermal comfort, relative humidity plays a critical role as a result of the dry-bulb and wet-bulb temperatures to provide a sense of comfort/discomfort. High levels of relative humidity can work against the evaporative cooling effects of sweating and leave the body prone to over-heating. When relative humidity gets too high, discomfort develops, either due to the feeling of the moisture itself *(ASHRAE, 2005)* which is unable to evaporate from the skin, or due to increased friction between skin and clothing with skin moisture *(ASHRAE, 2005)*.

Relative humidity can also be measured using several commercial instruments in the form of water vapor pressure, wet-bulb temperature, relative humidity, due point temperature and etc. Most of the hand held instrument also measure relative humidity. When measuring the relative humidity it is important to:

1. Calibrate the instrument before any measurements. The actual relative humidity can be significantly different from a measurement using uncalibrated instrument.

2. Take several measurements at a same location to insure that the measurement is not influenced by unusual activities.

3. If humidity is measured in a form other than relative humidity, three psychrometric parameters are needed to calculate the relative humidity. Therefore, it is a much easier to measure relative humidity if possible.

4. When a continuous measurement method is used, the measurements should be used with caution if the relative humidity is higher than 80%.

4.1.3. Air velocity

Airflow Velocity: is the average speed (with respect to location and time) of the air to which the worker's body is exposed. Airflow velocity distribution is a key factor influencing heat and mass transfer. Airflow velocity affects both the convective and evaporative heat transfer coefficients, and thus influences thermal comfort conditions *(McIntyre, 1978)*. The reaction of a worker to air movement is likely to be a complicated phenomenon as it depends on the climatic parameters including temperature, humidity, clothing, metabolic rate, and resulting skin temperature *(McIntyre, 1978)*. The designed airflow velocities along working faces of underground mines tend to range from 1.0 to 3.0 m/s *(McPherson, 1984; Mousset-Jones, 1986)*.

There are several instruments that can be used to measure the relative air velocity in an airway including van anemometer, thermoanemometers, pitot-tube and hand-held instruments. Several methods can also be used to measure the air velocity including fixed point measurement, smoked tube, Pitot-static tube, fixed point traverse, and moving traverse. It is usually recommended to take the average of at least three measurements with 5% difference as the relative air velocity.

4.1.5. Barometric pressure

Barometric pressure is the pressure exerted by the weight of air. Barometric pressure is elevated in deep underground mines and reduced at high altitude mines *(Donoghue, 2004)*. Increased barometric pressures in deep mines increase air temperatures, increase convective heat exchange and reduce sweat evaporation rates *(Gagge & Gonzalez, 1996)*. Correct measurement of barometric pressure directly impacts upon the calculation of wet-bulb temperature *(Hardcastle & Butler, 2008)*.

4.1.6. Metabolic rate

Worker's Metabolic Rate: is the energy released per unit time by the oxidation processes in the human body and is dependent on the amount of muscular activity. Metabolic rate varies according to the intensity of activity performed. Metabolic rate is also proportional to the body weight, body surface area, health, sex, age, amount and type of clothing, fitness, acclimatization, and surrounding thermal and atmospheric conditions *(Auliciems & Szokolay, 2007)*. Metabolic rate can be measured directly or estimated using less accurate (but much more practical) methods on the basis of tables of energy expenditure or task analysis tables (Table 4.1).

Table 4.1. Estimate of metabolic rate for activity *(ISO 7243, 1989)*

Rating	Activity	Metabolic Rate
0	Resting	$M \leq 65$ W/m^2
1	Low metabolic rate	$65 < M \leq 130$ W/m^2
2	Moderate metabolic rate	$130 < M \leq 200$ W/m^2
3	High metabolic rate	$200 < M \leq 260$ W/m^2
4	Very high metabolic rate	$M > 260$ W/m^2

4.2. Continuous Monitoring Systems for Assessment of Climatic Conditions in Underground Mines

There are many options for the measurement and monitoring of dry bulb temperature (T_d), barometric pressure (PB) and relative humidity (RH) on the market. The monitoring systems can be categorized into three groups: hand-held climatic instruments, continuous monitoring systems, and real-time monitoring systems. Table 4.1 shows a comparison between these types of monitoring systems.

The intent of climatic modeling in Nevada's underground mines is to identify and quantify the heat generated from the various sources in underground mines and to design and modify current airflow delivery systems. Because of this, the monitoring system selection is limited by the necessity of having one durable unit to measure the climatic parameters on a continuous time interval with the capability of storing and downloading the climatic data. Data storage is necessary because of the need to record data while there is no activity in the area and during the various phases of the mining cycle (e.g. drilling, explosive loading, blasting and mucking). The continuous monitoring units that were used throughout this research project were the "ACR Smart-Reader Plus 4" multi-channel data loggers (Table 4.2). These units continuously monitor and record dry-bulb temperature (T_d), relative humidity (RH) and barometric pressure (PB). From these parameters, the wet-bulb (T_w) temperature can also be calculated. These small devices can typically be installed at strategic locations to collect climatic data repeatedly. The recorded data can then be used to assess the underground climatic conditions and determine the combined heat load of the mine. This unit was capable of recording data at intervals specified by the user and had a 128 KB storage capacity (records up to 87,000 readings).

Table 4.2. Comparison between different types of climatic monitoring systems

Configurations	Hand-held monitoring instruments		Continuous monitoring systems	Real-time monitoring systems
Accuracy (Temperature sensor)	VISALA	±0.2 ˚C	±0.2 ˚C	±1 ˚C
	Kestrel	±0.1 ˚C		
Sensor	VAISALA	Platinum RTD	Thermistor	Loop fiber
	Kestrel	Thermistor		
Storage and download capability	VISALA	Up to 30 readings	128 Kb up to 87000 readings – include software with MS excel file format	Real time monitoring
	Kestrel	Storage only		
Size and flexibility	VAISALA	Hand-held	Small (107 mm x 74 mm x 22 mm)	Dimensions of 390 mm x 344 mm x 85 mm with the length up to 20 km
	Kestrel	Hand-held		
Power supply	VAISALA	AA battery	Built-in battery for 10 years	115 or 230 VAC, 50-60Hz; max 300W
	Kestrel	AAA battery		
Application	VAISALA	Spot measurement	Continuous measurement, pressure survey, dynamic modeling	Real-time monitoring, fire detection
	Kestrel	Spot measurement		
Cost	VAISALA	Under 1000 $	Under 1000 $	Over 1000 $
	Kestrel	Under 500 $		

Table 4.3. ACR smart-reader 4 multi-channel data logger specification

Smart reader plus 4 specifications	
Temperature	Temp. range: -40 ˚C to 70 ˚C Accuracy: ±0.2 ˚C Resolution: 0.07 ˚C
Pressure	Pressure range: 0 to 200 kPa absolute Accuracy: ±0.5% at 25 ˚C Resolution: 0.1 kPa
Relative Humidity	RH range: 10% to 90% Accuracy: up to 5% (measured at room temperature)

4.2.1. Advantages of Using Continuous Data Logger Type Monitoring Systems

1. The monitoring units are lightweight, small and can be installed at different locations in underground mine workings without interfering with operations (Figure 4.1).

2. The monitoring units include built-in batteries and do not require any external power source.

3. The monitoring units are low maintenance, and the calibration procedure is straight forward.

4. Recording and downloading the data is simple and quick. Downloading the data on a mobile computer can be done at the location that the unit is placed.

5. These units are inexpensive compared to the real-time monitoring systems and are fairly accurate for common climatic and ventilation surveys.

6. The units can be placed at key locations that other monitoring equipment cannot be placed. For example, the unit can be placed near the face of a production stope to capture the change in temperature and humidity during any phase of the mining cycle.

7. The units can measure climatic parameters inside the auxiliary ducts. The external probe is fairly small and can be inserted into the duct without significant damage to the ducting system.

Figure 4.1. The monitoring units can be installed at different locations without interfering with development and production operations

4.2.2. Applications of Continuous Climatic Monitoring Systems

4.2.2.1 Climatic monitoring and climatic control

Climatic data measurements are usually used to evaluate the thermal condition of an underground mine, to both identify and quantify the heat generated from main sources and to pinpoint the optimum heat control method for the problem areas. As the temperature, pressure and relative humidity fluctuate considerably during the day and night, continuous monitoring of different parts of a mine will be critical to understand and control heat problems in the mine accurately. A continuous monitoring system is required to identify the heat sources underground, as there are transient heat exchange processes between the ventilating air and surrounding environments. Figure 4.2 shows an example of temperature trends as a result of heat generated by equipment during mucking. The measured climatic data showed that it could be up to 24 hours for a development heading to reach equilibrium with the surrounding environment (no activity temperature).

4.2.2.2. Auxiliary climatic control

Even if the real-time monitoring method has an advantage over the logging type monitoring systems in primary ventilation systems, they cannot be used to assess the climate provided by auxiliary ventilation systems (e.g. in the production stopes). This is because auxiliary

ventilation systems are temporary and they are frequently extended and moved. Utilizing real-time monitors would prove challenging as they are not easily accessible, they have a greater chance of being damaged (particularly because of equipment movement and blasting) and they are certainly not economical. These shortcomings are highly unfavorable to use real-time monitoring systems to assess the climatic conditions where auxiliary ventilation systems are employed. On the other hand, all the advantages of the data logger type monitoring units make them very suitable for use in the development and production workings. Figure 4.3 and 4.4 shows the monitoring layout in a development heading.
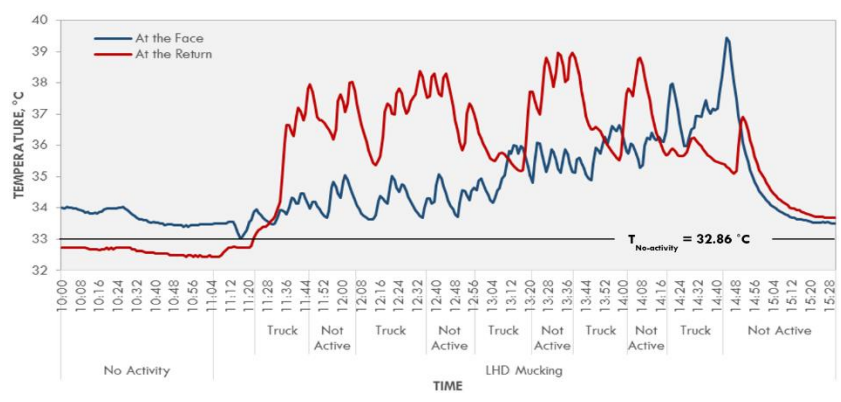
Figure 4.2. An example of dry-bulb temperature change during mucking and hauling operations
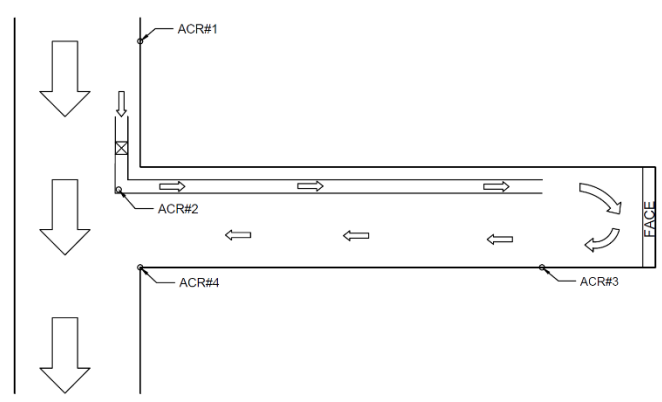
Figure 4.3. Typical layout of Data logger locations in a development heading
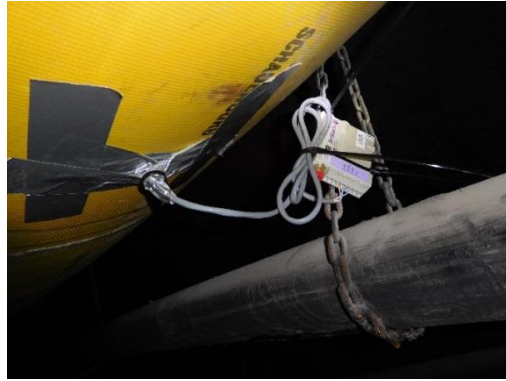
Figure 4.4. Data loggers installed at different locations in auxiliary ventilation system with minimal damage to the ventilation ducts

4.2.2.3. Barometry based pressure survey

Generally, two methods are used to determine barometric pressure differentials in underground mines. The Roving method can be performed by one person and the use of a surface barometer which records a stationary surface/atmospheric barometric pressure. The Roving method assumes that the barometric pressure in the mine and on the surface fluctuate concurrently. This limitation can be eliminated using the leapfrogging method when a barometric pressure survey is conducted simultaneously at two varying locations underground *(Loomis, 2004)*.

Both methods can be performed using continuous monitoring methods described in this paper. The most important advantage of using these types of monitoring systems is that there will be no requirement to have a team of one or two persons as the monitoring units continually log the data for the desired period of time. The second advantage of this method is that the pressure survey can be done in a safe manner and at a relatively lower cost, as it does not interfere with underground activities. With this method, the effect of any unusual activity (e.g. an open ventilation door) can be identified during the pressure survey.

4.2.2.4. Transient Heat Exchange Processes and Irregularities in Climatic Conditions

It is imperative that irregularities are incorporated into the measured data so that any unusual activities and rapid changes can be taken into account in ventilation system design. There are unknown sharp temperature fluctuations and data irregularities at different locations of an underground mine (Figure 4.6). The temperature fluctuations can be due to the release of gasses from the rib or back, oxidation, idling of equipment close to the unit, groundwater, etc. The fluctuation of temperature and other environmental parameters cannot be predicted using theoretical solutions and modeling. Dynamic heat exchange processes between the rock and ventilated air, like when an auxiliary fan is turned on and off, cannot be calculated using the standard climatic software. This information is critical particularly in cases where the environmental parameters are close to their threshold limit values (TLV). Continuous monitoring systems are the most suitable tools to identify and quantify these occurrences in an underground mine.
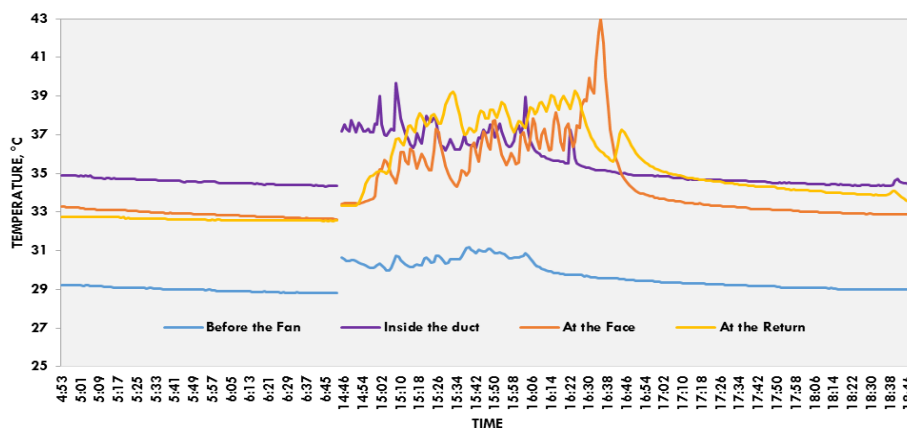
Figure 4.5. Sharp temperature fluctuation caused by unknown activities in the ramp before the auxiliary fan

Temperature damping is caused by the heat capacity of the rock mass that stores and then releases heat which then affects the temperature of the ventilating air. The way exterior air temperatures and heat flows affect an interior environment is also referred to as the

"thermal damping effect." For example, at the top of the shaft during summertime, the temperature on the surface fluctuates widely, from a high temperature of 33 °C during a sunny midday to a low temperature of 19 °C in the middle of the night. However, the bottom of the shaft will experience a much smaller temperature fluctuation. The shaft wall acts as an energy reducing mechanism and reduces the amplitude of the temperature wave *(Danko, 2013)*.

During day time, the dry bulb temperature (T_d) of the air in the intake shaft, heated by auto-compression, develops higher values than the Virgin Rock Temperature (VRT) of the surrounding rock at some locations. Consequently, sensible heat is transferred from the intake air into the surrounding rock, thus cooling the air. At night, however, there is a greater potential for the heat to flow from the surrounding rock formations into the ventilating air, increasing the air temperature. We recognize this phenomenon as the "thermal damping effect" (see Figure 4.6).
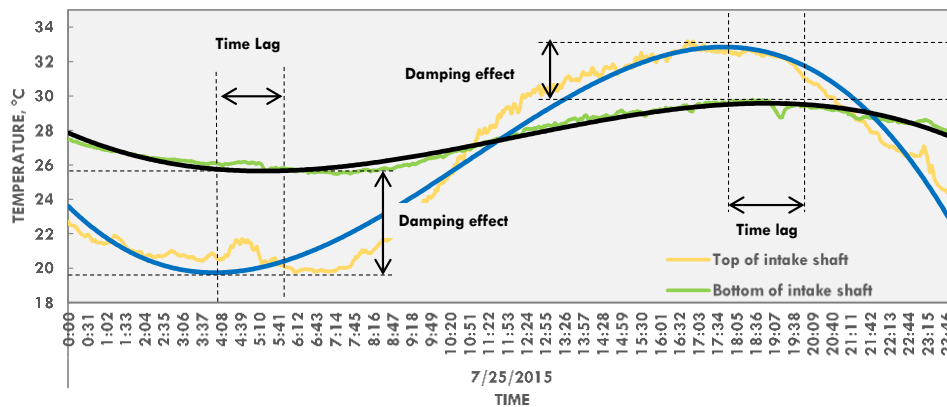
Figure 4.6. Thermal damping effect in an intake shaft

4.2.3. Challenges in Using Logging Type Monitoring Systems

1. For extreme climatic situations, particularly when the relative humidity is more than 85% to 90%, these types of monitoring systems fail to record the climatic parameters properly (see Figure 4.7). In particular, locations with high relative humidity (e.g. exhaust shafts) can take up to several hours for the monitoring units to recover.

2. These units are typically not built for extreme environmental conditions such as those in underground mines. Each must be cleaned on a regular basis (every two weeks) to remove the dust and other contaminants from the units in order to obtain accurate readings.

3. These units cannot be installed in hard to reach locations (e.g. close to booster fans) as they need to be accessible for data downloading and cleaning on a regular basis.

4. It is recommended to test and validate the accuracy of the units periodically as they may fail to record climatic data. In several circumstances, the units failed to record any data for a period of one month.

5. The size of the units can be a challenge because they can be damaged by mining equipment or mining operations (shotcrete, water seepage) without being noticed by the mine workers.

6. The logged data should be compared with a more accurate handheld instrument as dust and contaminants may cover the sensors and consequently can compromise the accuracy of the units. Relative humidity readings should be specifically examined.

7. The collected data must be verified with the operation schedules and mining cycles at the underground mine. There are always enormous fluctuations that need be removed from the data, particularly for thermal and management purposes.

8. The meaning of the vast amount of data is usually difficult to process and analyze.

9. The mine is never truly at steady state, and the measurements may be delayed such as during rapid and hazardous changes. In these cases, real-time monitoring systems are recommended.
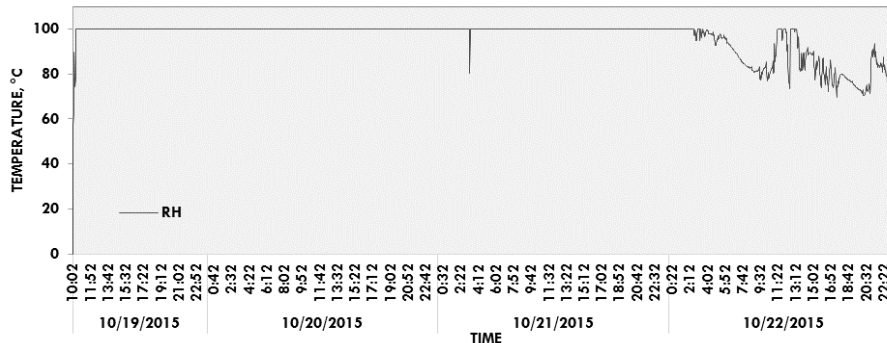
Figure 4.7. Failure of the monitoring unit when relative humidity (RH) readings exceed 90%

4.3. Climatic Monitoring Plan using Continuous Climatic Monitoring System

To assess the atmospheric and underground environmental conditions at one of our partner mines in Nevada, multi-channel climatic monitoring units were installed along vertical and horizontal airways from surface to the lowest production level. The climatic data collection program focused on monitoring both primary and auxiliary ventilation systems in order to: 1) determine the heat load and temperature changes due to auto-compression and geothermic gradient; 2) identify and quantify the damping effect (DE) and the thermal

flywheel effect (TFE), particularly in the intake shaft; 3) gather adequate data for development and calibration of steady state and dynamic ventilation-thermal (V-T-H) models; 4) quantify the heat generated by the primary and auxiliary fans, mining equipment and strata; 5) develop a best practice ventilation and climatic monitoring program for our partner mines in Nevada.

During this project, twelve multi-channel data loggers were used. Several hand-held instruments (e.g. VISALA, Kestrel, FLUKE, anemometer, barometer, etc.) were utilized to examine the accuracy of the data loggers and perform ventilation and climatic spot measurements throughout the mine. Equipment activities were also obtained from the mine in electronic format, in which equipment locations and the type of work were indicated at one-minute intervals. The activities were sorted by location and time so that they would correspond to the climatic data obtained. This was used to find periods of time that corresponded to the mining cycles. Table 2 demonstrates the monitoring program for the primary and auxiliary ventilation systems at the mine.

4.4. Calculation of Major Heat Sources in Underground Mines – A Case Study

Surface air sent down to the underground workings, through either natural or manmade ventilation, will experience a compression. This means that although the volume of air has been reduced, the amount of heat remains the same resulting in hotter air (McPherson, 2009).

To calculate the heat added to the ventilating air, the steady flow energy equation gives (McPherson, 2009) :

$$\Delta H = g.\Delta Z + \Delta q \hspace{4cm} Eq.\ 4.1$$

where ΔH is the change of enthalpy (J/kg), g is gravitational acceleration (g= 9.81 m/s2),

ΔZ is the depth of the opening, and Δq is the heat added from surroundings (J/kg). The

change in enthalpy as a result of autocompression can then be calculated as follow

(McPherson, 2009):

$$\Delta H = g.\Delta Z \hspace{4cm} Eq.\ 4.2$$

The temperature raise caused by autocompression is determined as (McPherson, 2009):

$$\Delta T = 0.0071(\Delta z) - 2428.7\ \Delta x\ \ (°C) \hspace{3cm} Eq.\ 4.3$$

where ΔT is the temperature raise (˚C) and Δx is the change of the moisture content

(kg/kg dry air). To calculate the temperature raise based on the climatic data, the vertical

shaft was modeled in Climsim. The same opening was modeled as a horizontal opening

in order to capture the temperature raise from the strata heat (Δq). The difference is the

temperature raise as a result of autocompression (see Table 4.5 as an example).

Table 4.2. Calculation of temperature raise caused by autocompression

Location	Vertical opening			ΔT_d (˚C)	Horizontal opening			ΔT_d (˚C)	Difference ΔT_d (˚C)
	T_d	T_w	BP		T_d	T_w	BP		
Top	22.71	10.48	84.116	4.22	22.71	10.48	84.116	-1.11	5.33
Bottom	26.93	13.08	89.136		21.6	10.4	83.65		
Top	20.73	9.04	84.253		20.73	9.04	84.253		
Bottom	25.02	11.73	89.317	4.29	19.69	8.97	83.783	-1.04	5.33
Top	20.03	8.73	84.323		20.03	8.73	84.323		
Bottom	24.36	11.44	89.403	4.33	19.03	8.66	83.851	-1	5.33
Top	22.22	9.6	84.323		22.22	9.6	84.323		
Bottom	26.42	12.25	89.366	4.2	21.09	9.52	83.855	-1.13	5.33
Top	28.99	11.95	84.323		28.99	11.95	84.323		
Bottom	32.75	14.45	89.255	3.76	27.41	11.86	83.865	-1.58	5.34

Calculating the heat load from mining equipment based on in-situ data can be conducted with two main methods: 1. Equipment activity surveys at production areas and throughout the mine site; 2. Mapping equipment activity based on the dispatch data. In this study, dispatch equipment activity data was used to quantify the heat load coming from equipment. Table 4.5 shows an example of equipment activity mapping at a development.
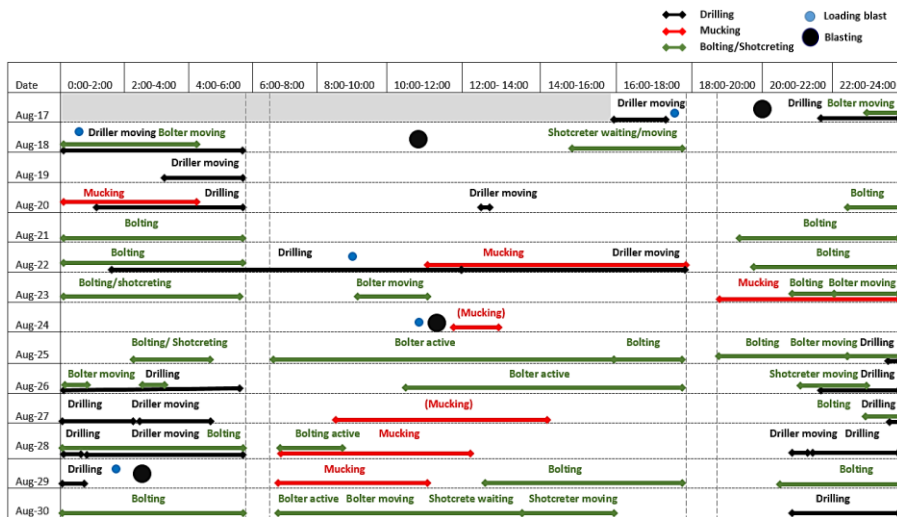
Figure 4.8. Equipment activity data based on the dispatch data at a development heading

The advantage of this method is that the heat generated by each equipment can be estimated at different time/location (see Table 4.6). The average temperature change by mining equipment can also be estimated. Figure 4.9 shows an example of the average temperature at the face and the return when there is an activity in the development.
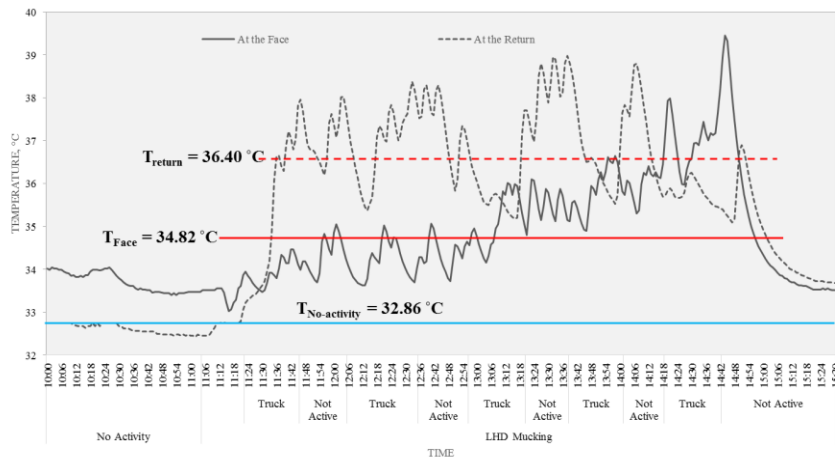
Figure 4.9. An example of equipment activity at the development and the average temperature change at the face and the return

Table 4.3. Temperature changes for each equipment activity and the average changes during a 24 hours period

Date	Activity	T_d (°C)	T_w (°C)
	Bolting	1.38	-0.11
9/18/2015	Average Activity	1.23	-0.22
	Bolting/Moving	5.34	0.37
	Driller moving	0.11	-1.05
	Mucking	4.80	1.53
	Bolting/Moving	1.73	0.38
	Powder truck	-0.01	-0.57
	Mucking	2.11	0.80
9/19/2015	Average Activity	1.96	0.47
	Bolting	1.24	1.95
	Powder truck	0.35	0.71
	Mucking	4.02	-0.23
	Bolting	0.15	-0.23
9/20/2015	Average Activity	2.04	0.82
	Mucking	3.07	2.79
	Mucking	3.22	2.79
9/21/2015	Average Activity	3.12	1.62

Figure 4.10 and 4.11 show the average dry-bulb temperature raise during fourteen days of data collection at the development face and the return. The heat flux can then be calculated from using the conductivity and convention coefficient of the air for each airway.
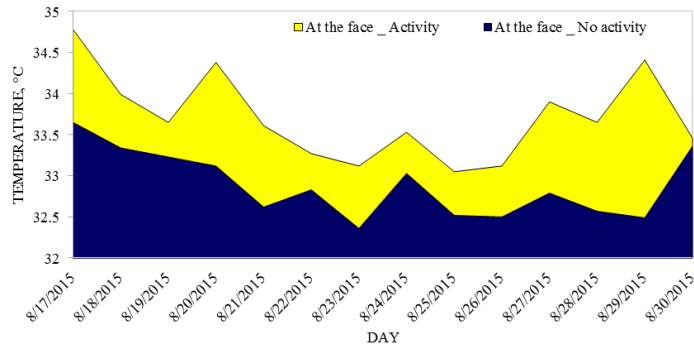
Figure 4.10. Dry-bulb temperature increase with equipment activity at the development
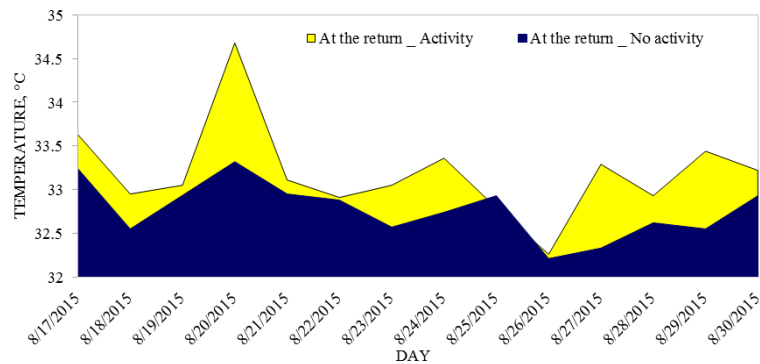
Figure 4.11. Dry-bulb temperature increase with equipment activity at the development

Heat emission from the strata depends on the type of rock, the exploitation method depth, and geometry of the airways. However, the amount of heat transmitted decreases over time, the working faces being where the greatest transmission takes place. The heat coming from strata can be calculated using theoretical solutions (heat flux from conduction and convection heat transfers). For accurate and detailed planning, a mine climatic simulation package can be employed. Heat from strata can be obtained using empirical methods based

on other similar mines. For example, Whillier *(1981)* exposed an equation method that defines two expressions depending on the time since an airway was opened:

$$q = 3.35 \, L \, k^{0.854}(VRT - T_{d.avg}) \qquad\qquad\qquad Eq. \ 4.4$$

$$q = 6 \, k \, (L + (4 \times DFA))(VRT - T_{d.avg}) \qquad\qquad\qquad Eq. \ 4.5$$

where q is the heat flow from strata (W), L is the length of the tunnel (m), k is the thermal conductivity of the rock (W/m˚C), VRT is the virgin rock temperature (˚C), DFA is the daily face advance (m), and $T_{d.avg}$ is the average dry-bulb temperature.

There are several other sources that add heat load to the ventilation system. Note that there was no information about the influx of underground water and backfilling. Calculations regarding the total heat load of the mine indicate that the contribution of this heat source is negligible. Heat generated by backfilling equipment were considered in the equipment heat load. The heat load profile of the mine site is shown in Figure 4.12 with the surface temperature is 16.3 ˚C. A heat load profile was also develop for the surface air temperature of 28.5 ˚C (Figure 4.13). The contribution of different major heat sources to the total heat load of the mine is presented in Table 4.7. A comparison between the heat load profiles shows that the heat exchanges in underground mine is dynamic. Therefore, the heat load profile of the mine should also be at a dynamic state. Furthermore, the surface temperature can drastically change the heat exchanges throughout the mine. Though often ignored, the temperature of the surface air can have a significant impact on the air temperature underground. The surface air temperature can influence the temperature of air flow in the

atmosphere of underground openings during particular seasons of the year and depend on the altitude of the mine.

HEAT LOAD PROFILE
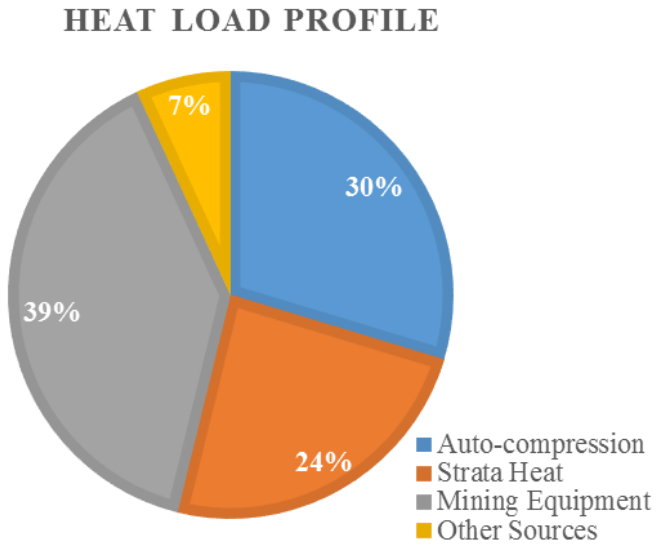
Figure 4.12. Quantifying major heat sources in our partner mine, $t_{d\ (surface)} = 16.32\ ^{\circ}C$

HEAT LOAD PROFILE
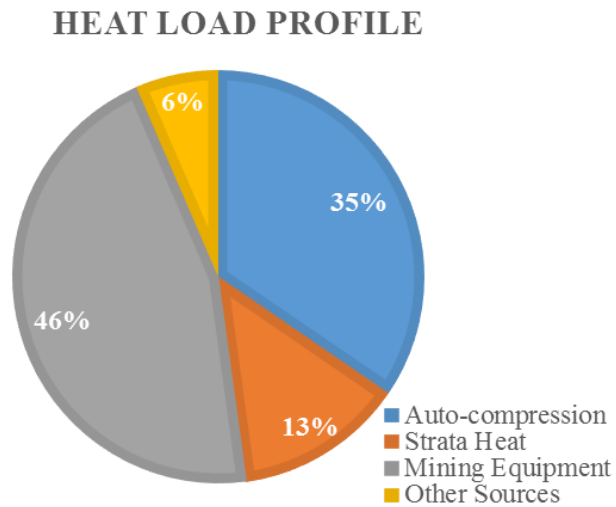
Figure 4.13. Quantifying major heat sources in our partner mine, $t_{d\ (surface)} = 28.5\ ^{\circ}C$

Table 4.4. Contribution of different major heat sources to the total heat load of the mine

	Air Heat content	21.44 kJ/kg
	Total Heat capacity	10376.40 kW
	$t_{d\,(surface)} = 16.32\ ^\circ C$	$t_{d\,(surface)} = 28.5\ ^\circ C$
Heat source	**Heat load (kW)**	**Heat load (kW)**
Auto-compression	3257.75	3257.75
Strata Heat	2651.2	1252.9
Equipment	4312.25	4312.25
Other Sources (Including backfill)	756.25	609.7

4.5. Discussion

Though the chosen monitoring units hold many advantages, they are useless for data collection without a well-designed monitoring program. Choosing the right unit for measurements of the required parameters, identification of critical locations to be monitored and the timing of monitoring are critical when these type of monitoring units are used. For example, if the distance between two units in the primary ventilation system is too large, there will be several occurrences that cannot be captured and the collected data will be rendered useless. It is important to install the monitoring units at the top and bottom of the intake shaft during each period of climatic and activity monitoring in order to have a robust understanding of the intake climatic condition.

Calculation of the heat make up in an underground mine is important to establish the total airflow requirement for metal/non-metal underground mines. The main objective of an efficient underground ventilation system is to supply oxygen to workers, to remove and dilute pollutants generated by mining processes (dust, heat, gasses) and to ultimately provide a suitable thermal environment for workers and machinery. Mine intake air

temperature gradually increases due to the depth and the length of air travel through underground openings. The main cause of heat transfer to the ventilating air underground is due to the increase of strata temperature with respect to depth, which is known as the "geothermic gradient." The geothermal flow of heat emanating from the core of the earth can be much higher in regions of anomalous geothermal activity. Furthermore, with increasing depth through a succession of various rock formations, the geothermal step, which is the inverse of the geothermic gradient, can also vary according to the thermal conductivity and diffusivity of the rock formations. Other sources of heat that can transfer to the ventilating air includes air auto-compression, mining equipment (diesel, electrical), explosive detonation, human metabolism and influx of thermal water.

To understand and model heat and humidity transport, all major heat sources in an underground mine need to be identified and quantified. There can be a considerable difference in the spectrum of the heat and mine power source distributions between different mines due to many factors such as depth, mechanization, power sources, geothermal activity and rock thermal properties *(Kocsis & Hardcastle, 2010)*. Figure 4.14 shows an example of the heat load profiles in three mines in Canada, Australia, and precious metal mine in Nevada. As shown in this figure the contribution of each heat load changes from mine to mine. Understanding the major heat source that has the highest contribution to the total heat load of the mine is also important to in order to select the optimum heat control method. For example, in the case that heat generated by autocompression is high, the design of the shaft should in a way that promote the heat transfer to the surrounding environment. On the other hand, when heat coming from the strata is high, localized cooling system can be applied to control the heat load in working

areas. The main airways can also be isolated so that the heat transfer from the rock to the ventilating air is minimized. Diesel equipment can be replaced with electrical equipment in the case that heat generated by mining equipment is significant. Apart from the electrical engines'' higher energy efficiency, less consumption of diesel would mean a drop in temperature and pollutants concentration.
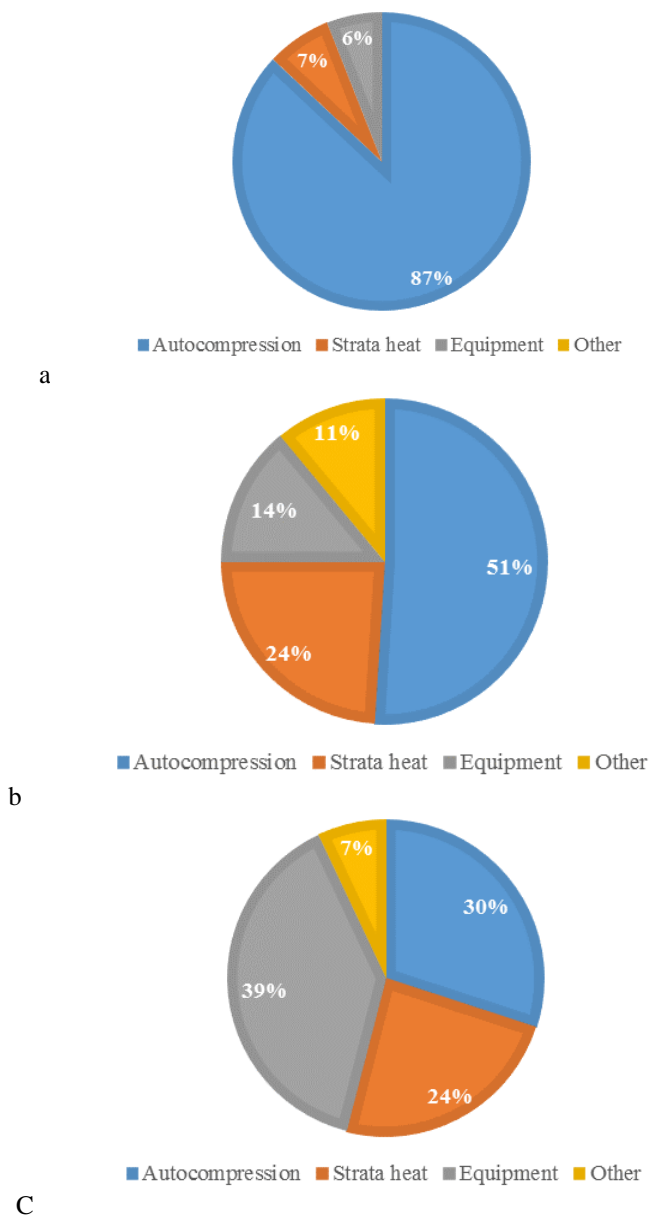
Figure 4.14. Comparison of heat load profile in different regions; (a) Canada *(Kocsis & Hardcastle, 2010)*; (b) Australia *(Brake, 2002)*, and USA

Table 4.5. Summary of the monitoring program at the mine

	Primary system (mine-wide)	Auxiliary system (work areas)	Intake shaft
Locations	Zone 1: At the top and bottom of the intake and exhaust shafts Zone 2: From the bottom of the intake shaft to the lowest production area Zone 3: From the lowest production area to the bottom of the exhaust shaft	Location 1: A dead-end development heading with an auxiliary fan Location 2: A production area with multiple production faces with a single fan Location 3: A production area with single/multiple production faces with a single or multiple fans	At the top and bottom of the intake and exhaust shafts
Purpose	1. To quantify the heat load from auto-compression, strata heat, groundwater and geothermal gradient 2. Develop and calibrate a dynamic ventilation-thermal-humidity (V-T-H) model	1. To quantify the heat load from equipment associated with backfilling, blasting and auxiliary equipment 2. To optimize auxiliary ventilation systems to mitigate heat transfer to the mine air	1. To identify and quantify the thermal damping effect 2. To understand the transient heat exchange processes between the mine air and the surrounding environment
Monitoring Plan	Twelve ACR units were installed throughout the primary systems in the direction of airflow to record climatic data at one-minute intervals for two weeks Spot measurements for ventilation/climatic parameters and surface rock temperature were performed to validate the continuous measurements Ventilation surveys were performed to measure air volumes and the barometric pressure at the locations of ACRs	ACR units were installed at top and bottom of the shaft to capture the intake air quality ACR units installed before/after the auxiliary fan, inside/outside the duct, near the face and along the return drift to record climatic data at one-minute intervals for two weeks Spot measurements for ventilation/climatic parameters and surface rock temperature were performed to validate the continuous measurements Ventilation surveys to measure air volumes and barometric pressures at the locations of the ACRs	ACR units were installed at top and bottom of the shaft to record climatic data at one-minute intervals for a month Record any rain, snow, outside temperature, barometric pressure and unusual activities that affect the intake air temperature

Chapter 5 - Improving the climatic conditions in development and production workings of hot underground mines by re-designing the auxiliary ventilation system - Case study # 1

5.1. Skin temperature as an index for evaluation of mine climatic condition

The skin, by means of function, is the body's thermostat. The body's heat exchange mechanism involves sensible heat transfer at the skin surface (via convection and radiation), latent heat transfer (via moisture evaporating and diffusing through the skin), and through sweat evaporation on the skin surface *(Arens & Zhang, 2006)*. The human skin regulates the body temperature by means of the actions of blood circulation through the vessels and by the process of sweating and evaporation. If the body is subjected to heat waves in hot climates, the mechanism of sweating is activated due to increased blood flow to the vessels. This process cools the body off as the sweat evaporates from the skin. The work of Bulcao et al. *(2000)* revealed the significance of skin temperature in evaluating thermal comfort in humans. The human body controls the skin temperature to balance the heat gain and heat loss. This makes the use of skin temperature a considerable potential as an index to determine thermal sensation and comfort. Thermal equilibrium in the human body is achieved through a balance between metabolic heat production and heat loss from the body. Heat storage in the body will result in an increase in the average body temperature, which is a weighted average of the core temperature and mean skin temperature *(Mehnert , et al., 2000)*.

5.1.1. Skin temperature as a heat stress index

Skin temperature depends on the air temperature and the time spent in that environment. Such climate factors such as airflow velocity and humidity cause changes in skin temperature. The normal temperature of the human skin is about 33°C. The flow of energy to and from the skin determines our sense of hot and cold. Heat flows from higher to lower temperature, so the human skin will not drop below that of surrounding air, regardless of the airflow. If a person was to be in a hot environment and his/her skin temperature was cooler than the air, his/her skin temperature would rise. The opposite would happen in a cold room and warm skin temperature. The person's temperature would decrease. Humans fight variations in air temperature by becoming warm or cold. When warm, they sweat. When cold, they get chill *(Elert, 2015)*.

Among the environmental parameters that determines thermal comfort, mostly air temperature, humidity, radiation and airflow velocity are often measured and combined into indices which will indicate, whether the climatic conditions at any time will produce satisfaction for its occupants *(Roghanchi et al 2015)*. In extreme hot climates all parameters are important, nonetheless only temperature and humidity have been combined into most commonly used indices *(Driscoll, 1992)*. Also, these indices conspicuously avoid including the physiological parameters of comfort in their prediction. The problem in combining these parameters and expressing them as a single reliable indicator of comfort is the reason for dangerous omissions. Another problem is related to the use of indices which, seemingly integrate these elements together, but often give an indicator very close to the actual ambient air temperature *(Driscoll, 1992)*, thereby introducing an element of erroneous impression that the air temperature can assess thermal comfort.

The inadequacies discussed above are avoided by using rational indices, of which, the skin temperature can be significant in playing the role of an index or a physiological input for comfort models. These indices often involve the six generally accepted comfort parameters in predicting thermal safety in extreme hot climates *(Roghanchi et al 2015)*.

5.1.2. Mean skin temperature calculation

Having established the significant role of skin temperature for comfort assessment in warm environments, it is important to define a method to accurately predict its numerical value. Several heat stress indices use either a fixed mean skin temperature or a prediction model, which incorporates some or all physical factors of the thermal environment as well as the clothing insulation and the metabolic rate *(Kocsis & Hardcastle, 2010)*. A fixed value is easy to use, however, in conditions with dynamic exposure to heat, this can result in over-estimations or under-estimations resulting in errors in the heat balance analysis *(Sunkpal, 2015)*.

Direct measurement of skin temperature is often not practically feasible *(Mairiaux et al., 1987)*. A lot of the methods available for predicting skin temperature have inherent limitations. Some are developed for resting subjects, while others are formulated based on insufficient data, or lack of comprehensiveness. For underground mining purposes, a predictor must involve a working subject and be able to predict with accuracy and precision over a wide range of environmental conditions *(Mairiaux et al., 1987)*.

The estimation of mean skin temperature can be achieved using the equation 5.1 proposed by Mairiaux et al. *(1987)* as follows:

$$t_{skin} = 30 + 0.138\ t_a + 0.254\ P_a - 0.57\ V_a + 0.0128\ M - 0.553\ Rcl \quad (°C) \qquad Eq.\ 5.1$$

There appears to be no compromise among comfort/environmental researchers regarding the effect of the metabolic rate on the skin temperature. Fanger's thermal comfort model was developed based on the proposition that skin temperature decreases with increasing metabolic rate *(Fanger, 1970)*. Some researchers reported a direct relation trend in results between skin temperature and activity rates *(Adams, 1977)*. Others found the metabolic rate to have no effect on the skin temperature *(Missenard, 1973)*. From the equation adopted for this study, it is apparent that the effect of the metabolic rate on the mean skin temperature, though minor compared to the contributions of the other comfort parameters, cannot be ignored.

5.2. Sensitivity Analysis of the Effect of Airflow Velocity on Thermal Comfort in Underground Mines

Ambient airflow velocity is acknowledged as one of the critical parameters to improve the thermal comfort of the mine workers, and it has been considered in all known comfort standards. Usually, minimum and maximum airflow velocity limits are determined and mandated in underground mines where mine personnel work and travel. To dilute most pollutants, a common minimum airflow velocity for airways where personnel work and travel is 0.3 m/s *(MacPherson, 2009)*. However, in production workings, airflow velocities usually vary from 1 m/s to 3 m/s. The recommended maximum airflow velocity in the production areas is 4 m/s. Above airflow velocity of 4 m/s, significant discomfort can be experienced by the underground workers because of the impact of large dust particulars that are carried by the airflow *(Houghton & Yaglou, 1923; Nevins, 1971; Fanger & Pedersen, 1977; McIntyre, 1979; Christensen et al., 1984; Fanger & Christensen, 1986; Berglund & Fobelets, 1987; Zhou, 1999; Toftum, 2002; Griefahn et al.,1997)*. Particularly

in underground metal and non-metal mines, where high airflow velocity may generate dust dispersion, which causes serious health hazards *(Kurnia et al., 2014; Donoghoue, 2004; MacPherson, 2009; Hartman et al., 2012).*

For decades air movement has been used as a strategy in hot and humid environments by mine ventilation and comfort engineers to increase the rate of the cooling of the occupants. For example, Humphreys *(1970)* developed an empirical equation to estimate the relative comfort temperature based on constant airflow velocity of 0.1 m/s and above. Mclntyre *(1979)* found 28 °C to be the highest comfortable temperature at 1.4 m/s for male occupants and 1 m/s for female occupants. Rohles et al., *(1983)* found pleasant levels beyond what had been previously considered reasonable (up to 1 m/s at 29.5 °C). Spain *(1984)* found that an airflow velocity of 0.25 m/s provided comfort for air temperatures up to 27.8 °C, while 1 m/s provided comfort up to 29.4 °C. Holm and Engelbrecht *(2005)* uphold that air movement at temperatures below 37 °C cools the body while it begins to heat it at temperatures above 37 °C. Candido et al., *(2010)* found that the minimally acceptable airflow velocity for Brazil's hot and humid climatic zone needs to be at least 0.4 m/s for 26 °C, reaching 0.9 m/s for operative temperatures up to 30 °C. As observed by Fountain and Arens *(1993)*, the focus of most mine ventilation practitioners is often to deliver the required air volumes to the production workings. This is often done to the disadvantage of achieving the required airflow velocity for thermal comfort. However, apart from air quality, what is also desired at the work-face by miners is comfort, safety, and satisfaction with their working environment.

A method was developed and adopted in the form of a "comfort model" to predict the optimum airflow velocity required to maintain heat comfort for the underground workforce

at different activity levels (e.g. metabolic rates). A detailed calculations and model development can be found in Roghanhci et al., *(2017)*. This study analyzed the effect of air velocity with air temperature on the thermal comfort of miners. The technique included the use of a two stress criteria of maximum skin wetness and maximum sweat rate, and the strain criteria of maximum dehydration. In this study, airflow velocities of 1 m/s and 2 m/s, which will guarantee thermal comfort, were determined by means of climatic modeling and simulation exercises. Based on the pattern of the results, the authors recommend an optimal airflow velocity of 1.5 m/s throughout production workings.

5.3. Climatic data collection layout

The mine being studied is located in central/western Nevada. The existing primary ventilation system is of exhaust type, with a booster fan located at the bottom of the ventilation shaft. The auxiliary ventilation systems are designed based on a "forcing" type setup, with the auxiliary fans sized to deliver the required fresh air to the face.

Fresh air is usually picked up from the ramp and delivered to the face along a flexible fabric duct under the assistance of a 100 hp auxiliary fan. The development heading is normally advanced with conventional drilling and blasting. Broken rock is removed using 3 and 6 yard^3 LHDs and 20 and 30 ton haul trucks. During the mine climate and equipment activity monitoring program, the 6 yard^3 LHDs and the 30-ton haul trucks were used.

The locations for the monitoring units were selected based on critical model development needs. A dead-end development heading in an underground mine ventilated by means of a "forcing" type auxiliary system was selected for our climatic study. The ACR monitoring units were installed as follows: (1) before the auxiliary duct in the main airway, (2) after

the auxiliary fan inside the fabric duct, (3) at the end of the duct, (4) at the working face, (5) along the drift in the return airway, and (6) at the main return.

An ACR monitoring unit was placed at each of these locations and they were set to record climatic parameters at one-minute interval. The unit in the main airway was used to establish an input baseline of temperature, pressure, and relative humidity. The unit after the auxiliary fan located inside the auxiliary duct was used to determine the heat added by the fan. The unit at the end of the duct showed the conditions of the fresh air before being delivered to the working face, so that the changes that occurred due to equipment activity and heat transferred to the mine air from the broken ore/rock could be determined. The ACR unit at the working face was removed during blasting and re-installed in the advancing heading to capture both strata heat and activity at the face. This unit was approximately 15 m away from the working face. The unit placed along the drift in the return air captured the combined heat and moisture added at the working face, as well as from passing equipment. The final unit in the main return captured the combined heat and moisture added to the return air throughout the system being modelled.

5.3.1 Climatic model development

A climatic model was developed to simulate the heat loads and the climatic conditions at the face and along the return drifts. The model was developed based on the intake ventilation and climatic parameters, the heat load from the auxiliary fans along the duct, and throughout the development. Various heat load zones were identified within the auxiliary ducting system and throughout the development heading. The climatic model for the current design is categorized into six zones to simulate the system, as follows:

Zone 1: auxiliary duct before fan

Zone 2: auxiliary duct with fan

Zone 3: auxiliary duct from fan to end of the duct

Zone 4: end of the duct to the face

Zone 5: development face to end of the duct (return)

Zone 6: end of the duct to end of return airway

In the current auxiliary ventilation system, air is forced to the development face by means of a 100 hp auxiliary fan through a flexible fabric duct. Approximately 23 m^3/s of fresh air with an average dry-bulb temperatures (T_d) of 32.17 ˚C and wet-bulb temperature (T_w) of 28.52 ˚C passes through the auxiliary duct. The dry-bulb temperature of the air in the duct after the auxiliary fan reaches values from 34.15 ˚C to 36.89 ˚C. When there is no equipment activity, hot air losses heat to the surrounding rock. Table 5.1 shows the climatic parameters of the mine throughout the development, which were than used for model development and simulation purposes.

Table 5.1. Measured data at the development

ACR Location	Dry-bulb Temperature (˚C)	Wet-bulb Temperature (˚C)	Barometric Pressure (kPa)
Auxiliary duct before the fan	32.17	28.52	90.762
Auxiliary duct after the fan	35.11	--	92.769
Approx. 15 m away from the face	33.99	33.99	90.528
At the development return	33.92	29.50	90.597

The climatic model was calibrated against the collected data. Table 5.2 shows the results from the climatic model runs compared to measured data. As shown in Table 5.2, the dry-bulb and wet-bulb temperatures at the interest points are in good agreement with the

collected data from the mine. However, the predicted wet-bulb temperature is quite lower compared to the measured values at the development face. The ACR unit at the face was unable to accurately record all variations in relative humidity during the mining cycles, as the unit recorded 100% relative humidity for values above 90% humidity. For such situations the wet-bulb temperature generated from model runs were compared to the wet-bulb temperature values that were measured manually. Figure 5.1 shows an example of dry-bulb temperature and relative humidity recorded by the ACR unit at the face.
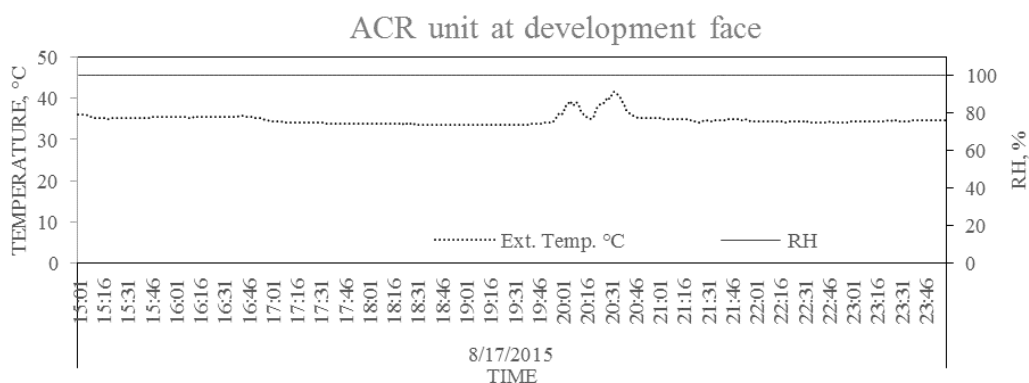
Figure 5.1. An example of recorded relative humidity at the face. Relative humidity stays at 100% for approximately 9 hrs.

Table 5.2. Comparison between measured data and climatic model results

Location	Dry-bulb Temperature (˚C)		Wet-bulb Temperature (˚C)	
	Measurement	Climatic model	Measurement	Climatic model
Auxiliary duct before the fan	32.17	32.17	28.52	28.52
Auxiliary duct after the fan	35.11	35.83	--	29.55
App. 15 m away from the face	33.99	34.69	33.99	29.41
At the development return	33.92	34.37	29.50	29.39

Different scenarios were simulated to identify and develop an improved auxiliary ventilation system where work can be performed for various activity levels. The wet-bulb temperature changes were plotted to illustrate the effect of various re-design strategies for auxiliary ventilation system. Maximum skin temperatures at face and along the return

airway were also compared with the maximum allowable skin temperature for different metabolic rates.

5.3.2. Case study 1 - Auxiliary ventilation system with no equipment activity

In the first case scenario, no active equipment was operating in the development area. This will be a phase of the mining cycle where geological surveys or borehole mapping is conducted at the face. Based on the equipment activity data, more than 40% of the time of monitoring the area was inactive. The results of heat modeling show that work at the face can be performed at low to moderate levels of metabolic rate ($M<300$ W/m^2). Furthermore, the working area is not safe for higher levels of metabolic rate ($M>300$ W/m^2). In order to maintain a safe working area, different scenarios were considered and examined which looked at re-designing the auxiliary ventilation system at this location. These scenarios included:

1. Use of a "forcing" system with:

a) Increasing airflow velocity at the face from 0.5 m/s to 1 m/s

b) Increasing airflow velocity at the face from 0.5 m/s to 1.5 m/s

2. Use of an "exhausting" system with:

a) Current condition assuming that the airflow velocity at the face is 0.5 m/s

b) *Increasing the airflow velocity at the face from 0.5 m/s to 1.5 m/s*

Climatic simulations showed that changing the auxiliary ventilation system from a "forcing" setup to an "exhausting" setup doesn't significantly affect heat removal at the face. This can be explained by considering the heat exchange between the ventilated air and surrounding rock. With a "forcing" auxiliary ventilation system, the heat from high air

temperatures goes into the surrounding rock, while with and "exhausting" setup heat is transferred to the ventilating air as a result of lower air temperatures than the surrounding rock temperature. Furthermore, the results generated through climatic simulations and presented in Table 5.3 demonstrate that increasing the airflow velocity in a "forcing" setup (e.g. scenario 1-b) is sufficient to mitigate the heat load from the dead-end development for metabolic rates ranging from 200 W/m^2 to 350 W/m^2. Figure 5.2 and Figure 5.3 illustrate the effects of re-designing the auxiliary ventilation system based on the wet-bulb temperature throughout the development heading.

Table 5.3. Comparison between the skin temperature limit and maximum skin temperatures

Auxiliary system	Metabolic rate (w/m^2)	Skin temperature limit (˚C)	Maximum skin temperature (˚C)	
			Face	Return
Current ventilation system	200	34.98	33.34	33.24
	250	34.38	34.12	33.92
	300	33.52	*34.10*	*34.64*
	350	32.29	*34.88*	*35.53*
1 m/s air velocity at the face	200	34.98	32.73	32.69
	250	34.38	33.25	33.21
	300	33.52	*33.78*	*33.76*
	350	32.29	*34.46*	*34.40*
1.5 m/s air velocity at the face	200	34.98	30.88	30.67
	250	34.38	31.50	31.25
	300	33.52	32.11	31.82
	350	32.29	32.25	31.98
Exhaust system	200	34.98	33.05	33.09
	250	34.38	33.60	33.62
	300	33.52	*34.39*	*34.42*
	350	32.29	*35.16*	*35.19*
Exhaust system with 1.5 m/s velocity at the face	200	34.98	31.98	31.99
	250	34.38	32.62	32.65
	300	33.52	33.10	33.11
	350	32.29	*33.51*	*33.53*
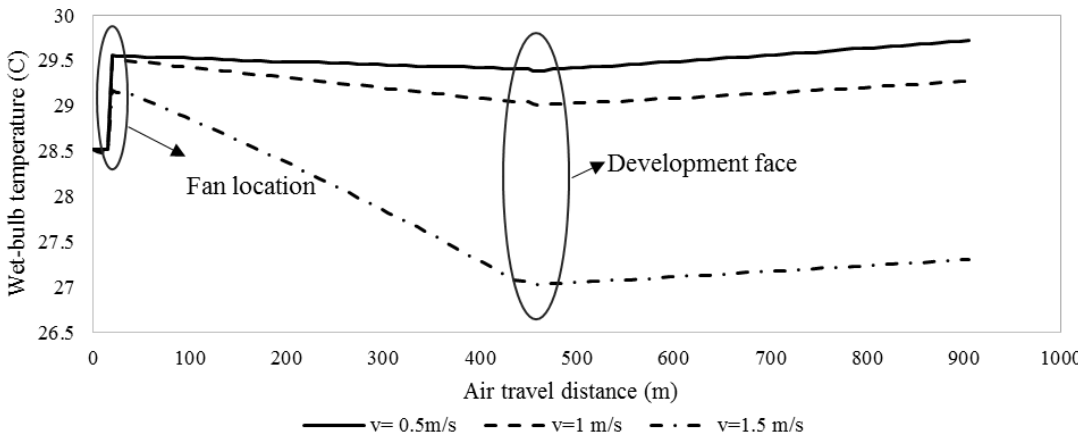
Figure 5.2. The effect of air velocity on the wet-bulb temperature for forcing auxiliary systems
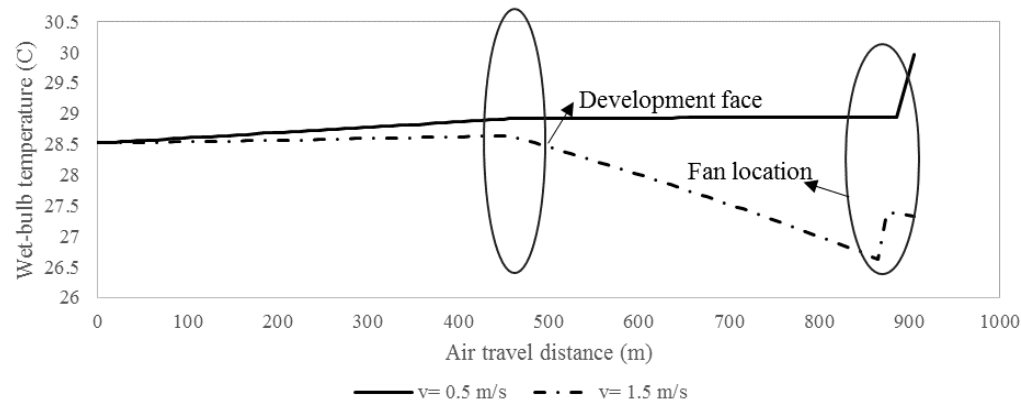
Figure 5.3. The effect of air velocity on the wet-bulb temperature for exhausting auxiliary systems

5.3.3. Case study 2 - Auxiliary ventilation system with an active drilling equipment

For climatic modeling purposes, a 75 kW CAT electric Jumbo Drill was considered to be operating at 5 m from the development face. The climatic model was calibrated against the collected climatic data. The results generated through climatic simulations showed that with the current auxiliary ventilation system, the underground climatic condition will only allow low activity levels with metabolic rates less than 250 W/m^2. Different scenarios were examined to improve the efficiency of the auxiliary ventilation system in order to mitigate

the heat load when the Jumbo Drill is active at the face. These scenarios included the use of a "forcing" system with:

a) *Increasing the airflow velocity at the face from 0.5 m/s to 1 m/s*

b) *Increasing airflow velocity at the face from 0.5 m/s to 1.5 m/s*

c) *Placing a 200 kW spot cooling system at approximately 15 meters away from the face with 1.5 m/s airflow velocity*

d) *Placing a 250 kW spot cooling system at approximately 15 meters away from the face with 1.5 m/s airflow velocity*

Figure 5.4 shows the changes in wet-bulb temperature for the airflow delivery scenarios mentioned above. As shown in Table 4, for high activity rates (M>300 W/m^2), a spot cooling system is required to remove the heat load at the face. To maintain a safe working area throughout the development heading, a 250 kW spot cooling system is required. Climatic simulations show that a cooling system is needed when the temperature of the temperature of the fresh air is more than the comfort limit temperature (t_w=28 ˚C). It can be assumed that same ventilation system delivers sufficient air volumes when the bolter is active at the face.
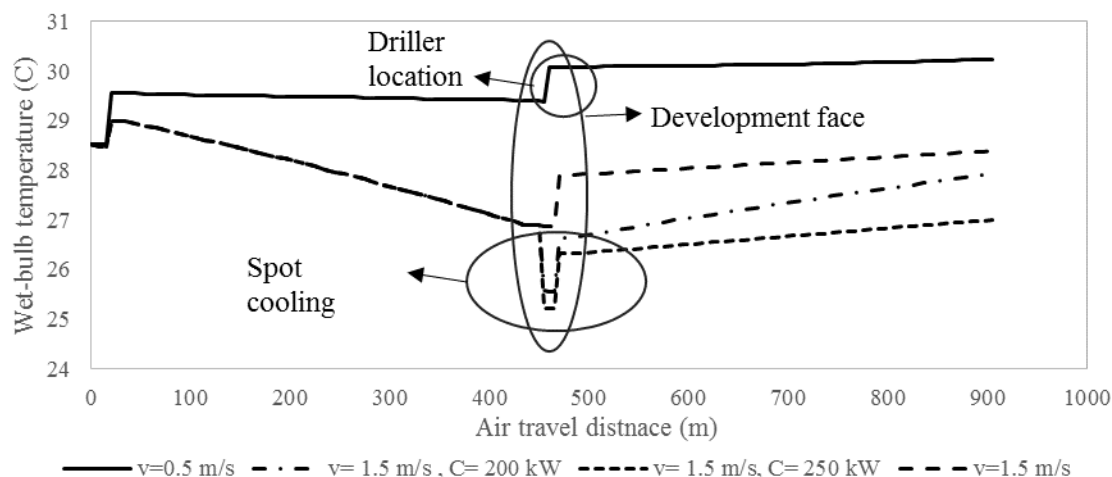
Figure 5.4. Wet bulb temperature changes based on different scenarios when the drill is active

4.3.3. Case study 3: Auxiliary ventilation system with an active LHD and haul truck:

LHDs and haulage trucks produce the largest amount heat in dead-end development headings. At this mine, 3 to 6 yard^3 LHDs are usually utilized for moving fragmented rock and ore along the development headings and production areas. LHDs are also used to move the fragmented ore from the draw-points to the ore/rock pass if the hauling distance is appropriate. For longer distances (when the fragmented ore/rock needs to be taken to the ore/rock pass at a significant distance from the draw-pint), haulage trucks are used. Figure 5.5 shows the change in dry-bulb temperature (T_d) at the development face and at the development return.

Table 5.4. Comparison between allowed skin temperature limits and maximum skin temperatures for drilling operations

Auxiliary system	Metabolic rate (w/m^2)	Skin temperature limit (˚C)	Maximum skin temperature (˚C)	
			Face	Return
Current ventilation system	200	34.98	33.37	33.72
	250	34.38	*34.83*	*34.44*
	300	33.52	*35.60*	*35.15*
	350	32.29	*36.34*	*35.84*
1.5 m/s air velocity at the face	200	34.98	30.90	31.82
	250	34.38	31.50	32.40
	300	33.52	32.10	32.88
	350	32.29	*32.67*	*33.31*
200 kW with 1.5 m/s air velocity at the face	200	34.98	29.51	31.1
	250	34.38	30.21	31.41
	300	33.52	31.69	32.00
	350	32.29	31.54	*32.56*
250 kW with 1.5 m/s air velocity at the face	200	34.98	29.26	30.58
	250	34.38	29.96	31.19
	300	33.52	30.65	31.78
	350	32.29	31.30	32.28
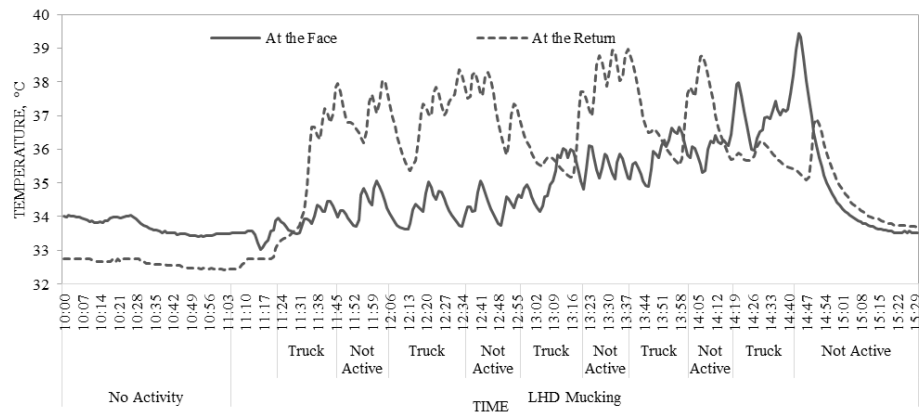
Figure 5.5. Example of dry-bulb temperature variation during mucking and haulage activities

For modeling purposes, a 6 yard^3 LHD is considered to be operating at 5 m away from the face (zone 4). A 30-ton haul truck is simulated as a linear heat source along the development heading (zone 6). This simulation does not take into account the time that is needed for the air to travel from a point to another point and the temperature changes generated by the haul truck when idling of waiting to be loaded by the LHD. However, comparisons between model simulation results and measured ventilation and climatic parameters show relatively good agreements. The results generated through model simulations (see Table 5.6) indicate that the current ventilation system cannot deliver sufficient air volumes to the face of the dead-end development heading for even low activity levels. Figure 5.6 illustrates the effects of re-designing the auxiliary ventilation system based on the wet-bulb temperature throughout the development.
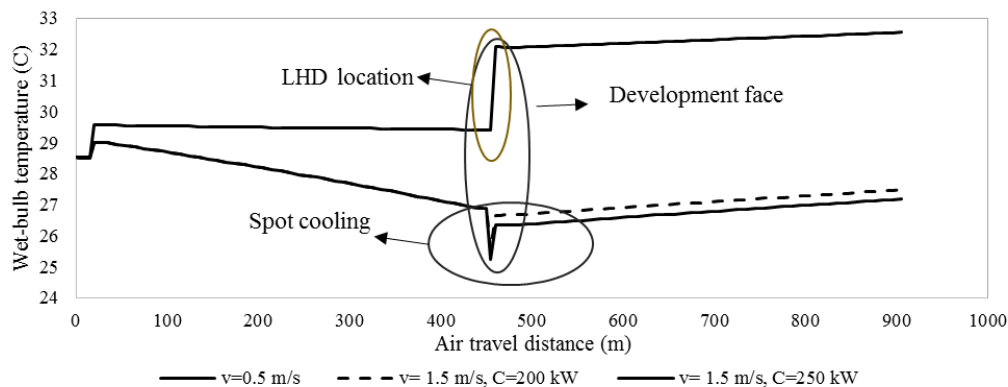
Figure 5.6. Wet-bulb temperature changes based on different scenarios for mucking and hauling

Table 5.5. Comparison between allowed skin temperature limits and maximum skin temperatures during mucking

Auxiliary system	Metabolic rate (w/m²)	Skin temperature limit (˚C)	Maximum skin temperature (˚C)	
			Face	Return
Current ventilation system	200	34.98	*35.91*	*35.94*
	250	34.38	*36.65*	*36.61*
	300	33.52	*37.38*	*37.28*
	350	32.29	*37.94*	*37.80*
200 kW with 1.5 m/s air velocity at the face	200	34.98	30.06	30.62
	250	34.38	30.72	31.23
	300	33.52	31.37	31.82
	350	32.29	*32.58*	*33.39*
250 kW with 1.5 m/s air velocity at the face	200	34.98	29.83	30.41
	250	34.38	30.50	31.01
	300	33.52	31.16	31.61
	350	32.29	31.79	32.18

5.4. Conclusions

This case study aimed to evaluate heat load and its distribution in a dead-end development heading at one of our partner mine in Nevada. Climatic monitoring units were installed at the entrance of a development heading, inside the auxiliary ducting system, at the development face and along the return drift to measure and record the dry-bulb temperature, relative humidity and barometric pressure. Numerical models for three case studies were developed and calibrated against the collected data to evaluate the heat load in the development heading. Comparison between maximum skin temperatures and allowable skin temperatures indicate that a 0.5 m/s airflow velocity at the face does not

deliver sufficient fresh air in order to mitigate the heat load at the face and maintain adequate climatic conditions during the mining cycles. Furthermore, the results show that spot cooling systems may be required if the mine workers are performing heavy work at high metabolic rates. Climatic simulation showed that re-designing the auxiliary ventilation system from a "forcing" arrangement to an "exhausting" arrangement would not reduce the dry-bulb and wet-bulb temperatures at the face of development headings, even when there is no activity.

Chapter 6 - Improving the climatic conditions in development and production workings of hot underground mines by re-designing the auxiliary ventilation system - Case study # 2

6.1. Auxiliary Ventilation Systems in Underground Metal Mines

Auxiliary ventilation systems are used to supply fresh air to the working areas and development headings. In metal mines, the auxiliary system includes auxiliary fan(s) and a ducting system. The auxiliary system should not have any impact on the primary ventilation system and the distribution of airflows throughout the main ventilation network. The choice between forcing or exhausting systems depends on the pollutants at the face such as dust, gasses and heat.

6.1.1. Forcing auxiliary ventilation system

Forcing auxiliary ventilation systems, also known as pushing systems, deliver fresh air to the face of production headings without intake air contamination from external sources. Use of forcing ventilation systems also provides cooler air to the immediate face *(Carpenter et al., 2015)*. Air leakage from the duct is not completely wasted because it aids in reducing the contamination along the return airways. Another advantage of a forcing system is that flexible ducting can be used due to positive pressure along the ducting system. The main disadvantage of using forcing auxiliary ventilation systems is that pollutants added to the air at the face will affect the entire length of the drift as the return air passes back along it. Furthermore, high velocity air flow at the face may create dust control problems.

6.1.2. Exhausting auxiliary ventilation system

The main advantage of using exhausting ventilation systems, also known as pulling systems, is that the pollutants, blasting gases and dust within the immediate vicinity of the face can be immediately drawn into the duct while allowing fresh air to flow through the length of the drift. The contaminated air routes will extend from the face to the ducting system and will not affect the return airways. Dust filters can also be used to capture dust from the contaminated air before exiting the auxiliary duct. The main disadvantage of exhausting auxiliary ventilation systems is that the end of the duct needs to be maintained close to the face in order to avoid uncontrolled recirculation at the face. Another disadvantage is that the fresh air traveling through the heading to the face can draw heat from the surrounding rock formations and other sources. Consequently, the intake air at the face will be likely hotter compared to forcing auxiliary ventilation systems. In addition, exhausting ventilation systems require rigid, non-collapsible ducts. This means higher capital costs in the short term.

6.2. Assessment of the climatic conditions along the production headings

The mine being studied is located in Northern Nevada. The current primary ventilation system is an exhaust type system with a booster fan located at the bottom of the exhaust shaft. The auxiliary ventilation consists of forcing type systems with auxiliary fans ranging from 50 to 150 hp as a function of ducting length and air volume requirements.

A typical auxiliary system consists of fresh air being drawn from the ramp and delivered to the face through flexible fabric ducts under the assistance of a 100 hp auxiliary fans. The production headings are normally advanced with conventional drilling and blasting. Broken rock is removed using 3 and 6 cubic yards LHDs and 20 and 30-ton haul trucks.

During the climatic and equipment activity monitoring program the 6 cubic yard LHD and the 30-ton haul truck were used.

The locations where the ACR monitoring units were installed were as follows: on the rib of the ramp or access drift before the auxiliary fan, inside the duct after the auxiliary fan, at the working face, along the heading to capture the climatic parameters of the return air and at the combined return drift in case of multiple production faces. A monitoring unit was placed at each of these locations and each were set to record the climatic parameters every minute. The unit installed in the main airway was used to establish an input baseline of temperature, pressure and relative humidity. The unit installed after the fan in the auxiliary duct was used to establish the heat added by the fan. The unit at the working face was removed during blasting and re-installed in the advancing heading to capture both strata heat and activity at the face. This unit was installed approximately 15 m away from the working face. The units placed along the drift in the return air captured the combined heat and moisture added at the working faces, as well as by the passing equipment. The final unit in the main return gave the total moisture and heat added to the system being modelled.

A climatic model was developed to simulate the individual heat loads and the climatic conditions at the production faces using Ventsim^{TM} software. The model was developed based on the intake airflow conditions, the heat load throughout the auxiliary ducting system and along the production faces. In the current auxiliary ventilation system, air is delivered to the production headings using a 100 hp auxiliary fan through a flexible fabric duct. Approximately 32 m^3/s of intake air with an average dry-bulb temperatures (T_d) of 29.5 ˚C and wet-bulb temperature (T_w) of 25.6 ˚C passes through the auxiliary duct. Table

1 shows the characteristics of the intake air throughout the production area used for climatic simulation purposes.

Table 6.1. Climatic data at the production area when there is no equipment activity (median)

Locations	V (m/s)	T_d (°C)	T_w (°C)	BP (kPa)
Before the auxiliary fan at the main airway		29.5	25.6	91.010
After the auxiliary fan inside the duct	2.15	33.8	-	-
APH # 1	0.3	31.69	28.51	90.697
APH # 2	0.2	31.29	31.29	90.941
APH # 3	0	31.42	26.1	91.045
Main Return	0.5	32.56	26.78	90.804

The climatic model was calibrated against the collected data (Table 6.2). As shown in the Table 2, dry-bulb and wet-bulb temperatures at the interest points support the collected data from the mine. However, the predicted wet-bulb temperatures are quite lower compared to the measured wet-bulb temperatures at the development face. The ACR unit at the face was not able to record the correct relative humidity since the humidity at this location exceeded the unit's capability. The ACR unit recorded 100% for humidity above 85%-90%. Figure 6.1 shows an example of the recorded data by the ACR unit at the production face.

Figure 6.2 shows the contribution of main heat sources in the production area. The total heat added to the system is approximately 82.3 kW in which the auxiliary fan has the highest contribution to the total heat load of the system. Note that there was no information about the influx of underground water. Calculations regarding the total heat load of the mine indicate that the contribution of this heat source is negligible.

Table 6.2. Simulation results of climatic parameters from the calibrated Ventsim model

Locations	V (m/s)	T$_d$ (˚C)	T$_w$ (˚C)	BP (kPa)
Before the auxiliary fan at the main airway	2.2	29.4	25.6	91.0
After the auxiliary fan inside the duct	--	32.9	26.2	92.1
APH # 1	0.3	31.3	26.1	90.9
APH # 2	0.2	31.3	26.0	90.9
APH # 3	0.1	31.3	26.1	91.0
Main Return	0.6	31.3	26.1	90.9
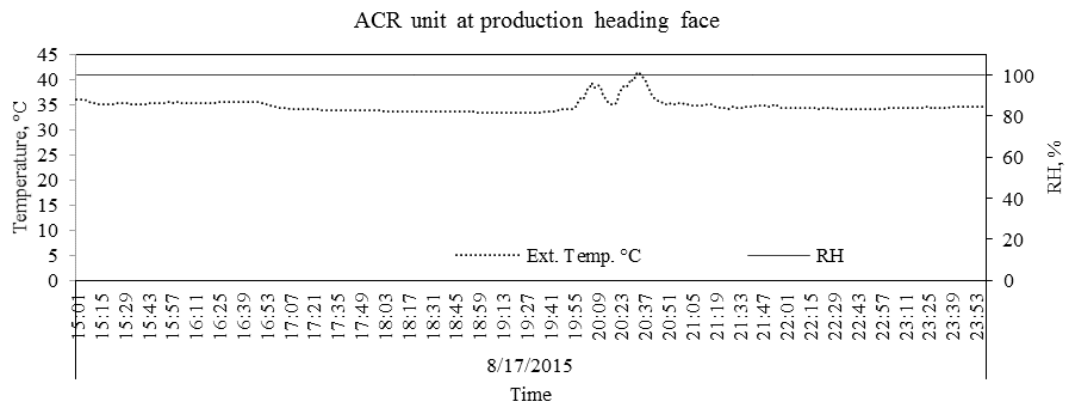
Figure 6.1. An example of measured relative humidity values at the face. Relative humidity stays at 100% for approximately 9 hours
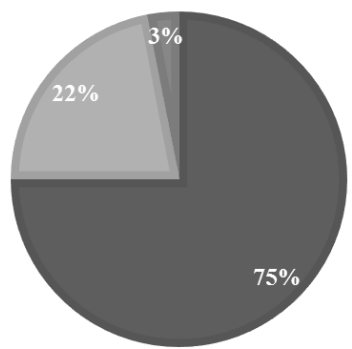
Figure 6.2. . Heat load profile in the production area when there is no activity (total heat load of 82.3 kW)

6.3. Modeling Results

Several other pertinent scenarios have been studied in order to develop optimized auxiliary ventilation systems at this location of the mine. The scenarios included different mining operations as well as no activity time frames (geological surveys or borehole mapping), drilling operations (75 kW CAT electrical jumbo drill) and mucking operations (3 cubic yards LHD and 30 ton haulage truck). For all scenarios, wet-bulb temperature and WBGT were recorded and compared when forcing or exhausting systems are employed. Furthermore, spot cooling systems were placed at different locations in production headings in order to decrease the temperatures in the immediate areas of the production faces. For each scenario it was assumed that a notable concentration of arsenic was present at the active heading.

For example, it was assumed that a 3 yard^3 LHD is active at the APH #2 production heading. Considerations were also given to the fact that arsenic concentrations may be present at the APH # 2 face. Different cases were simulated to examine both forcing and exhausting auxiliary ventilation systems to determine the optimum auxiliary ventilation arrangement where work can be comfortably performed. Table 6.3 shows the results of the simulations for both forcing and exhausting systems. For each scenario, environmental and climatic parameters were recorded at each face of a production working and at the returns. The results of the climatic simulations demonstrate that employing an exhausting auxiliary ventilation system is advantageous in order to decrease the air temperature in the working areas and the return airways. When a forcing system is used, the heat generated by the auxiliary fan(s) affects the whole production area and the return airways. Furthermore, the energy added by a larger auxiliary fan (150 hp) increases the air temperature at the

immediate face which results in hotter air compared to an exhausting system. Use of multiple intake fans (150 hp & 50 hp) decreases the heat load at the face significantly. However, a comparison between this scenario and a single 150 hp exhausting system reveals that exhausting system delivers the same atmospheric condition. Therefore, use of an exhausting system may be more economical.

Another advantage of using an exhausting system is that spot cooling systems can be placed at locations relatively far from the working face without interfering with the work cycles. When a forcing system is used, spot cooling system must be placed either in the intake airways before the auxiliary fan or close to the immediate face of the dead-end heading or production face. The problem with placing a spot cooling system before the auxiliary fan is that the cooled intake air will draw an increased amount of heat from the surrounding rock formations and will be heated by the auxiliary fan. Spot cooling system near the face of a production working will interfere with the mining cycle and may not be economically feasible.

The use of exhausting auxiliary ventilation systems is definitely beneficial if a contaminant such as arsenic dust is present at the immediate face. Table 6.4 shows the results of various auxiliary ventilation simulation scenarios where 100 units of arsenic dust concentrations were present at the face. Dynamic simulations of contaminant dilution demonstrate that although the initial concentration of arsenic dust might increase at the stope and along the main return, the reduction and clearance time of the contaminant is faster at higher air volumes.

Table 6.3. Results of different simulation scenarios using Ventsim Model

Location	V (m/s)	Q (m³/s)	T_d (°C)	T_w(°C)	WBGT (°C)	V (m/s)	Q (m³/s)	T_d (°C)	T_w(°C)	WBGT (°C)
	Pushing Auxiliary System					*Exhausting Auxiliary System*				
	75 hp auxiliary fan (32 m³/s) – No activity					*75 hp auxiliary fan (32 m³/s) – No activity*				
APH 1	0.3	15.1	30.7	25.9	27.6	0.3	15.2	29.4	25.7	26.8
APH 2	0.2	7.9	32.5	26.6	29.2	0.2	8	32.9	26.9	28.7
APH 3	0.1	5.7	30.6	26	27.6	0.1	5.7	29.8	25.9	27
Return APH 2/3	0.4	14.1	33.9	27.1	29.1	0.3	14.2	29.4	25.7	26.8
Return	0.7	30.6	32.1	26.5	28.3	0.7	30.4	29.4	25.7	26.8
	150 hp auxiliary fan (41 m³/s)					*150 hp auxiliary fan (41 m³/s)*				
APH 1	0.4	15.1	32.3	28.1	27.6	0.4	19.8	29.4	25.7	26.8
APH 2	0.3	7.9	33.5	29.4	29.2	0.2	10	32.1	26.7	28.3
APH 3	0.2	5.7	32.3	28.1	27.6	0.2	7.2	29.7	25.8	27
Return APH 2/3	0.5	14.1	34.3	29.2	29.1	0.4	17.8	29.4	25.7	26.8
Return	0.9	30.6	33	28.6	28.3	0.9	38.5	29.4	25.7	26.8
	150 hp auxiliary fan (41 m³/s) and 50 hp auxiliary fan (28 m³/s) before APH 2 intake					*75 hp auxiliary fan (32 m³/s) – Block APH # 1 and APH # 3 ducting system*				
APH 1	0.3	11.2	31.9	26.2	27.9	-	-	-	-	-
APH 2	0.3	15.7	33.9	26.8	28.5	0.6	26.8	30.4	26.1	27.3
APH 3	0.3	11.4	33.1	26.5	28.5	-	-	-	-	-
Return APH 2/3	0.6	27.9	34.3	27	29.2	0.6	27.7	29.4	25.7	26.8
Return	0.9	39.2	33.4	26.8	28.8	0.7	29.7	29.4	25.7	26.8
	75 hp auxiliary fan (32 m³/s) – Block APH # 1 and APH # 3 ducting system					*Intake with 150 hp auxiliary fan (41 m³/s) - Block APH # 1 and APH # 3 ducting system*				
APH 1	-	-	-	-	-	-	-	-	-	-
APH 2	0.6	26.7	32.7	26.5	28.3	0.7	33.5	30.1	26	27.2
APH 3	-	-	-	-	-	-	-	-	-	-
Return APH 2/3	0.6	27.8	33.9	26.6	29	0.8	34.7	29.4	25.7	26.8
Return	0.7	30.3	33.6	26.8	28.9	0.8	37.2	29.4	25.7	26.8
	150 hp auxiliary fan (41 m³/s) - Block APH # 1 and APH # 3 ducting system					*150 hp auxiliary fan (41 m³/s) - Block APH # 1 and APH # 3 ducting system – 100 kW spot cooling system before the APH # 2 intake*				
APH 1	-	-	-	-	-	-	-	-	-	-
APH 2	0.8	33.9	35.1	26.9	29.2	0.7	33.5	27.7	25.4	26
APH 3	-	-	-	-	-	-	-	-	-	-
Return APH 2/3	0.8	35.3	35.6	27.2	29.1	0.8	34.7	26.9	25.1	25.6
Return	0.8	38.5	35.2	27.2	28.3	0.8	37.2	26.9	25.4	25.8
	150 hp auxiliary fan (41 m³/s) - Block APH # 1 and APH # 3 ducting system					*150 hp auxiliary fan (41 m³/s) - Block APH # 1 and APH # 3 ducting system – 100 kW spot cooling system before the APH # 2 intake*				
APH 1	-	-	-	-	-	-	-	-	-	-
APH 2	0.8	33.9	35.1	26.9	29.2	0.7	33.5	27.7	25.4	26
APH 3	-	-	-	-	-	-	-	-	-	-
Return APH 2/3	0.8	35.3	35.6	27.2	29.1	0.8	34.7	26.9	25.1	25.6
Return	0.8	38.5	35.2	27.2	28.3	0.8	37.2	26.9	25.4	25.8

Table 6.4. Results of different simulation scenarios using Ventsim Model

Location	Forcing system	Exhausting system
	Dilution time (min)	Dilution time (min)
	75 hp auxiliary fan (32 m³/s)	*75 hp auxiliary fan (32 m3/s)*
APH 2	*48*	*48*
APH 2 return	*45*	*0*
APH 2 & 3 return	*42*	*0*
Return	*36*	*37*
	150 hp auxiliary fan (41 m³/s)	*150 hp auxiliary fan (41 m3/s)*
APH 2	*32*	*28*
APH 2 return	*31*	*0*
APH 2 & 3 return	*29*	*0*
Return	*26*	*25*
	150 hp auxiliary fan (41 m³/s) - Block APH # 1 and APH # 3 ducting system	*150 hp auxiliary fan (41 m3/s) - Block APH # 1 and APH # 3 ducting system*
APH 2	*9*	*7*
APH 2 return	*7*	*0*
APH 2 & 3 return	*7*	*0*
Return	*6*	*6*

6.4. Conclusions

In this study, climatic models were developed and calibrated using measured climatic data. Considerations were also given to the fact that arsenic dust concentrations may be present at the face. The results of the simulation model demonstrate that exhausting systems provide relatively cooler air when there are multiple auxiliary fans serving multiple dead-end headings or production workings. Forcing systems provide increased airflow velocities at the face compared to exhausting systems. It is one of the advantages of using a forcing system especially when a higher air flow is required at the face to assist in turbulent mixing of gasses (e.g. methane) that may be emitted from the fragmented ore or newly exposed surfaces. Furthermore, when there is a notable arsenic concentration or dust at the face, an exhausting system is preferred as the contaminated air is drawn directly into the ducting system. Air and dust filters can also be included within the exhausting system to reduce the arsenic and dust concentration. However, the additional pressure drop across the filter and the cost of changing the air filter must be taken into account. Increasing the air flow at the

production heading decreases the heat load and decrease the dilution time of arsenic dust concentration at the working faces.

When a spot cooling system is required, an exhausting system has an advantage over a forcing system. When forcing system is used, spot cooling systems must be placed either in the intake airways before the auxiliary fan or close to the immediate face of the dead-end heading. However, there will be more flexibility in placing spot cooling systems when an exhausting ventilation system is used. The advantages of both forcing and exhausting systems can be merged when an overlap ventilation system is used. A push-pull ventilation system provides adequate air velocity at the face of production headings and the contaminated air will be directed into the ducting system. The problem with an overlap ventilation system is that it requires a large cross sectional area where two ducting systems can be installed. For this case study the use of an overlap ventilation system is not feasible because of the cross-sectional area of the drift.

Chapter 7 Quantifying the Thermal Damping Effect in Underground Vertical Shafts using the Nonlinear Autoregressive with External Input (NARX) Algorithm

7.1. Introduction

Climatic models are usually developed and used to predict the climatic conditions in future underground mines and determine whether a mine's ventilation system (primary/auxiliary) can provide adequate thermal conditions in the development and production workings. Climatic models can also be developed and used for existing underground mines to quantify the heat generated by various heat sources, and to assess what cooling strategy would be the most cost-effective method to control the thermal environment. For existing operations, ventilation and climatic data collection are essential to validate the ventilation and climatic models, which can then be used to understand transient heat transport processes along vertical and horizontal airways, determine the heat profile of the mine and to prepare short-term and long-term airflow delivery plans. To design and manage an underground ventilation system with respect to safety and cost, it is important to incorporate time-dependent heat exchange processes in the system, so that any unusual activities and rapid changes can be taken into account. For future underground operations, there are several key elements which need to be captured and incorporated into the climatic model to accurately predict temperature and humidity levels. These key elements include the thermal damping effect, the dynamic heat exchange processes between the ventilating air and the surrounding rock, and equipment activity profiles throughout localized production and development areas and mine-wide.

With the exception of one mine ventilation software that is under development and testing *(Danko, 2013)*, no other ventilation or climatic modeling software packages have the ability take into account the "*thermal damping effect (TDE)*" (also known as thermal flywheel effect) when modeling the thermal environment in deep and hot underground mines. The major difficulty in incorporating TDE comes from a large number of variables interacting with each other plus the time-dependent heat and mass transport processes that control the flow of strata heat into/from the mine airways. Stroh *(1979)* introduced the TDE in the mine ventilation literature as a phenomenon that was observed in several shaft surveys, and he defined the thermal damping *"… as a value which varies from mine to mine."* Danko et al., *(1988)* developed analytical solutions to take into account the temperature damping based on the transient thermal mass transport processes, which are presently incorporated into a mine ventilations simulator. Brake *(2002)* reported a descriptive explanation of TDE (as low and high) for the intake airways in two underground mines in Australia. Brake *(2008)* defined TDE as a function of the travel time and contact distance for air traveling in the intake airways. McPherson *(2009)* mentioned that because of significant surface temperature variations during daytime and nighttime, it is common for the walls and the surrounding rock to absorb heat during the day and to emit heat during the night. Describing thermal damping, he noted *"… the phenomenon continues along the intake airways and tends to dampen out the effects of the surface temperature variation as the air travels down vertical airways into an underground mine."* Kocsis & Hardcastle *(2010)* observed TDE experimentally during climatic data collection in deep underground mines in Canada. Their study showed that during summer and winter there is a change in the phase angle of the periodic and harmonic air temperature variations. A

recent study also verified this phase shift and its effect on the temperature of the mine air through climatic simulations performed on a ventilation-thermal-humidity model *(Danko, 2013)*.

7.2. The Thermal Damping Effect (TDE)

Heat is transferred to the mine air from a variety of sources including auto-compression, strata, mining equipment, explosives, and more. In many cases, the airflow itself is sufficient to remove the heat which has been transferred to the mine air along vertical and horizontal airways and during the mining processes *(Roghanchi et al., 2015)*. In deep metal mines, however, the heat removal as the dominant environmental problem, may necessitate the use of some method of cooling (e.g. mine-wide, localized). When cool air passes through a horizontal airway, its temperature usually increases. This is caused by the natural geothermal heat being conducted through the rock towards the airway. The geothermal heat will then pass into the mine air through the boundary layers that exist in the air close to the rock surface *(Carpenter et al., 2015)*. The envelope of rock close to the newly driven airway will rapidly cool at first, and there will accordingly be a relatively high rate of initial heat release into the mine air. This will decline in time, and the rock surface will gradually cool and approach an equilibrium state when its temperature equals that of the air *(Roghanchi et al., 2016)*. Furthermore, if the airway is wet, then the increase in the dry-bulb temperature is less noticeable, or it may even fall. This is a result of the cooling effect of evaporation. Heat may still emanate from the strata. However, much of this heat is utilized to transfer the water molecules into the mine air in the form of water vapor. The heat content of the air-water mixture will rise due to the internal energy of the added water vapor *(McPherson, 1993)*.

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 damping effect.

Figure 7.1 and Figure 7.2 illustrate the thermal damping effect in a production shaft. Figure 2, for example, shows that during summertime, the temperature at the top of the shaft varies widely, from a high value of 33 ˚C during a sunny midday to a low value of 19 ˚C in the middle of the night, which represents a temperature difference of $\Delta T_{d\text{-surface}} = 19$ ˚C. However, at the bottom of the shaft, the amplitude of the air temperature variation is much smaller and varies from 29.5 ˚C to 25.5 ˚C, which represents a temperature difference of $\Delta T_{d\text{-bottom}} = 4$ ˚C. Measured climatic parameters indicate that the lining of the shaft and the surrounding rock act as an energy reducing mechanism, which reduces the amplitude of the temperature wave. Furthermore, during the daytime, at some depth down the intake shaft, the air temperature in the intake shaft, which is also heated by auto-compression, develops higher values than that of the virgin rock temperature (VRT) of the surrounding rock. Consequently, sensible heat is transferred from the intake air into the rock, actually cooling the air. However, during the night, as the temperature of the air on surface cools, there is a greater potential for the heat to flow from the rock into the mine air.
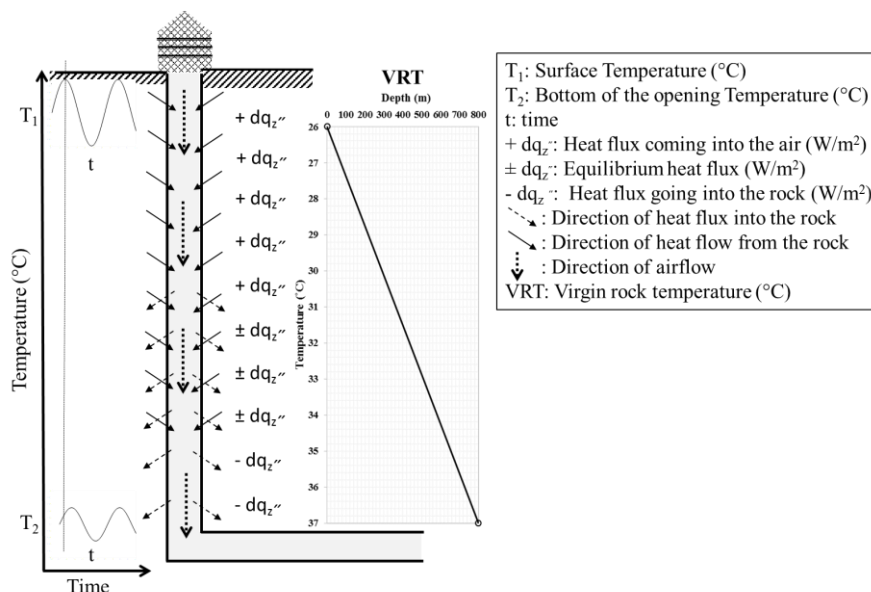
Figure 7.1. Heat exchanges in a vertical opening during day and night as a function of ambient temperature and virgin rock temperature.
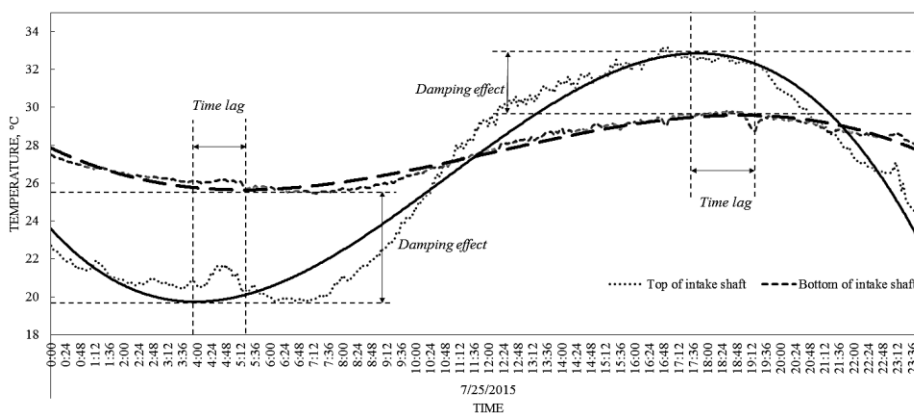
Figure 7.2. Dry-bulb damping in an intake shaft during a 24 hours period.

There are many conventional mine ventilation and climatic simulation programs available to conduct heat studies and predict the climatic conditions in future underground mines. Most relevant transport processes for heat and humidity can be modeled with any of these software packages. However, short-time variations such as hourly or daily and more importantly seasonal temperature changes can induce significant modeling errors if the strata heat does not follow a true instantaneous heat flux model. As shown in Figure 7.2, the daily temperature variation at the bottom of the intake shaft can be much less than at

the top of the intake shaft, which is a function of many factors including the contact time between the mine air and the lining of the shaft and travel distance. It is important to accurately predict the temperature and the humidity levels at the bottom of the intake airways for future underground mines because a well design ventilation system may be sufficient to provide adequate climatic conditions. However, climatic modeling errors that are induced by ignoring the thermal damping effect can indicate that a refrigeration system is needed to provide adequate work conditions. In some cases, the additional capital and operating costs related to the cooling system could indicate that otherwise, a viable underground operation would be unfeasible.

To evaluate the accuracy of the standard ventilation software, the intake shafts at our partner mines were modeled using Climsim^{TM} and Ventsim^{TM} programs. A comparison between measured climatic values at the bottom of an intake shaft and parameters generated through the use of ventilation and climatic models is shown in Figure 7.3. This figure indicates that current, commercially available mine ventilation software do not take into account the thermal damping along the vertical shaft. Therefore, the models predict same diurnal temperature variations without considering the thermal damping at the bottom of the intake shaft as for the top of the intake shaft. One software package with its time-dependent solution may have the ability to simulate the thermal flywheel effect and the associated time lag *(Danko, 2013)*. However, this program is under development and testing, and it not yet commercially available.
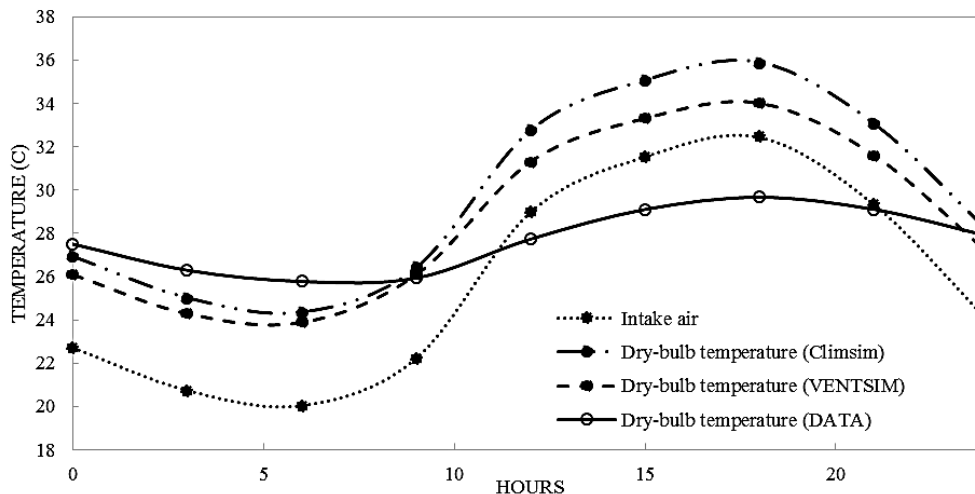
Figure 7.3. Comparison between measured air temperatures (e.g. DATA) at the bottom of an intake shaft and predicted air temperatures by ventilation and climatic simulation programs.

The thermal damping effect on the mine air depends on many ventilation, climatic and geotechnical parameters including the air temperature of the surface, air volume, contact distance, wall wetness, the virgin rock temperature, the thermal properties of the rock, etc. For instance, it has been observed that the thermal damping effect along an intake decline is much higher than the thermal damping effect of a similar amount of air that travels to the same production level through a vertical airway. Longer the intake, the tempearture damping is higher. This is why the air temperature underground at some point, which is located at some distance from the collar if the intake shaft is not affected by daily air temperature variation on the surface (See Figure 7.4). The most important environmental, physical and dynamic parameters that affect temperature damping in underground mines are summarized in Table 7.1.

Table 7.1. Critical parameters that influence temperature damping in underground vertical openings

Environmental Parameters	Physical Parameters	Dynamic Parameters
Surface temperature	Size of opening	Air quantity
Intake relative humidity	Shape of opening	Travel time
Barometric pressure	Wall roughness	Contact distance
Groundwater	Wall wetness	
Air density	Disturbance objects	
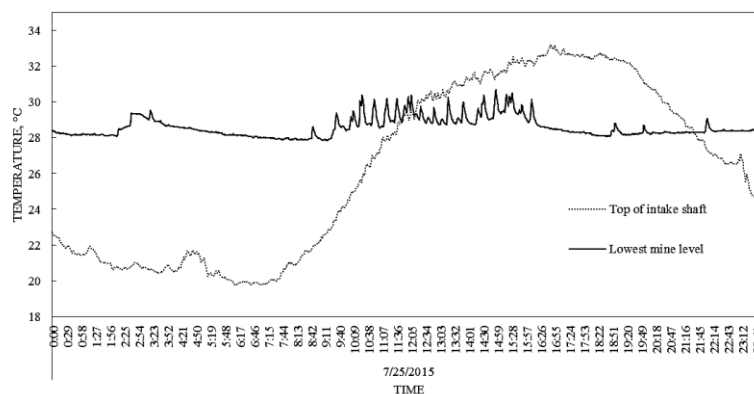
Figure 7.4. The thermal damping effect depends on the travel time and airflow-wall contact distance - For an airway located at a long distance from the collar of the intake shaft, daily temperature variations are negligible.

7.2. Quantifying the Thermal Damping Effect using NARX

7.2.1. Climatic Data Collection at Underground Mines

Climatic and ventilation parameters were collected at two underground mines in Nevada. The primary ventilation system in both mines is of exhaust type, with the primary fans located at the top of the exhaust shaft. The selection criteria for the climatic monitoring units focused on data storage and their capability to continually measure and record climatic and ventilation parameters. Other requirements included: (1) the monitoring units should be lightweight and easy to instal and should not interfere with the mining operations; (2) the monitoring units should include built-in batteries with no external power source requirements; (3) the monitoring units should require minimum maintenance, and the calibration procedure to be straight forward; (4) recording and downloading the climatic data must be straightforward and quick; (5) the units should be fairly accurate for climatic and ventilation surveys.

The "ACR Smart-Reader Plus" multi-channel monitoring units (See Figure 7.5) were selected to monitor and record the climatic parameters in the production stopes, dead-end development headings and throughout the mine. The units continually measured and recorded T_d, RH, and BP. From these parameters, T_w was then calculated. The monitoring units were capable of recording these values at various time intervals specified by the user, and each unit had a storage capacity of 128 KB. The climatic parameters were downloaded on a mobile computer as shown in Figure 5. The collected climatic and ventilation data was used to validate the climatic models.

Figure 7.5. The climatic data recorded by the monitoring units was downloaded on a laptop.

At two underground precious metal mines in Nevada, two production shafts and one ventilation shaft (intake) were selected for climatic data collection. The climatic monitoring units were programmed to collect T_d, RH and BP readings at two-minute intervals for a 4-week time frame. Table 7.2 summarizes the geometrical elements of the production and ventilation shafts and their intake air volumes. One monitoring unit was installed on the surface to measure and record the climatic conditions during daytime and nighttime. The following unit was installed just below the collar of the production/ ventilation shaft to capture any heat added to the mine air around the collar of the shaft and to eliminate the effect of radiation. Monitoring units were also installed at the bottom of

the production and ventilation shafts. Table 7.3 presents the locations where the units were installed and the climatic monitoring plan. It should be mentioned that no cooling system was employed at these tow underground mines.

Table 7.2. The geometrical elements of the production and ventilation shafts

	Type of shaft	Shaft diameter (m)	Shaft area (m^2)	Shaft depth (m)	Quantity (m^3/s)
Shaft #1	Production shaft	7.3	41.85	580	205
Shaft #2	Production shaft	6.7	35.26	579	241
Shaft #3	Ventilation shaft	6.1	29.22	503	223

Table 7.3. Climatic monitoring plan at two underground precious metal mines in Nevada

Intake Shafts (production/ventilation)	
Locations	On surface, and at the top and bottom of the production/ventilation shafts
Purpose	To identify and quantify the thermal damping effect To understand the transient heat exchange processes between the mine air and the surrounding rock
Monitoring plan	The ACR units were installed at the top and at the bottom of the shafts to record climatic data at two-minute intervals for four weeks at a time. The unit on surface was set to record the surface climate and any unusual activities that can affect the temperature of the intake air

7.2.2. The Nonlinear Autoregressive with External Input (NARX) Algorithm

An artificial neural network (ANN) is an interconnected group of nodes, where each node represents an artificial neuron, and an arrow represents a connection from the output of one neuron to the input of another. Artificial neural networks can be considered as a form of machine learning, in which the system learns to recognize an output variable based on a series of input variables *(Hang et al., 2014; Majidi et al., 2015)*. Data is processed through a number of interconnected neurons which form synaptic connections from the input nodes through a hidden layer before converging on the output neurons. Each input and hidden neuron consist of statistical weights which are capable of adapting the exact parameters that are modified by an algorithm over the course of network training procedures *(Kriesel,*

2007; Khodabandelu and Fadali, 2016). These weights essentially form the synaptic connections among neurons, which will activate during network construction. This form of computation is capable of operating in parallel units, much like the human nervous system. The ANNs are capable of nonlinear modeling and can, therefore, provide a useful alternative approach to a number of both theoretical and real-world problems *(e.g. Ticknor, 2013; Ruiz et al., 2016; Doucoure et al., 206; Ding et al., 2016).*

In this study, artificial neural network modeling was used as a time series predicting tool to estimate the temperatures at the bottom of the production and ventilations shafts by taking into account the thermal damping effect as a function of the surface temperature. The NARX algorithm is a class of discrete-time and non-linear system that can be presented as Eq. 1. The topology of an NARX network is shown in Figure 7.6.

$$y(n+1) = f[y(n), ..., (y(n-d_y+1); x(n-k), x(u-k+1), ..., x(n-d_u-k+1)]$$

Eq. 7.1

Where: x(n) and y(n) donate, respectively, are the input and output of the model at discrete-time step "*n*," while $d_x \geq 1$, $d_y \geq 1$, and $d_y \geq d_x$, are the input memory and output memory orders, respectively. The parameter k ($k \geq 0$) is a delay term, known as the process dead-time (Ding et al., 2016).Considering k = 0, the NARX model can be simplified as:

$$y(n+1) = f[y(n), ..., (y(n-d_y+1); x(n), x(u), ..., x(n-d_u+1)] \qquad \textit{Eq. 7.2}$$
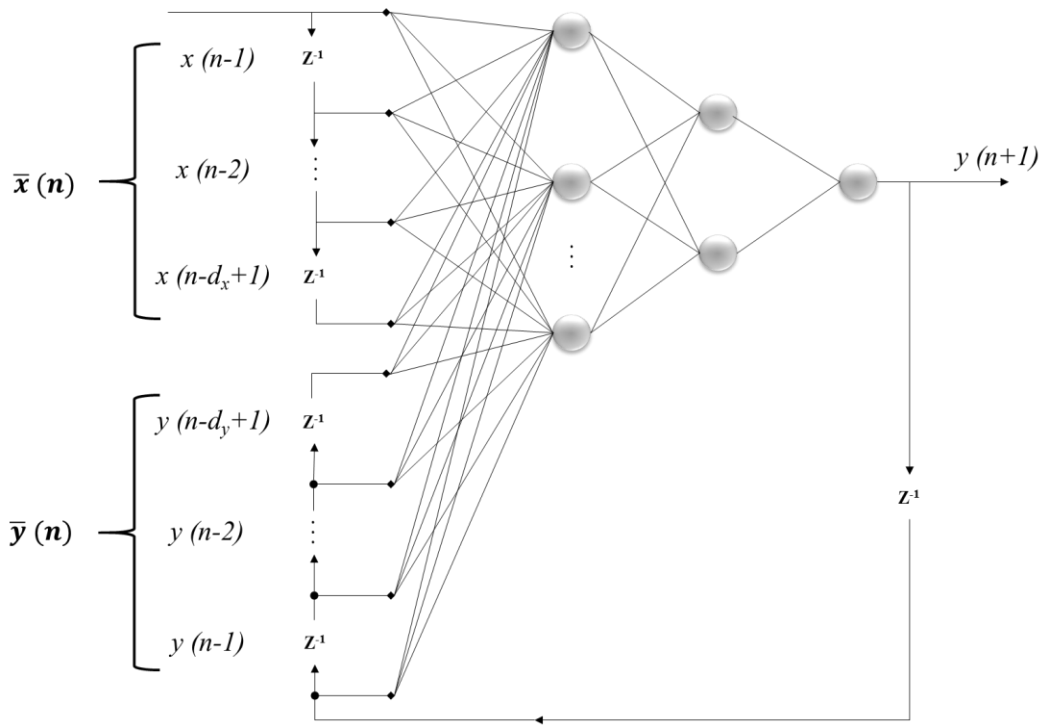
Figure 7.6. Topology of the NARX model (Z^{-1} is the unit time delay)

The most common learning rule for the NARX network is the Levenberg-Marquardt backpropagation procedure (LMBP) *(Marquardt, 1963; Hagan & Menhaj, 1994; Alwakeel & Shaaban, 2010; Hong et al., 2014)*. This training function is often the fastest backpropagation-type algorithm. The LMBP algorithm was designed to approximate the second-order derivative with no need to compute the Hessian matrix, therefore increasing the training speed. However, this training function is not powerful in forecasting values for small and "*noisy*" datasets such as the datasets of daily temperature fluctuations in underground mines. The Bayesian regularized artificial neural networks are more robust than standard back-propagation networks and can reduce or eliminate the need for lengthy cross-validation procedures *(Hong et al., 2014)*. The Bayesian regularization is a mathematical process that converts a nonlinear regression into a well-posed statistical problem in the manner of a ridge regression. This algorithm typically takes more time but

can result in good generalization for noisy data sets *(Hong et al., 2014)*. The Bayesian regularization adds a term to this equation *(Forsee & Hagan, 1997)*:

$$F = \beta E_D + \alpha E_w$$ *Eq. 7.3*

where: F is the objective function, E_D is the sum of squared errors, E_w is the sum of the square of the network weights, and α and β are objective function parameters (MacKay, 1992). In the Bayesian network, the weights are considered as random variables, and thus their density function is written according to the Baye's rules *(Forsee & Hagan, 1997)*, as follows:

$$P(w \mid D, \alpha, B, M) = \frac{P(D|w,\beta,M)\ P(w|\alpha,M)}{P(D|\alpha,\beta,M)}$$ *Eq. 7.4*

Where: w is the vector of network weights, D represents the data vector, and M is the neural network model being used. Forsee & Hagan *(1997)* assumed that the noise in the data was Gaussian, and with this assumption, they were able to determine the probability density function for the weights. Forsee & Hagan *(1997)* proposed a Gauss-Newton approximation to the Hessian matrix, which is possible if the Levenburg–Marquardt training algorithm is used to locate minimum values. This technique reduces the potential for arriving at local minima, thus increasing the generalizability of the network.

The novelty of this technique is the probabilistic nature of the network weights in relation to the given dataset and model framework. As a neural network grows through additional hidden layer neurons, the potential for overfitting increases dramatically, and the need for a validation set to determine a stopping point becomes crucial. In the Bayesian regularized networks, overly complex models are penalized, as unnecessary linkage weights are effectively driven to zero. The network will calculate and train on the non-trivial weights,

also known as the effective number of parameters, which will converge to a constant as the network grows (Burden & Winkler, 2008). The mean square error (MSE) is then used to calculate the performance of the NARX model, as follows:

$$SSE = \sum_{i=1}^{n}(\hat{y}_i - y_i)^2 \qquad\qquad Eq.\ 7.5$$

$$MSE = \frac{SSE}{n} \qquad\qquad Eq.\ 7.6$$

7.3. The Performance of the NARX Model when Predicting the Thermal Damping Effect in Vertical Shafts

Data selection was carried out by a preliminary pre-processing algorithm, which considered all ventilation and climatic parameters which were collected during a 3-month period on the surface, along the production shafts (intake), as well as parameters collected during a 2-month period along the ventilation shaft (intake). There are several unknown sharp temperature fluctuations, which should be removed from the climatic data, as shown in Figure 7.7. The "*smoothed out*" graph was obtained using the exponential smoothing approach, which is provided in equation 7.7:

$$y(t) = \alpha x(t) + (1 - \alpha)\, y(t - 1) \qquad\qquad Eq.\ 7.7$$

Where: α is the smoothing factor $(0 < \alpha < 1)$, and t is the time step $(t > 0)$.

The climatic data that is influenced by natural occurrences such as rain/snow should also be detected and be treated so that the model performance is not influenced by unusual temperature changes. Furthermore, a subsequent step was also performed to separate data into a "*training*" dataset and a "*test*" dataset. For each intake shaft, an ANN model was developed and tested based on processed datasets. The data is not normalized because

firstly, both input and output are in the same units and secondly, the actual values were needed to identify the damping ratio in the vertical production and ventilation shafts.

Figure 8 illustrates the performance of the NARX model for Shaft #1. A set of data was selected, which consists of dry-bulb temperatures collated at the top and bottom of Shaft #1 during a 24-hour time frame. The performance of the NARX model for the production and ventilation shafts is provided in Table 7.4 and Figure 7.8. As shown in Table 7.4, the model can successfully predict the temperature at the bottom of the intake shaft, which was diminished by the effect of thermal damping. The same procedure was applied for Shaft #2 (production) and Shaft #3 (ventilation) to predict the dampened temperatures at their bottom.
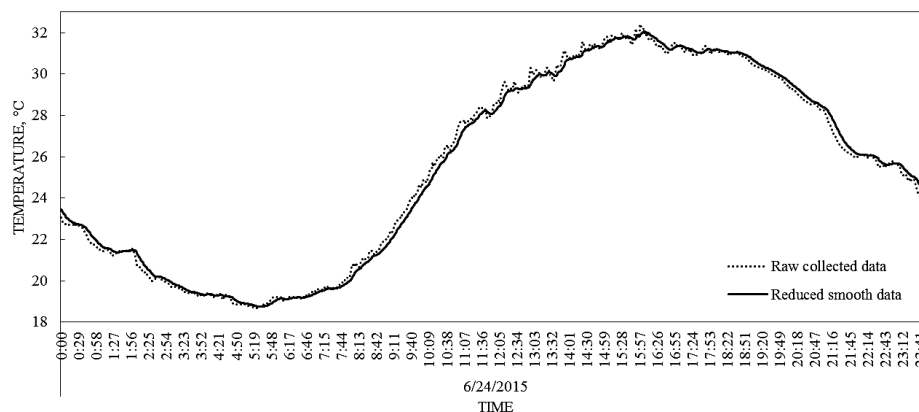
Figure 7.7. Smoothed out data to eliminate unknown sharp temperature fluctuations within the database.
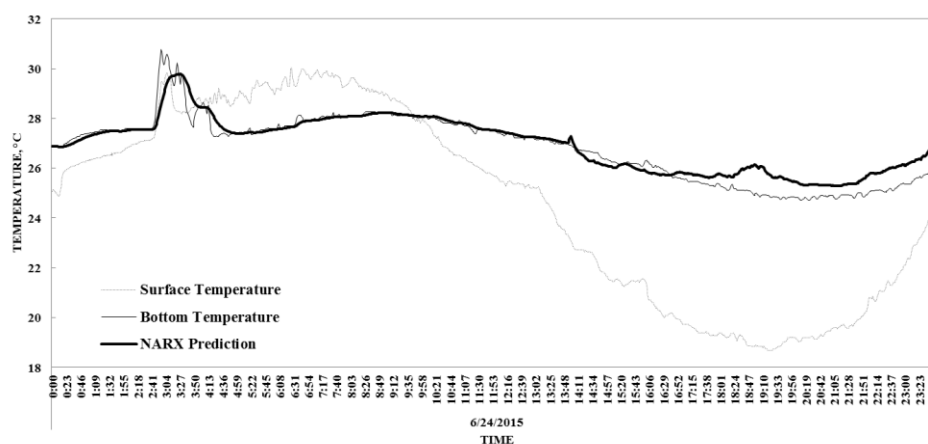
Figure 7.8. NARX performance in Shaft #1 ($R^2 = 0.99$; MSE = 0.923)

Table 7.4. The performance of NARX model for the production and ventilation shafts

Shaft Number	Type of shaft	R^2	MSE
Shaft #1	Production shaft	0.99	0.129
Shaft #2	Production shaft	0.99	0.217
Shaft #3	Ventilation shaft	0.97	0.276

The ANN models based on NARX can be applied to any numerical method based ventilation and climatic modeling software to predict the thermal damping effect in vertical airways. The NARX network provides an appropriate prediction accuracy, while the complexity of the system is reduced through exogenous data. Despite the fact that the ANN model based on the NARX algorithm is powerful and successful in forecasting diminished temperature values in vertical airways, it may not be practical to apply this method to predict the temperature at the bottom of the production and ventilation shafts due to the complexity of modeling work. Consequently, the time series model was simplified to a conventional time series model in an attempt to determine simple damping ratios for the intake shafts.

A nonlinear input-output time series equation can be written as:

$$y(n) = f[x(n), \dots, x(n - d_u + 1)]$$ <div style="text-align: right">*Eq. 7.8*</div>

Where: $f(.)$ can be approximated using a neural network.

These nonlinear input-output time series can be simplified to a "*linear regression*" model as shown in Equation 7.9, and even further to a simple linear regression, as shown in Equation 7.10:

$$y(n) = f[x(n) + \dots + x(n - d_u + 1)] = a_1 x(n) + \dots + a_n x(n - d_u + 1)] + b$$ <div style="text-align: right">*Eq. 7.9*</div>

$$y(n) = f[x(n)] = b + a x_n$$

$$a = f[Q, TDE, dimension, Frictional\ heat];$$

$$b = f[Autocompression, VRT, depth, strata\ heat]$$ <div style="text-align: right">*Eq. 7.10*</div>

Table 7.5 shows these simple linear regression equations, which were developed for the production and ventilation shafts at two underground mines. The constant value "*b*" for each intake shaft is different due to the heat added to the system, which can vary as a function of depth and the virgin rock temperature profile of each mine (e.g. geothermal step). However, because the production shafts have comparable geometrical elements (e.g. diameter) and the intake air volume descending the production shafts is also comparable, the values of the damping coefficient "*a*" are very close (e.g. 0.29 versus 0.31).

The damping coefficient "*a*" for the ventilation shaft has a relatively different value as for the production shafts, because the ventilation shaft is not equipped with a hoisting system, and it is clear of steel frames that support the guiding systems for the cage and skips, as these objects are also acting as a heat sink medium. Above all, the substantial benefit of these "*simple linear regression*" equations presented in Table 7.5 is that for similar airways

such as production shafts or ventilation shafts, simple equations can be developed, which can be used to determine the temperature at the bottom of vertical airways at an acceptable level of accuracy. Furthermore, these damping coefficients could be used by ventilation and climatic modeling software, thus eliminating the need to code and incorporate complicated transient heat and mass transport algorithms to quantify the thermal damping effect along vertical airways.

Table 7.5. Simple linear regression equations to predict the dry-bulb temperature at the bottom of intake shafts.

Shaft Number	Equation	R^2	MSE
Shaft # 1 (Production)	$T_B = 20.68 + 0.29 \times T_S$	0.78	1.12
Shaft # 2 (Production)	$T_B = 25.47 + 0.31 \times T_S$	0.81	0.98
Shaft # 3 (Ventilation)	$T_B = 21.59 + 0.40 \times T_S$	0.73	1.58

T_B: dry-bulb temperature at the bottom of the shaft, T_S = dry-bulb temperature on surface

Table 7.6 and Figure 7.9 illustrate an example of error calculations when predicting the dampened temperatures at the bottom of production Shaft #1, based on various forecasting methods such as NARX, nonlinear time series, and simple linear regression models. As shown in Table 7.5, NARX has the most accurate prediction with $R^2 = 0.99$. By decreasing the complexity of the model to a simple linear regression, the model prediction accuracy decreases to $R^2 = 0.81$, with minimum and maximum temperature errors of -1.5 ˚C and 1.9 ˚C, respectively. While these errors are noticeable compared to the NARX model, these simple linear regression models have a much better performance in predicting the thermal damping effect than any of the currently available ventilation and climatic simulation programs, with the most advanced of them returning minimum and maximum errors of 2.5 ˚C to 6.6 ˚C, respectively. Furthermore, field observations in large and deep metal mines have shown that when the thermal damping effect is not taken into account, the difference

between simulated and measured temperature values at the bottom of intake airways can vary from 6 ˚C to 10 ˚C *(Kocsis & Hardcastle, 2010)*. These simple linear regression equations derived from the NARX algorithm can be used to estimate the damping effect along vertical intake airways, thus minimizing the errors when predicting the climatic conditions at the bottom of intake airways for future underground mines.

Table 7.6. Comparison of different time series prediction models performance for the shaft #1.

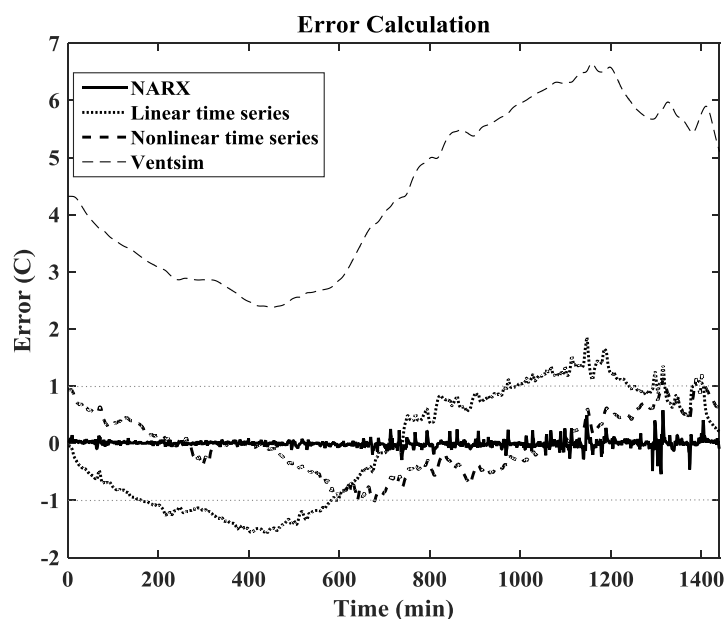| Time series method	R^2	MSE	Error (˚C)		
			Average	Maximum	Minimum
NARX	0.99	0.123	-0.01	0.58	-0.54
Nonlinear time series	0.97	0.712	0.04	1.34	-1.39
Simple linear regression	0.81	0.986	0.08	1.93	-1.58

Figure 7.9. Comparison of error estimations based on NARX, nonlinear time series, and simple linear

regression

7.4. Conclusions

An artificial neural network (ANN) based on nonlinear autoregressive time series algorithm with external input (NARX) was used as a novel method to predict T_d at the bottom of the production and ventilation shafts. The performance of the ANN model based on NARX model was excellent in predicting the temperatures at the bottom of the intake shafts. However, due to the complexity of the modeling work, the *input-output time series* model was simplified to a linear regression model, which can be easily used to predict the temperature at the bottom of the intake shaft at an acceptable level of accuracy. The substantial benefits of these simple linear regression equations presented in Table 7.5, can be used in conjunction with commercially available mine ventilation or climatic simulation programs to predict more realistic temperature values by taking into account the thermal damping effect in vertical airways. Furthermore, the damping coefficients (*a* and *b*) for the production and ventilation shafts could be easily implemented into ventilation and climatic modeling programs, thus eliminating the need to incorporate complicated time-dependent heat and mass transport algorithms in order to quantify the thermal damping effect in vertical airways. A future related study should look at the development of a general model, which would take into account the characteristics of the intake airways and the rock thermal properties at various underground operations such as shaft diameter, depth, lining material, virgin rock temperature and air volume. The same approach presented in this paper can also be used to predict the thermal damping effect on the wet-bulb temperature (T_w) at the bottom of production and ventilation shafts.

Chapter 8 Conclusions

8.1. Objectives

Heat is a hazard that may underestimated in most mining operations. This is mostly because people are unaware of its effects due to less education or lack of it thereof and its salient consequences. Heat stress in the underground environment is influenced by numerous factors including virgin rock temperature, geothermal gradient and mining equipment. The significance of mine workers to maintain relative body comfort in deep hot underground mines is of paramount importance. This is because productivity, health, safety and the overall performance of the mines largely depend on it. When the underground working places become excessively hot, the volume of a mine's intake air, its temperature and humidity can be altered in order to improve the underground climatic conditions.

Nevada's underground precious metal mines are becoming gradually deeper while employing large diesel powered mining equipment to increase the production rates. The ability of ventilation systems to assure appropriate climatic conditions for the underground workers will decrease as a function of increasing mining depth and an ever rising level of mechanization. Most of Nevada's underground metal mines are not considered to be hot mines due to the fact these mines do not have an extensive spread-out heat problem. However, there are several localized areas where temperature and humidity can exceed the threshold limit values during development and production operations. Consequently, heat may rather be considered a contaminant, which must be reduced by means of redesigning the mines' ventilation system, and as a last resort by employing localized spot cooling systems. The main focuses of this research work were to 1. Develop a new methodology

to select appropriate heat stress indices for underground mining application 2. Develop recommendation regarding best practices for design and use of climatic monitoring systems in hot US mines; 3. Identify and quantify the thermal damping effect in underground openings using artificial neural network.

8.2. Research Results

- Selecting an appropriate heat stress index for underground mines

A method was proposed coupled to a defined strategy for selecting and recommending heat stress indices to be used in underground metal mines in the US and worldwide based on a thermal comfort model. The performance of current heat stress indices used in underground mines varies based on the climatic conditions and the level of activities. Therefore, by carefully selecting or establishing an appropriate heat stress index is of paramount importance to ensure the safety, health and increasing productivity of the underground workers. This method presents an important tool to assess and select the most appropriate index for certain climatic conditions in order to protect the underground workers from heat-related illnesses. Although complex, the method presents results that are easy to interpret and understand than any of the currently available evaluation methods.

- Best practices for design and use of climatic monitoring systems in hot US mines

Employing the most effective underground climatic monitoring systems depend mainly on the purpose of climatic monitoring, the magnitude of the heat load to be removed, monitoring locations and costs. The process of developing a monitoring program includes determination of required parameters to be measured, selection of monitoring units, identification of key locations to be monitored and the timing of monitoring. However, the

challenges are numerous: the key locations are not always accessible, the mine is never truly at steady state, there are always unknown temperature fluctuations during the monitoring phase, and the measurements can be delayed due to rapid changes, to list a few. The lessons learned from the climatic monitoring programs, which were conducted over one year at two underground metal mines in Nevada, were discussed. The practices and challenges in using continuous climatic monitoring systems in deep and hot metal mines was highlighted. Heat generated by various heat sources were quantified and a heat load profile was developed for our partner mine in Nevada. The importance of use of continuous climatic monitoring systems were demonstrated based on variability of contribution of heat generation by major sources as a function of surface temperature. Auxiliary ventilation systems in our partner mines were modified in order to maintain the comfort limits for underground workers.

- Quantify the thermal damping effect in underground vertical openings

There are several occurrences that cannot be captured when simple spot units are being used for climatic monitoring purposes. This includes the thermal damping effect, dynamic heat exchanges between the ventilating air and surrounding environments and unknown sharp increases in temperature during production cycles. These elements are particularly important to predict the underground climatic conditions within newly located orebodies and in future mines. As air falls down the intake shaft, its lining and the strata will emit heat during the night when the incoming air is cool and, on the contrary, will absorb heat during the day when the temperature of the air becomes greater than of the strata. This cyclic phenomenon, also known as the "thermal damping effect." will continue throughout the year reducing the effect of surface air temperature variation. An artificial neural

network (ANN) based on nonlinear autoregressive time series algorithm with external input (NARX) was used as a novel method to predict Td at the bottom of the production and ventilation shafts. The performance of the ANN model based on NARX model was excellent in predicting the temperatures at the bottom of the intake shafts. However, due to the complexity of the modeling work, the input-output time series model was simplified to a linear regression model, which can be easily used to predict the temperature at the bottom of the intake shaft at an acceptable level of accuracy.

8.3. Research recommendations

− Employing the most effective underground climatic monitoring systems depend mainly on the purpose of climatic monitoring, the magnitude of the heat load to be removed, monitoring locations and costs.

− In hot and humid underground mines, the heat index used for comfort evaluation must be carefully selected. This heat index shall provide protection for the mine workers as much as possible. The primary objective in selecting a heat stress index is simplicity. It is more likely that mine ventilation engineers and the mining crew in general will approve a thermal index due, in part, to the fact that the index can be presented in a format that they can understand and apply. That is, if the index is simple.

− On the other hand, a simple thermal index may limit its relevance to a very specific case or a localized area. However, the necessity to apply numerous modifications to simple indices in order to adjust them for various work conditions, can negate the apparent advantage of a thermal index to be directly used to protect the mine workers.

− Airflow velocities of 1 m/s and 2 m/s, which will guarantee thermal comfort, were determined by means of climatic modeling and simulation exercises. Based on the

pattern of the results, the authors recommend an optimal airflow velocity of 1.5 m/s throughout production workings.

– In general, forcing auxiliary ventilation system has must be considered over exhausting ventilation system because 1. Fresh air is delivered to the working face where workers are present, 2. Forcing systems provide increased airflow velocities at the face compared to exhausting systems, 3. It is one of the advantages of using a forcing system especially when a higher air flow is required at the face, 4. Another advantage of a forcing system is that flexible ducting can be used due to positive pressure along the ducting system.

– When there is a notable gas concentration or dust at the face, an exhausting system is preferred as the contaminated air is drawn directly into the ducting system. Air and dust filters can also be included within the exhausting system to reduce the arsenic and dust concentration. However, the additional pressure drop across the filter and the cost of changing the air filter must be taken into account. Increasing the air flow at the production heading decreases the heat load and decrease the dilution time of arsenic dust concentration at the working faces.

– When a spot cooling system is required, an exhausting system has an advantage over a forcing system. When forcing system is used, spot cooling systems must be placed either in the intake airways before the auxiliary fan or close to the immediate face of the dead-end heading. However, there will be more flexibility in placing spot cooling systems when an exhausting ventilation system is used.

– Assessments of climatic conditions showed that the underground mine environment is a rather complex system. The mine is never at steady state and there are always transient heat exchanges between the ventilating air and surrounding environments. There are

several important occurrences, which cannot be captured when simple spot measuring units are used for climatic monitoring purposes. This includes the thermal damping effect, dynamic heat exchanges between the ventilating air and surrounding environments and unknown sharp increases in air temperature during monitoring phases. It is therefore critical to incorporate time and phase changes throughout the mine.

– This study shows that hourly, daily and monthly temperature changes at surface itself can produce significant modelling errors. The difference between simulated and measured climatic parameters is the result of the dynamic time delay of temperature spikes along pathways of the ventilating air due to the thermal damping effect. The presence of different heat sources throughout a mine changes the system completely.

– It is critical to incorporate irregularities into the measured data, so that any unusual activities and rapid changes can be taken into account when designing primary and auxiliary ventilation systems. There are unknown sharp temperature fluctuation and data irregularities at different locations of an underground mine. The temperature fluctuations can be due to inflow of gasses from the rib or back, ore oxidation, auxiliary fans, mining equipment, groundwater and more.

– Dynamic heat exchange between the rock and the mine air, similar to the case when an auxiliary fan is turned on and off, cannot be calculated by means of standard modeling software. The accuracy in predicting the climatic conditions in future underground mines is critical, particularly in cases when the environmental parameters are close to their threshold limit values (TLV).

– There are many conventional mine ventilation and climatic simulation programs available to conduct heat studies and predict the climatic conditions in future underground mines. Most relevant transport processes for heat and humidity can be modeled with any of these software packages. However, short-time variations such as hourly or daily and more importantly seasonal temperature changes can induce significant modeling errors if the strata heat does not follow a true instantaneous heat flux model.

8.4. Future Research Works

While much is known about the heat balance of the human body and its tolerance to the hot and humid environment, many questions still remain. The effect of heat on worker health, safety, and productivity is extremely complex. The behavioral parameters can be a very critical rule on the reaction of human body to heat exposure. On the top of that, with respect to heat, underground mine environment is complex since the mine is never in steady state. The challenges in climatic monitoring are numerous: the key locations are not always accessible, the mine is never truly at steady state, there are always unknown temperature fluctuations during the monitoring phase, and the measurements can be delayed due to rapid changes, to list a few. Future work on heat issues in underground mines may include:

- Development of dynamic heat load profile in underground mines

- Development of the thermal management policy for underground mines

- Study the effect of behavioral parameters on the human body response to heat exposure

- Application of Ventilation on Demand (VOD) control system to decrease the heat load in underground environment

- Development of a general model to quantify the thermal damping effect, which would take into account the characteristics of the intake airways and the rock thermal properties at various underground operations such as shaft diameter, depth, lining material, virgin rock temperature and air volume.

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