Examining the Potential of Utilzing Geothermal Energy From Ejected Mine Water Towards Mine Heating

and

Peliminary Assessment of Deep Lake Cooling Systems for Deep Underground Mines

Mohannad Dabbas

Department of Mining and Material Engineering

McGill University, Montreal

August 2018

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Engineering

Acknowledgements

First of all, I would like to thank my supervisor, Professor Ferri Hassani, who welcomed me into his research team and provided the guidance and support needed throughout the projects discussed in this thesis. I am also grateful for working with Jeff Templeton and Leyla Amiri who are great colleages and friends.

I also thank my family who always provide me with love, support and encouragement throughout my life.

Abstract

Renewable energy is becoming a key topic nowadays with increasing research topics surrounding sustainable energy. The mining industry in Canada consumes a great amount of non-renewable energy resulting in huge contribution to the nation's green house gas emissions. Therefore, this thesis investigates new possibilities for the mining industry to increase their dependence on renewable, non-polluting, sources of energy. The first part of the thesis illustrates the potential geothermal energy that can be obtained from the ejected water of active underground mining operations. The thesis illustrate the economic and environmental potential of 15 mines within Canada. Site visits were conducted to all of these underground mines and information about the ejected mine water, such as the temperature and pumping rate, was used in this analysis. The study starts with a preliminary economical and environmental assessment for the 15 mines using specifications of heat pumps catalogues. Then, a mine was selected for a real life scenario by providing a custom designed chiller that fits the water pumping requirements for that particular mine, which involved meetings with a geothermal heat pump suppliers.

The second part of this thesis demonstrate the potential of utilzing deep surface water bodies towards the cooling of active underground mining operations. A candidate mine was selected for this preliminary assessment and site visits were conducted. Information about both the lake and the mine were gathered throughout site visits. Then, Air Handling Unit (AHU) catalogues were used to give preliminary economical and environmental assessment of deep lake cooling for active underground mines. The results from both studies show promising results for the applications of these renewable energy resources within the mining industry.

Résumé

L'énergie renouvelable est en train de devenir un sujet clé de nos jours avec des thèmes de recherche croissants autour de l'énergie durable. L'industrie minière au Canada consomme une grande quantité d'énergie non renouvelable, ce qui contribue énormément aux émissions de gaz à effet de serre du pays. Par conséquent, cette thèse étudie de nouvelles possibilités pour l'industrie minière d'accroître sa dépendance à l'égard de sources d'énergie renouvelables non polluantes. La première partie de la thèse porte sur l'énergie géothermique potentielle pouvant être obtenue à partir des eaux éjectées des exploitations minières souterraines actives. La thèse illustre le potentiel économique et environnemental de 15 mines au Canada. Des visites sur place ont été effectuées dans toutes ces mines souterraines et des informations sur les eaux de mine éjectées, telles que la température et le taux de pompage, ont été utilisées dans cette analyse. L'étude commence par une évaluation préliminaire de l'économie et de l'environnement pour les 15 mines utilisant des catalogues de pompes à chaleur. Ensuite, des réunions avec des fournisseurs de pompes à chaleur géothermiques ont fourni un scénario réel grâce à un refroidisseur conçu sur mesure qui répond aux exigences de pompage de l'eau de une mine de chois.

La deuxième partie de cette thèse démontre le potentiel d'utilisation de masses d'eau de surface profondes pour le refroidissement des exploitations minières souterraines actives. Une mine candidate a été sélectionnée pour cette évaluation et les visites sur place. Des informations sur le lac et la mine ont été recueillies sur tout le site. Les catalogues des unités de traitement de l'air donnent une évaluation économique et environnementale préliminaire du refroidissement des lacs profonds pour les mines souterraines actives. Les résultats de ces études montrent des résultats prometteurs pour les applications de ces ressources d'énergie renouvelable dans l'industrie minière.

Table of Content

Part I

Part II

List of Figures

List of Tables

Nomeclature

Units of Measurement

°C	degree Celsius
cfm	cubic feet per minute
ft	feet
gpm	US gallons per minute
g	gram
hr	hour
m	metre
W	watt

Prefix

G	Giga- (1 x 10^9)
M	Mega- (1 x 10^6)
K	Kilo- (1 x 10^3)

Part I

Examining the Potential of Utilzing Geothermal Energy From Ejected Mine Water Towards Mine Heating

1. Introduction

As the global environmental wake continues, more countries are adapting into new technology with the goal to harvest energy at lower cost and minimize the environmental impact while generating that energy. Many cities have been successful in transforming their old non-renewable energy generating methods to greener renewable ones. In Canada, the mining industry contributes greatly to the nations green house gas emissions through the energy intensive mining and processing activities. Introducing new, and stricter, carbon tax in Canada have signaled the movement of many mining companies towards renewable sources of energy. One of those renewable energy sources that has the potential to be used widely in the mining industry is geothermal energy.

Geothermal energy is a source of energy that utilizes the thermal energy stored and generated within earth. Geothermal energy can be used for heating or cooling residences and industrial buildings. If the temperature source is of low temperature, as the case in Canada, the aid of heat pumps or chillers can provide the energy needed for cooling or heating. Many deter away from the idea of geothermal energy because of the cost associated with drilling wells to tap into the geothermal source. Therefore, it is possible to access that energy from underground mines whether a mine is active or inactive. There are numerous successful examples in Europe and North America where open loop mine water systems are designed to harness the geothermal energy from abandoned underground mines. However, very few studies were carried out for active underground mining operations.

This research project contains four objectives. The first is to examine successful mine water geothermal projects that can be found in Europe and North America. This is important to understand the principals and logistics of geothermal energy that can be extracted from mine water.

The second objective consist of visiting active underground mining operations to perform detailed assessment of the potential geothermal energy that can be harvested, as well as, the logistics needed to harvest that energy. In this step, numerous information was collected to calculate the amount of geothermal energy. In addition, visiting the underground mines helped us design the location to install the heat pumps or chillers and their parameters. The third objective was to further examine the economic and environmental benefits of active mine water geothermal energy. The fourth and final objective was to communicate with heat pump and chiller suppliers to obtain a real life scenario of implementing geothermal energy in an active mine operation and the pricing of that equipment.

This project is part of a joint research project between the Earth Mine Energy Research Group (EMERG) of McGill University Mining and Material Engineering Department, numerous international mining companies operating in Manitoba, Ontario and Quebec, and the Ultra-Deep Mining Network (UDMN).

The part of the thesis is divided into six chapters starting with an introduction in Chapter 1. This is followed by literature review of geothermal energy in Chapter 2. The literature review contains the classification of geothermal energy, its global use, and case examples where geothermal energy has been successfully implemented. The next chapter contains the methods and steps of this research project. Chapter 4 illustrates the obtained results and a brief discussion of these result. This is followed by chapter 5 which lists some recommendations the author has made to expand the scope of this research project. Chapter 6 contains a conclusion made by the author in regard to this study.

2. Literature Review

2.1. Geothermal Energy Classification

Geothermal energy sources can be classified into three categories based on the temperature of the geothermal fluid. High temperature geothermal sources have the temperature of geothermal fluid above 200 °C [1]. In that category it is possible to generate electricity from the geothermal energy source with powerplants that are designed for that purpose [2]. If the temperature of the geothermal fluid is between 200 to 100 °C then the geothermal sources is classified as intermediate temperature geothermal source [1]. This category cannot produce electricity directly, however, it still can be used as a source of energy by generating heat directly [1, 3]. This is particularly useful in heating industrial buildings, as well as residential and commercial buildings. The third class of geothermal energy sources is low temperature sources which has geothermal fluid temperature of less than 100 °C [1]. This class of geothermal energy source requires a geothermal heat pump in order to upgrade the energy to make it usable directly as a heat source similar to the case of intermediate geothermal energy sources [4]. Therefore, this class requires an input of energy to the heat pumps to make use of the geothermal energy.

Regardless of the class of geothermal energy source, geothermal energy remains as an environmentally friendly source of energy. In addition, geothermal energy is a sustainable source of energy since it is continuously restored by the upwards flow of heat from the earth's interior. Harvesting geothermal energy can reduce the dependency on fossil fuels which in turn can reduce greenhouse gas emissions. Unlike fossil fuels, geothermal energy can be utilised with little land disruption and minimal effect on the ecosystem.

2.2. Global Utilization of Geothermal Energy

Geothermal energy has an estimated accessible electrical potential within the range of 35 to 200 GW. Still, this type of energy contributes to a small fraction of the world's energy production. Even though the estimated electrical potential of geothermal energy is massive it produces less than 1% of the world's electricity output [5]. In some countries where fossil fuel resources are scarce, such as the Philippines, geothermal energy contributes significantly in the energy supply. As shown in Figure 1, the global production of electricity from geothermal energy is lead by the united states at 3,500 MW, followed by the Philippines at 2,000 MW, and then Indonesia at 1,500 MW [5].

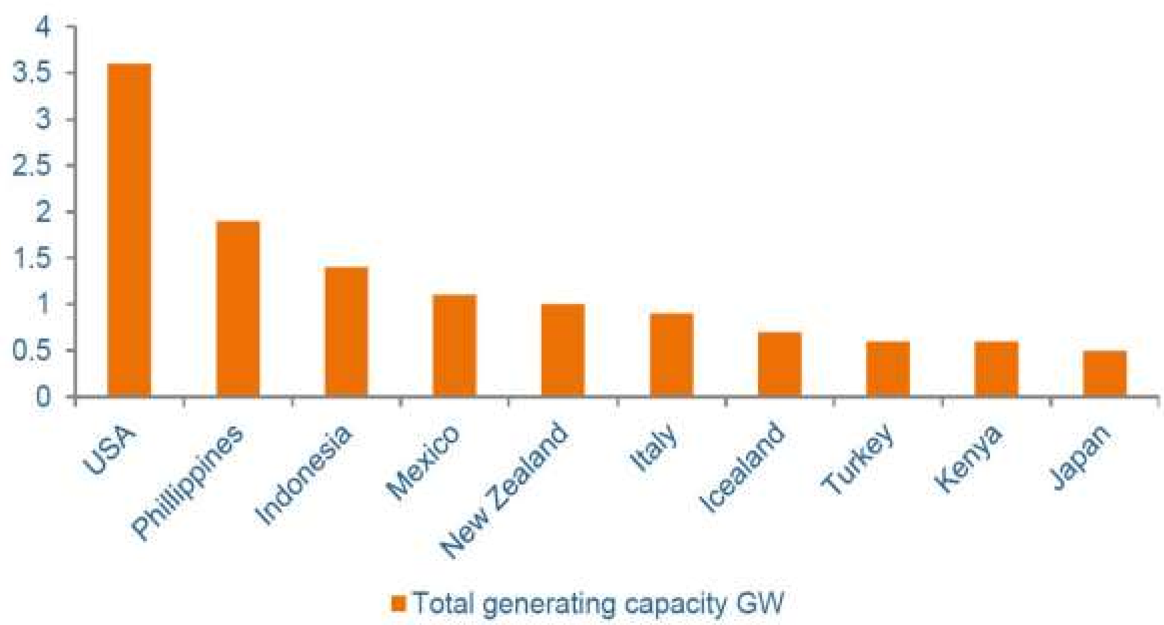


Figure 1. Top Countries in Generating Electricity from Geothermal Energy. Figure taken from [5]

When it comes to direct use of geothermal energy as a heat source, the country with the highest utilization of geothermal energy is China at 20,000 MWh, followed by Turkey at 12,000 MWh, then Iceland and Japan at 7,500 MWh. Figure 2 shows the countries with the highest direct use of geothermal energy for heating, which account for roughly 70% of global direct utilization of geothermal energy.

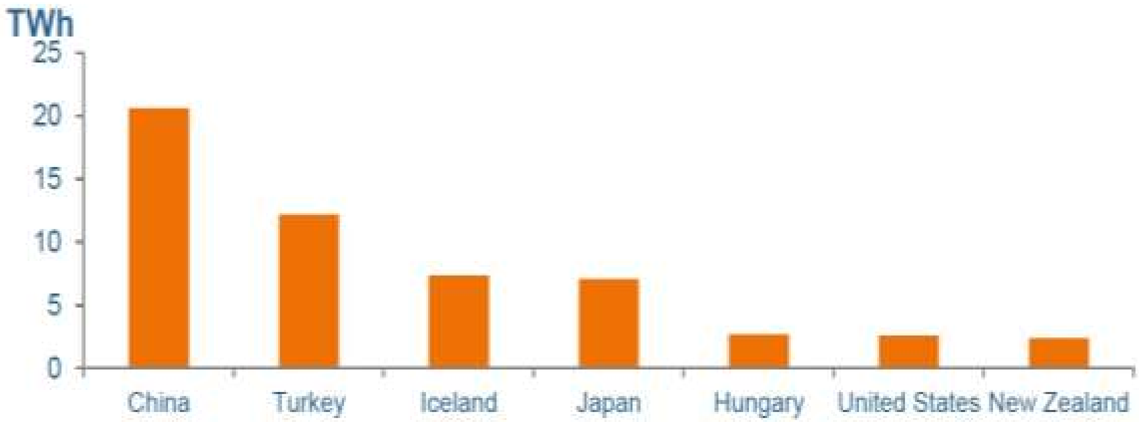


Figure 2. Top Countries in Direct Utilization of Geothermal Energy. Figure taken from [5]

The shift towards geothermal energy has a correlation with fossil fuel prices. As shown in Figure 3, years with higher oil prices showed increase in the installation of geothermal generation capacity. This is particularly for countries such as Iceland and the Philippines which lack fossil fuel resources. Approximately 54% of the total installed geothermal generation capacity resides in such countries to ensure energy dependency and lower electricity costs compared to importing fossil fuels [5]. Furthermore, international agreements to reduce greenhouse gas emissions such as the Kyoto Commitment in 2005 and the Paris Agreement in 2016 are crucial factors in pushing countries towards renewable energy resources such as geothermal energy.

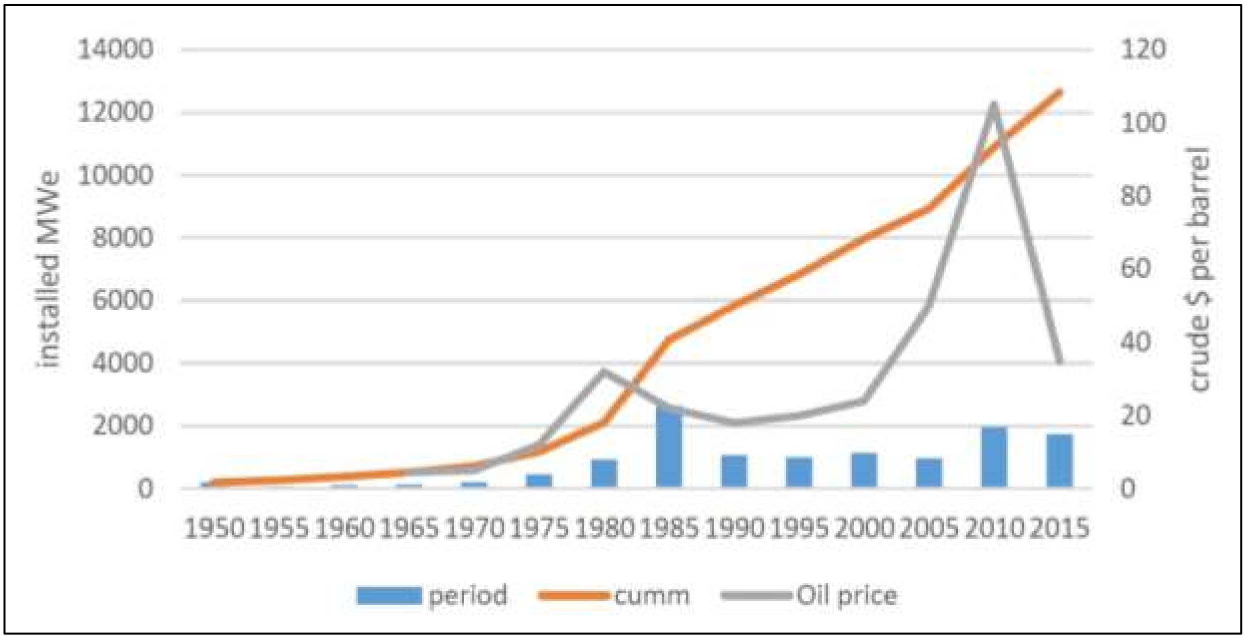


Figure 3. Installed Geothermal Generation Capacity Comparison to Oil Prices. Figure taken from [5]

2.3. Geothermal Energy in Canada

From coast to coast, Canada has abundant resources of geothermal energy. High temperature geothermal resources can be found in British Columbia, Yukon and the Atlantic Provinces. Intermediate temperature geothermal resources are available in British Columbia, Yukon, Alberta and Northwest Territories. The western Canadian sedimentary basin, which stretches from the Rockies to the Canadian Shield, contains an enormous amount of deep circulating warm water that can be utilized as a geothermal energy resource [6]. In fact, the extractable geothermal energy from the western Canadian sedimentary basin is estimated to be more than the overall Canadian oil sand reserves [7]. Figure 4 below illustrates the geothermal potential in Canada based on the possible end use of the geothermal source.

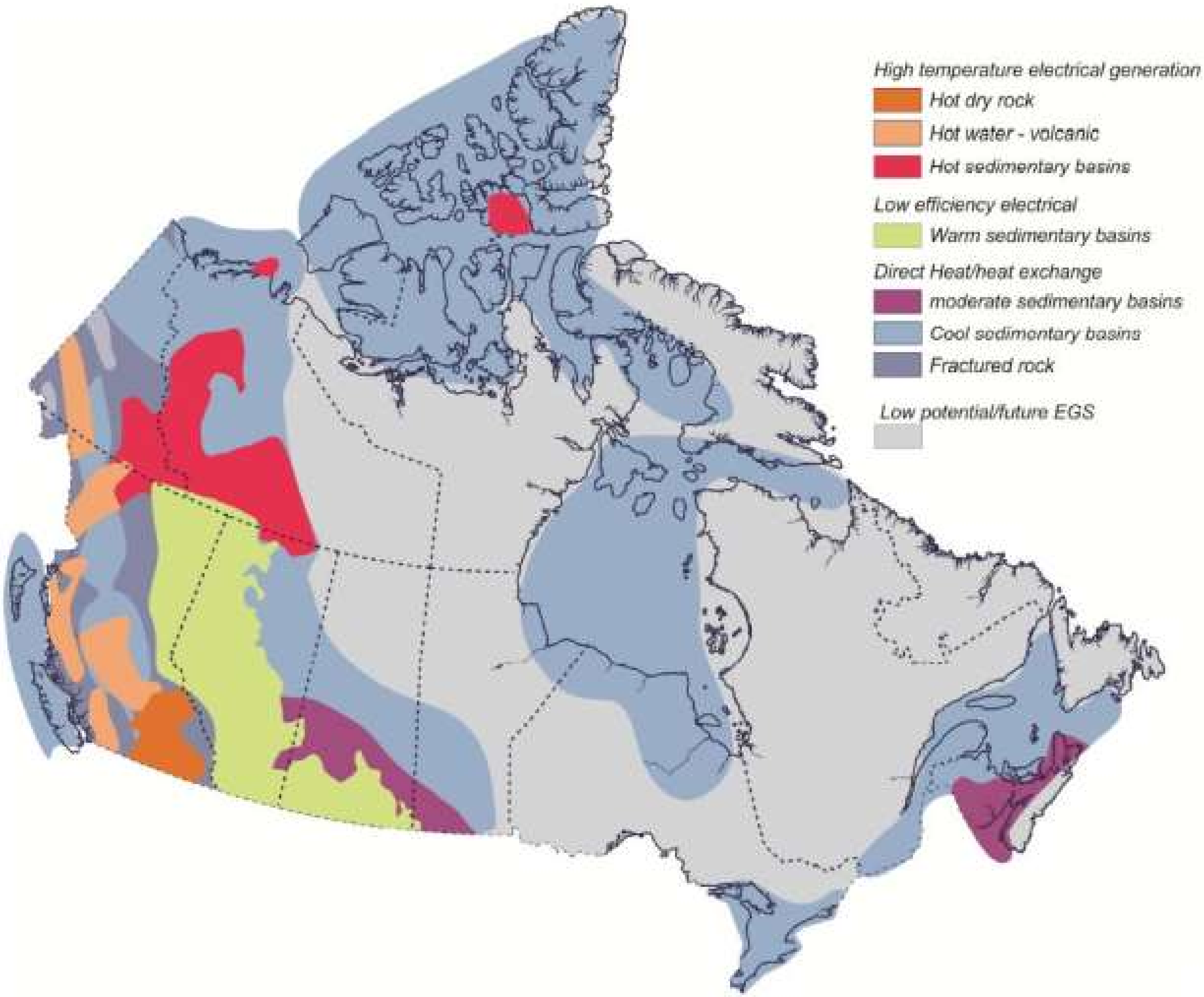


Figure 4. The Geothermal Energy Potential in Canada. Figure taken from [8]

Although Canada has abundant resources of geothermal energy, there are no geothermal electrical production thus far. There were several attempts to initiate electrical production from geothermal energy throughout the pas but were stopped due to low energy prices, the lack of governmental incentives, and the financial constraints associated with the costs of deep drilling [6, 8]. This is expected to change due to the increase in fossil fuel prices as well as the decrease in the costs of harvesting geothermal energy. Not to mention the increased awareness about greenhouse gases and the attempts to reduce their emission. Furthermore, it is possible to decrease the costs associated with drilling by using water from deep active or abandoned underground mines as a geothermal energy resource.

Intermediate and low temperature geothermal resources are currently used in all Canadian provinces with a promising future seen through growing interest in geothermal energy. Canada has seen an exponential growth of geothermal heat pump utilization with more than 30,000 heat pumps installed in residential, commercial and institutional buildings. One third of the installed geothermal heat pump systems are implemented in commercial, institutional or multiple residential buildings [6]. The cost savings from heat pumps depends on the region it is implemented in. For example, in the Prairies and Eastern Provinces which has very cold winters and hot summer the high requirement for heating and cooling greatly affect cost savings using geothermal energy. The heat pump market has seen a 10% to 15% annual growth since the beginning of the millennium. Canadian geothermal heat pump users contribute to 600 million kWh of energy savings annually which corresponds to approximately 200,000 tonnes of reduction in greenhouse gas emissions [6].

2.4. Heat Pumps and Chillers

As mentioned earlier, low temperature geothermal energy sources require a geothermal heat pump or a chiller in order to upgrade the energy and turn it into a usable form. These machines can be used for domestic, industrial and commercial applications. Figure 5 below shows a simple schematic of a heat pump unit with its four essential components. When the geothermal source water reaches the heat pump it encounters the evaporator of the unit resulting in the refrigerant fluid warming up by heat exchange and evaporating. This also results in the geothermal liquid to cool down. The refrigerant then passes through the compressor which is where energy input into the system occurs. The compressor function is to further heat the refrigerant by means of compression. The refrigerant then goes to the condenser where a heat exchange occurs between the refrigerant and the heating fluid or airflow. This result in the refrigerant cooling down and condensing in the condenser. The condensed refrigerant then passes through the expansion valve which cools the refrigerant fluid further by means of expansion. Then the refrigerant is returned to the evaporator in order to start a new cycle [9]. It is critical to note the importance of selecting the appropriate refrigerant since it is a key factor in upgrading low temperature geothermal energy sources. Furthermore, the cooled geothermal water is returned to the ground to regain heat to ensure a sustainability.

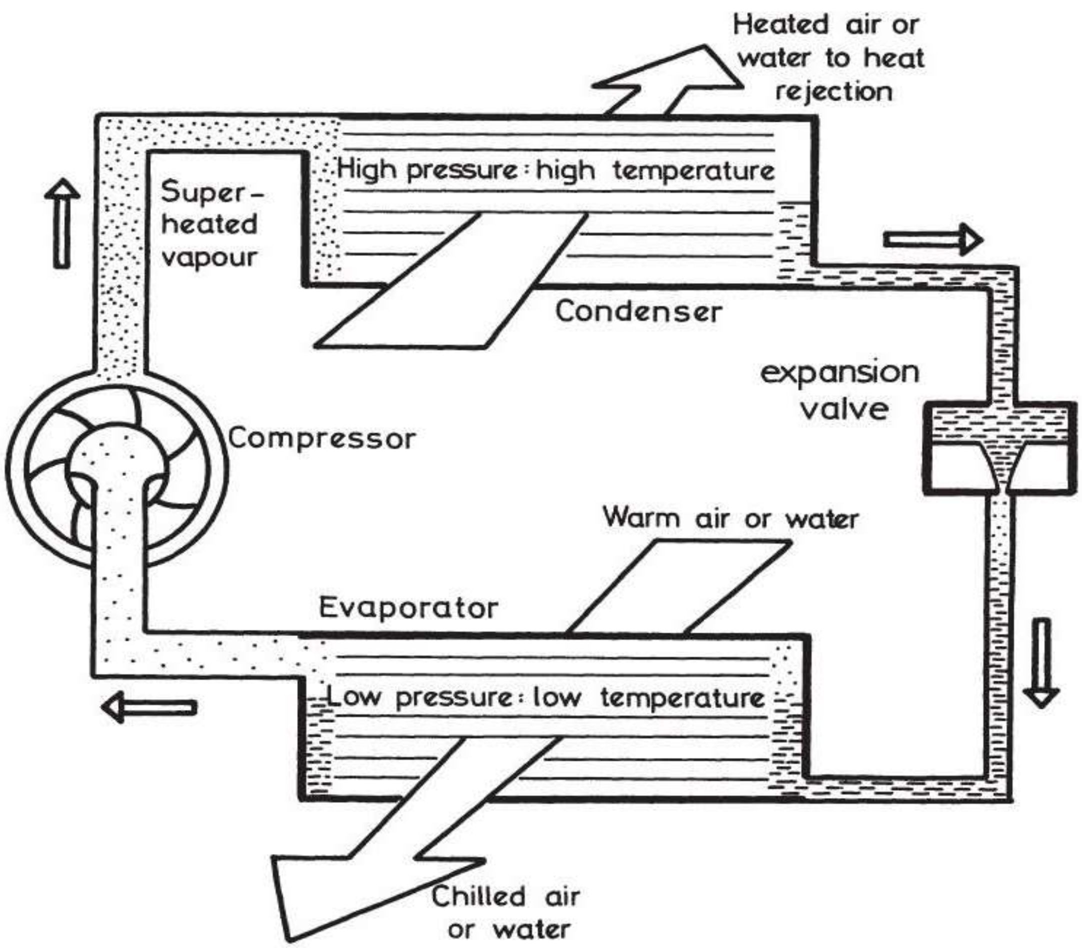


Figure 5. Major Components of a Heat Pump or Chiller. Figure taken from [9]

Not all heat pumps or chillers work at the same performance for the amount of external energy provided to it. Therefore, the performance of a heat pump or a chiller is measured by the Coefficient of Performance (COP). It is a ratio that measures the amount of energy output through heating or cooling to the amount of energy provided to the heat pump or chiller [9]. The COP of a heat pump or a chiller is critical as it can determine the overall economic potential of a geothermal energy system. The COP ratio can be presented as follows:

$$COP = \frac{Total\ Energy\ Output\ of\ a\ Heat\ Pump\ or\ a\ Chiller}{Electrical\ Energy\ Input}$$

2.5. Geothermal Heat Exchange System Design

The two main designs for geothermal heat exchange systems: open loop or closed loop configuration [10]. While this thesis focuses mainly on open loop design for geothermal systems, both will be explained in this section.

In open loop geothermal heat exchange system, the heat exchangers interact directly with the geothermal energy source. The geothermal energy source can be a groundwater such as abandoned mines or a surface water such as lakes. The water is pumped into a heat exchanger and then, after the energy is extracted, the water is returned into the source [10]. There are three types of open loop systems: extraction wells, extraction and reinjection wells, and surface water. The most common of these three types is the extraction and reinjection wells system. In this design water is pumped from a drilled extraction well to be passed into the heat exchanger. After passing through the heat exchanger the geothermal fluid is reinjected back into the source but at a distance from the extraction well [10]. This ensures the geothermal fluid is being replenished and ensures the extraction well temperature is not affected, which leads to the sustainability of the geothermal source.

In the case of closed loop geothermal heat exchange system, the heat transfer fluid circulates within an enclosed loop and it never comes in direct contact with the geothermal energy source. Heat transfer from the geothermal source is therefore dependant on the piping material of the loop and the type of the heat transfer fluid [10]. To increase the heat transfer, the closed loop pipes are designed as a continuous piping loops to increase the surface area contacting the geothermal source (Figure 6). The pipes are usually filled with anti-freeze like liquid that is effective in transferring heat from the geothermal source to the heat exchanger [10].

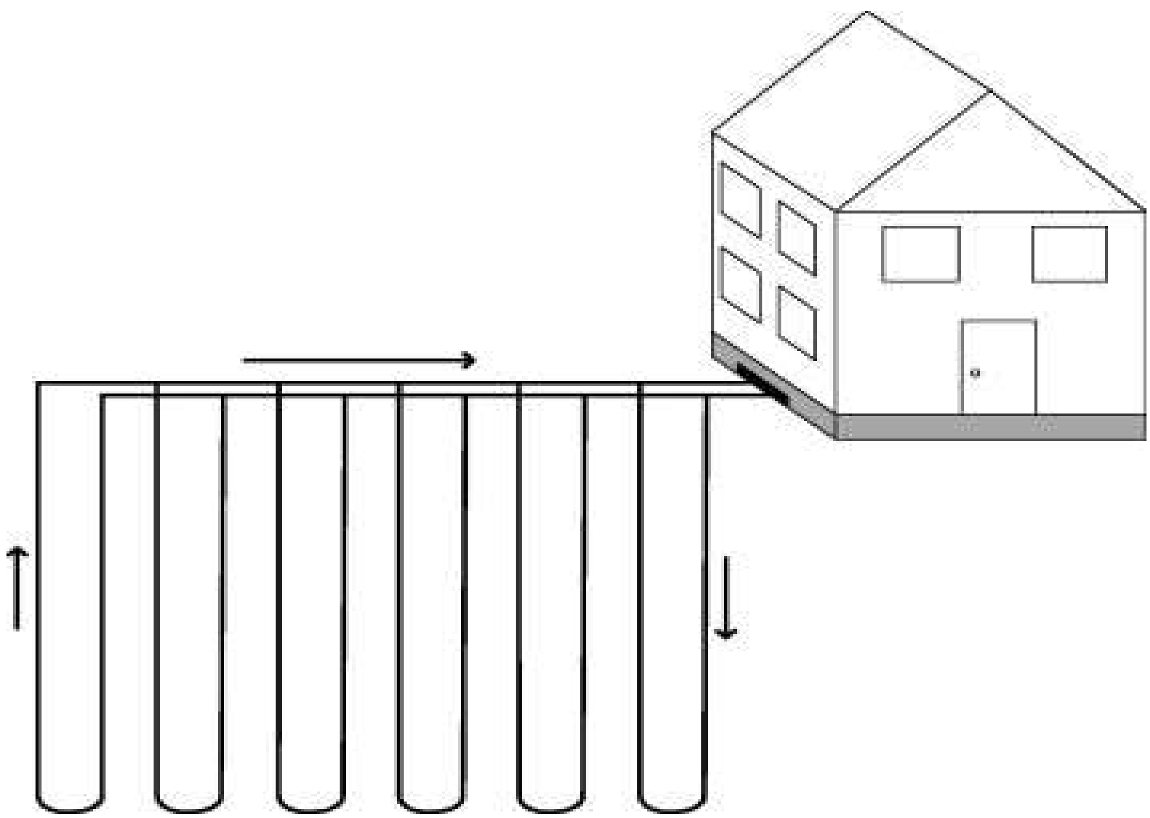


Figure 6. An Example of a Closed Loop Heat Exchange System. Figure taken from [10]

Each geothermal heat exchange system has its own advantages and disadvantages. The advantage of an open loop design is the high efficiency of the heat exchange process compared to closed loop systems [10]. This is because there is only one step for the heat exchanging between the geothermal source and the heat exchanger, compared to the two steps found in closed loop systems (one step is between the geothermal source and the liquid in the closed pipes, the second is between the liquid in the pipes and the heat exchanger). Furthermore, open loop designs usually require less drilling than closed loop systems which equates to lower initial costs [10].

On the other hand, the advantages of the closed loop system are mainly due to the fact that there is no direct contact between the geothermal source and the heat exchanger. If the quality of the source water is not neutral in chemistry and/or have high amount of minerals the heat exchangers may be subject to corrosion, fouling and/or scaling. This can be observed in water with high chemical contents, hard water or sea water [10]. A result of utilizing water which is not neutral in chemistry and have high amount of minerals is an increase maintenance costs of an open loop system. Another advantage of a closed loop system is the fact that it can be used even with limited geothermal source water. Furthermore, with many open loop systems the water returned back to the environment should be tested and treated to ensure it is released in accordance with the local water regulations [10]. This is not needed in closed loop systems since the liquid inside the loop's pipes does not come into contact with any element outside of the pipes. These factors can result in having a closed loop design as a better solution despite the lower coefficient of performance.

2.6. Successful Implementation of Geothermal Energy

2.6.1. The City of Heerlen, Netherland

Overview of the region

The city of Heerlen is located within Parkstad Limburg region which is situated southeast of the Netherlands. The municipality of Heerlen occupies an area of 45.53 km2 with an estimated population of approximately 88,000 individuals. The Parkstad Limburg region is a collaboration of eight municipalities (including Heerlen) within the province of Limburg. The region of Parkstad Limburg covers total area of 211 km2 where Heerlen is the main city. Parkstad Limburg is considered as the powerhouse of the Netherlands' economy. It is estimated that approximately 15,000 company and institutions are centered in the region. The province generates a GDP of €29,700 per capita, which is 83% of the total GDP of the Netherlands of €35,800 per capita [11].

History of Heerlen

Heerlen was part of what is formerly known as the Eastern Coal Mining District (Oostelijke Mijnstreak). As the name suggests, Heerlen was a centre for the coal mining industry within the Netherlands during the late 19th century and early 20th century. Coal was discovered in the area in 1874, and coal production remained until 1975 when coal mines were shut down. Throughout that period the city of Heerlen contained numerous coal mines in which two of them, the Oranje Nassau I and the Oranje Nassau III, are used for the Mijnwater Geothermal Project [11]. The closure of the coal mine operations in the region has led to the slow dissipation of the industrial environment. As a result, the region faced an era of economic, social and cultural decline. The municipality of Heerlen was face with a challenge to recreate a new spirit for the citizens of the city. Therefore, it was important for the municipality of Heerlen to rehabilitate the region and create a stepping stone that can not only flourish the city but also is futureproof. This incentive resulted in the initiation of the Mijnwater Project in 2003 which was a new milestone for the city of Heerlen.

The Mijnwater Project

The Mijnwater Project in Heerlen is a mine water initiative (hence the name) that started in 2003. The project initially started with the concept of utilising water stored in abandoned coal mines as a geothermal source of sustainable energy. The project has a great significance for the region due to the history of the city of Heerlen as the heart of energy in the Netherlands [11]. In addition, the project utilizes the water accumulated in the abandoned coal mines and so it offers a new prospective of extracting energy from coal mines. However, unlike coal mining the Mijnwater Project is an innovative green technology that utilizes a sustainable geothermal energy stored in the water of the abandoned coal mines.

Minewater 1.0 is the initial pilot geothermal system developed in the city of Heerlen. It was developed between 2003 until 2008. The gaol of that phase was to study the possibility of utilizing the mine water of the abandoned Oranje Nassau coal mine in order extract sustainable energy for heating and cooling. The pilot projects consisted of five well. Two hot water wells, two cold water wells, and a fifth well in the middle of these four wells. The two hot water wells are at depth of 700 meters below the surface and are designed to extract hot water. The temperature of the hot water extracted is approximately 28 °C. The two cold water wells are at depth of 250 meters and are designed to extract cold water. The temperature of the extracted cold water is about 16 °C.

The fifth well in the middle part of Heerlen is used for the injection of the cooled hot water or warmed cool water. The well is at a depth of 350 meters and the temperature of the water injected is between 18 to 22 °C [11].

At first and until 2012, there were only two end users that benefited from the geothermal energy from the mine water. The first one is the office of the Central Bureau of Statistics with an area of 22,000 m2 and the Heerlerheide Centrum Complex of homes, supermarket, offices and community facilities that has an area of 30,000 m2. Mijnwater 1.0 showed great economic and environmental benefits, however, it also came with some shortcomings. One of the most important drawbacks is water return with intermediate temperatures to the HLN3 well (located in the middle), it is believed that this process will eventually affect the sustainability of producing warm water and cold water from the HH1 well and HLB3 well, respectively [11]. If the reservoir started to homogenize then the hot or cold water produced won't be sufficient for the heat exchange process. It is clear that using the HLN3 well has an important role in the process of mine water utilization, however, it also makes the operation a less attractive long-term solution.

In addition to the restriction of the sustainability of Mijnwater 1.0, other restrictions within the systems exist. One would be the limited hydraulic and thermal capacity of the system. Another would be the fact that the system is not demand driven [11]. This means the system can only supply cold water during summer (April until September), or supply heat during winter (October till March). Therefore, if heating is needed during the summer period or cooling during the winter period it would not be possible to rely on Mijnwater 1.0. In addition, Mijnwater 1.0 does not provide energy exchange between buildings. This can be a great method to further save energy as well as reduce the amount of water returned to the return well. These shortcomings have led to the development of Mijnwater 2.0 system.

Mijnwater 2.0 is designed to overcome the restrictions of Mijnwater 1.0 pilot system and make the Mijnwater system future proof. As a result, Mijnwater 2.0 introduced new techniques that result in energy exchange within the system rather than energy supply. In addition, it enables energy storage and maximizes the hydraulic and thermal capacity. Moreover, it is a fully automated system that is demand driven [11]. All in all, Mijnwater 2.0 system is designed to overcome the Mijnwater 1.0 shortcomings and prepare the system for long term usability.

The design of Mijnwater 2.0 is based mainly on cluster grids that provide instant energy exchange between the connected buildings within the cluster. The mine water function to supply the hot and cold water from the mine to the backbone of the cluster grid [12]. As a result, a building does not only function as a consumer of energy but also as a supplier of energy. When a building extract heat from the grid it then can supply cold water to the grid which can directly be used by other facilities connected to the grid. This not only result in a conservation of the mine water hot and cold water, but also result in a significant cost reduction. In addition, the cluster grids operate with clean water in a closed system [11]. Since the mine water is not used within these clusters there are no need for special corrosion resistant materials such as stainless steel or plastic pipes to be used and iron cast pipes would be sufficient. This results in further reduction in the capital and maintenance cost of the system.

In Mijnwater 2.0, the extraction wells HH1 and HLN1 supply hot and cold water, respectively, from the mine water to the grid of clusters. Then surplus hot and cold water are returned to the mine water reservoir for storage through the hot and cold injections wells HH2 and HLN2, respectively. The previous injection well (HLN3) is not used in Mijnwater 2.0 unless in exceptional situations [11]. With this arrangement of production and injection wells there is no mixing between the hot and cold water in the mine reservoir. In addition, this will create a hot and cold bubble that will build up and increase the energy capacity stored in the mine reservoir.

Minewater 2.0 transformed the geothermal mine water project from a straightforward pilot system into an advanced network grid. It is estimated that in 2015 the area that utilizes Minewater 2.0 would approximately reach 500,000 cubic meters. This will lead to an estimated reduction of CO2 emission of 65% for heat and cooling within the municipality of Heerlen [12]. Still, in order to reach the carbon neutral goal further technical development is needed. This will lead to Minewater 3.0, which besides the fine tuning of the previous stage, it introduced an intelligent system that increases the efficiency of Minewater 2.0.

The Minewater project has evolved significantly from Minewater 1.0 to Minewater 2.0. The changes made are revolutionary for that step. In the case of Minewater 3.0, the system evolves from Minewater 2.0 and, instead of completely changing the system, adjustments, fine tuning, and the addition of intelligence into the Minewater project was performed. The goal of Minewater 3.0 is to decrease carbon emission from the estimate 65%, achieved by Minewater 2.0, to a carbon neutral range of 80-100% [12].

Minewater 3.0 is depends on the application of time based controls for the supply and demand management. This depends on using data from different times of the year in order predict and adapt the supply of hot and cold water in the clusters. It includes control strategies such as peak shaving, cell/cluster balancing, and market interaction [12]. This intelligent system will lead to adjusting the supply of hot or cold water depending on need. As a result, it will increase the efficiency of the Minewater system. Another addition to Minewater 3.0 is the use of multiple renewable sources of energy to power the pumps and heat exchangers of the system. This includes renewable sources such as the use of photovoltaics panels and wind turbines [11, 12]. These steps are aimed to further increase the efficiency of the Minewater system in order to achieve the targeted 80-100% decrease in carbon emission.

The Mijnwater Project has led to a reduction in the carbon footprint to 65% with the third phase aimed to further reduce it to 80-100%. Therefore, resulting in a carbon free region. This geothermal energy project aided Parkstad Limburg region to regain its status as the energy capital of the Netherlands. In 2011, the municipality of Heerlen made the decision to make the Mijnwater project as a private company [11, 12]. This is done to promote local employment, involve research institutions, and to generate social involvement and sustainability awareness.

2.6.2. The Town of Springhill, Nova Scotia

<u>Overview and History of the Springhill</u>

Springhill is a town located in north central of Nova Scotia. It lies within the Cumberland Basin which contains coal bearing sedimentary rocks. Due to the coal rich region, coal mining commenced in 1872. As a matter of fact, the town was originally created to accommodate the coal miners working in the region. However, due to a series of rock bursts coal mining was deemed unsafe and the mines were closed in 1958 as a result [13]. This lead to period of adjustment where the town needed to develop new economic attraction.

Upon closure of the mines, the underground coal mines were left to fill with seeping water. Then, in 1985, a feasibility study was conducted to examine the potential of using the water from the flooded mines for space heating. The study showed that the concept can provide heat energy with great savings compared to hydrocarbon heat sources. Since capacity of the geothermal source depends on its volume and temperature, the study worked on measuring these two factors within the water flooding the mines. And so, the study concluded that the amount of water in the mines to be approximately 4,000,000 m^3 with a temperature of about 20 °C [14]. In addition, having the numerous interconnected levels of the mines which can reach to depths of about 1,400m provides channels for water circulation which prevent the generation of hot or cold water pockets when returning the water back to the mines [15].

Ropak Can-Am Geothermal Project

Putting the data of the feasibility study into a practical example was carried out by Ropak Can-Am, a manufacturer of plastic packaging products. The factory is placed in the industrial park on the west side of Springhill, which is right on top of the abandoned coal mines (Figure 7). The manufacturer pump water from the 140m level of No. 2 mine into the heat pumps at a constant rate of 4 L/s. Then it is returned to the 30m level of No. 3 mine. Throughout operation the inlet water temperature is constant at 17.9 °C, however, the outlet temperature varies throughout the year depending on the heating or cooling requirements. This is because the rate of heat extraction is proportional to the flow rate (which is constant) and the difference between the intake and outlet temperatures. Therefore, when heating is required during winter the outlet water temperature can reach a minimum 13 °C. On the other hand, when cooling is needed during summer the outlet temperature can reach a maximum of 23 °C [16] . Since No.2 and No. 3 mines are interconnected at numerous levels the water is recirculated, thus making the geothermal system sustainable.

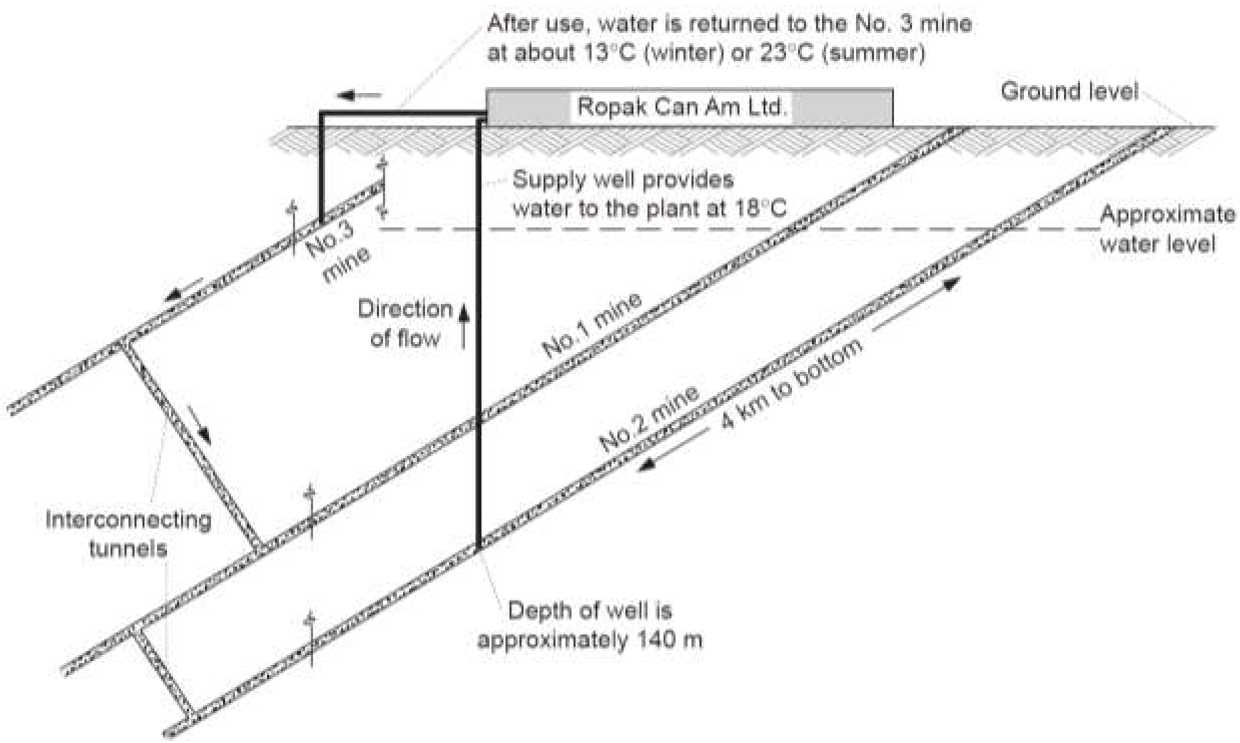


Figure 7. Schematic of the Ropak Can Am Geothermal System. Figure take from [16]

Ropak Can-Am is considered the first industrial site in Canada that illustrated the technical possibility and the economical benefits of utilizing geothermal energy. The water taken from the mine is passed through 11 heat pumps. 10 of these heat pumps are installed in plastic molding and manufacturing area while 1 heat pump is installed for the offices area [13]. Together the 11 water-to-air heat pumps provide space heating in winter months and air cooling for summer months.

When it comes to the economics of the project, the cost of the heat pump system was 110,000 CAD. This is higher than the estimated 70,000 CAD needed for a conventional or propane system. However, this capital cost can be offset by a saving of 110,000 CAD in cost for the required dehumidification if conventional or propane system were chosen [16]. In addition, Ropak Can-Am have calculated a gross annual savings of approximately 65,000 CAD. After adjusting for the operation cost, such as the electricity for running the heat pumps and maintenance of the system, the net annual saving is estimated to be 45,000 CAD which is equivalent to 600,000 kWh [16].

In addition to the economical and environmental benefits of the project, the system provides a healthier work place. This is observed through a decrease in employee absence, reduction in down times, increase in production efficiency by 9%, and increase in staff morale after the installation of the geothermal heat pumps [16]. The result also proves that geothermal energy can provide cooling or heating to large buildings using heat pumps. This lead to other businesses such as Surette Battery Ltd, a lead battery manufacturer, and even the community center of the Town of Springhill to jump onto geothermal energy technology [14].

3. Methodology

This part of the thesis is intended to examine the finances of extracting geothermal energy from active underground mines. While there are several successful geothermal projects that utilizes abandoned mine water as a source of geothermal energy, this thesis handles ejected mine water from active underground mining operations. Extracting geothermal energy from abandoned underground mines has been extensively studied for over twenty years. Still, very little research has been done when it comes to active underground mining operations. In addition, utilizing mine water as a geothermal source while a mine is active has never been implemented in the mining industry to this point. The study gives an insight to the mining industry about the financial and environmental benefits of utilizing geothermal energy.

There are several financial reasons for considering water from active underground mining operations as a source of geothermal energy rather than from abandoned mines. For starters, in many underground mining operations underground water constantly seeps into the mine and so pumping that water is required for operation. Utilizing that water, which in any case has to be pumped out of the mine, as a geothermal source will integrate the pumping cost of the geothermal system with the operation cost of the mine. If a mine is within the feasibility phase the capital cost of the geothermal energy equipment can replace the capital costs of other heating or cooling equipment. Also, costs associated with drilling can be saved if an active underground mine water is utilized as a geothermal energy source. In addition, information about the ejected water of active underground mining operations including the quality of the water and its temperature is constantly monitored by the operator of the mine due to environmental requirements. This adds more savings when compared to abandoned underground mines since most abandoned mines do not have the information of the geothermal water readily available. Since geothermal energy reduces greenhouse gas emissions of a mine operation carbon tax savings will play a crucial part in the overall savings of the active mine operational cost. This is especially important in Canada as the government is currently in the process of implementing new higher carbon tax into the mining industry. Furthermore, extracting geothermal energy from active mine operations can also provide excess heat or coolness into nearby communities. Even after mining is done and the mine is closed these communities can keep benefitting from geothermal energy which makes the system economical beyond the life of the mine.

In order to examine the finances of extracting geothermal energy from active mining operations, fifteen mines within Canada were visited to obtain the necessary data needed for the study. This data includes the amount of water ejected by the mine, the quality of the water, and its temperature. In addition, numerous heat pump and chiller suppliers were contacted to obtain cost information of the heat pumps and chillers. Then, a mine with the average ejected water volume and temperature was selected for a prefeasibility study to give a real-life example of the financial savings of implementing geothermal energy in an active mining operation. This required several visits to the mine to determine the logistics of implementing the geothermal equipment, and several meetings with the heat pump supplier which provided a custom build geothermal system.

3.1. Data Gathering

When carrying out this project the first step was to gather as many information as possible regarding active mines in Canada, the amount of water ejected by the mine, the temperature of that water and the quality of the water. This was done first by gathering data from literature to determine the active deep underground mines in Canada and their location relative to the geothermal energy potential map of Canada (Figure 4). Then mining companies were contacted in order to obtain data of the mine dewatering system and the water being ejected, as well as the possibility for a mine visit. After the needed data about the mines visited were gathered, contacting geothermal heat pump suppliers was carried out to get the specifications of the geothermal heat pump systems suitable for the data of the mines visited and their associated costs. Then an economic prefeasibility study was carried out in order to get the potential economic and environmental benefits of installing geothermal heat systems within active mines. It is worth noting that the data were gathered prior to contacting the geothermal heat pump suppliers to give them exactly what we need for our system so that we get the most suitable custom designed equipment.

Along with the data of geothermal energy that can be extracted from active underground mining operation, the type of heating within a mine was obtained to assess the environmental benefits and carbon savings within a mine. This was used calculate carbon dioxide emissions per kWh of energy produced from electrical or thermal systems such as natural gas or propane systems (Table 1 and Table 2). Since the mines visited were in Manitoba, Ontario and Quebec, the percentage of energy type used in these provinces to supply electricity was used to calculate carbon dioxide emissions per kWh produced from electrical heating systems (Table 3). From these data it was possible to obtain the carbon savings of a geothermal heating system per kWh of energy used in the mine.

Electricity Source	CO_2 Emission ($kgCO_2/kWh$)
Nuclear	0.115
Coal and Oil	0.62
Water Power	0.011
Natural Gas	0.37
Wind, Solar, Biomass	0.011

Table 1. Carbon Dioxide Emissions from Electricity Production

Heating Source	CO_2 Emission ($kgCO_2/kWh$)
Natural Gas	0.1836
Propane	0.21

Table 2. Carbon Dioxide Emissions from Natural Gas and Propane

Type of Energy	Electrical Energy Source Breakdown		
	Manitoba (%)	Ontario (%)	Quebec (%)
Nuclear	0.00	32.20	0.00
Coal and Oil	1.90	32.00	2.21
Water Power	92.90	27.60	91.82
Natural Gas	4.80	5.90	2.21
Wind, Solar, Biomass	0.40	2.3	3.76

Table 3. Electrical Energy Sources in Manitoba, Ontario and Quebec

3.2. Calculations

The amount of energy generated from a heat pump or a chiller can be calculated using the following equation:

$$Q_h = Q_c + W_{net} \quad (1)$$

In this equation Q_h represents the total energy output of the system in kilowatt (kW), Q_c is the potential heat energy from water (kW), and W_{net} is the supplied energy needed to run the heat pump (kW).

The potential heat energy gain by the water (Q_c) is calculated based on the flow rate of water ejected from the mine, which will go through the heat pump. Therefore, the heat gain by water can be calculated with this equation:

$$Q_c = Q \times C_w \times \rho_w \times \Delta T \quad (2)$$

Where Q is the flow of water into the heat pump (m^3/s), C_w is the specific heat capacity of water (J/kg °C), ρ_w is the density of water (kg/m^3), and ΔT is the difference between the water temperature entering the heat pump (inlet water temperature) and the water temperature exiting the heat pump (outlet water temperature) in degrees Celsius (°C). From this equation it can be observed that the amount of water supplied to the heat pumps is proportional to the amount of potential heat gain. In addition, the change in temperature between the inlet water temperature and the outlet water temperature is also proportional to the amount of potential gain from water.

On the other hand, the supplied energy needed to run the heat pump (W_{net}) can be calculated using Equation (3), where COP is the coefficient of performance of the heat pump:

$$W_{net} = \frac{Qc}{COP-1} \qquad (3)$$

Therefore, the total amount of energy generated from a geothermal system, Equation (1), can be calculated using the values from Equation (2) and Equation (3). From the equations above the total amount of energy generated from a geothermal system (Q_h) can also be calculated from:

$$Q_h = W_{net} \times COP \qquad (4)$$

Since COP value correlates with the ΔT of the water, the average value of ejected mine water temperature was considered. Larger ΔT results in higher COP, which means there is more energy gain per energy input from the heat pump.

Two set of prefeasibility economic calculations were carried out in this thesis. The first is using a Florida Heat Pump WW-420 (FHP WW-420), while the other calculation was done using a custom made chiller from Trane. The FHP WW-420 was utilized after examining the company's catalogue and concluding its specifications match what is needed for the operations (see Appendix 1 for full specification). On the other hand, the custom made chiller from Trane was selected after meeting sessions with a company representative. In each scenario, the calculations were made using the average water temperature recorded.

In the case of the FHP WW-420 where the specification sheet contains the operating information based on a variation of the inlet temperature, the electric power input and the output heating capacity was extrapolated using the interpolation formula:

$$Y = Y_1 + (Y_2 - Y_1) \times (X - X_1) / (X_2 - X_1) \qquad (5)$$

The COP was then calculated from rearranging Equation (4) after extrapolating the power input and the heating capacity of the heat pump system. It can be noted from the FHP WW-420 specification sheet the COP of the heat pump increases with the increase in the source water temperature. This is as source water inlet temperature increase the electrical power input is decreased while the heat gain from the heat pump increases. Therefore, it is possible to summarize the relation between the coefficient of performance with the total energy output and electrical energy input as follow:

$$COP = \frac{Total\ Energy\ Output\ from\ the\ Heat\ Pump}{Electrical\ Energy\ Input} \qquad (6)$$

Another factor that affect the potential heat gain is the amount of water flowing into the heat pump. This is normal considering multiple heat pumps can be used in parallel depending on the amount of water ejected from the mine.

In the case of the custom made chiller, only one mine was considered for this study. This is because the sales representative agreed to design a custom built chiller for only one mine of the 15 mines that are being studied. Therefore, one mine was selected (mine Ontario O9) which has a water flow rate close to the average flow rates of the mines visited, as well as, water temperature that is also representative of the average water temperature of the studied mines. Appendix 2 contains the specification sheet of the custom built chiller.

In order to assess the financial benefits of implementing geothermal heat pumps or chillers in active underground mining operations, it is important to estimate the current cost of heating in these underground mines. Since these mines use heating either from natural gas, propane or from electricity, the cost of both possible heating source was estimated. The prices of electricity and natural gas or propane for the different mines were obtained from mine personnel. The heating hours per year is estimated based on seven months of heating between October to April and so the heat pumps or chiller is estimated to operate 5040 hours per year. Table 4 summarizes the obtained electricity, natural gas and propane prices in the three provinces where the mines were visited. It is worth noting that the price of electricity needed to operate the heat pumps or chiller is the same price value as the one used for conventional electrical heating.

Province	**Heating hours per Year (hr/yr)**	**Price of Electricity and Thermal Heating per kWh**		
		Electricity	**Natural Gas**	**Propane**
Manitoba	5040	0.035	-	0.064
Ontario	5040	0.112	0.035	0.064
Quebec	5040	0.052	0.0123	-

Table 4. Summary of Prices of Electricity, Natural Gas and Propane

After obtaining these values it was possible to calculate the potential savings per year. This is done by first calculating the price value of heat ($Price_{Heat}$) generated by the heat pump or chiller (Q_h). The price value of heating ($Price_{Heat}$) is dependant on the heating source being from electricity, natural gas or propane. Then we subtract from that value the electricity cost ($Price_{Elec}$) associated with operating the heat pump (W_{net}) to get the savings per unit per hour. Multiplying by the number of units and number of operating hours will then yield the annual savings from utilizing geothermal energy. The annual savings calculation can be summarized by Equation (6):

$$Annul\ Savings = (Q_h \times Price_{Heat} - W_{net} \times Price_{Elec.}) \times Number\ of\ Units \times hrs \qquad (6)$$

The next step is to calculate the environmental benefits of geothermal energy through the reduction of carbon dioxide emissions. This was done by estimating the amount of CO_2 being produced per kWh of energy from electrical heating sources or thermal heating sources (natural gas or propane). While the amount of CO_2 produced from natural gas and propane is mentioned in Table 2, electrical heating sources requires calculating the fractions of the electrical energy sources to measure a weighted average of CO_2 emissions per kWh of electricity produced. In other words, it is done by combining Table 1 with Table 3, which gives Table 5 shown below. Just as the case with the financial analysis reduction in carbon emissions will be calculated for both electrical heating systems and natural gas or propane systems. This is done using the following Equation:

$$Annul\ CO_2\ Reduction = Q_h \times Number\ of\ Units \times hrs \times CO_2\ Emission \qquad (7)$$

Where Q_h is the heat generated by the heat pump or chiller, hrs is the annual operating hours, and CO_2 Emission is the carbon dioxide emissions from the conventional heat source whether it is electricity, natural gas or propane. However, since the heat pump or chiller needs an electrical power input (W_{net}), the net annual CO_2 reduction is the value that should be considered when assessing the reduction of CO_2 emissions from utilizing the geothermal energy system. This can be calculated similarly to Equation (7) but with subtracting the weighted average of CO_2 emissions per kWh of electrical power input (W_{net}). This is done as illustrated below:

$$Annul\ CO2\ Reduction = (Q_h - W_{net}) \times Number\ of\ Units \times hrs \times CO2\ Emission \qquad (8)$$

Electrical Source	**CO_2 Emission ($kgCO_2/kWh$)**	**Electrical Energy Source Breakdown**		
		Manitoba (%)	**Ontario (%)**	**Quebec (%)**
Nuclear	0.115	0.00	32.20	0.00
Coal and Oil	0.620	1.90	32.00	2.21
Water Power	0.011	92.90	27.60	91.82
Natural Gas	0.370	4.80	5.90	2.21
Wind, Solar, Biomass	0.011	0.40	2.3	3.76
Overall Emission (kgCO2/kWh)		**0.0398**	**0.2605**	**0.0324**

Table 5. Carbon Dioxide Emissions per kWh of Energy Produced in Manitoba, Ontario and Quebec

This thesis contains the economic and environmental analysis when using geothermal heat pumps or chiller to replace conventional heating whether it is electric, natural gas or propane. In Ontario and Quebec mines, electrical and natural gas is used for heating except for one mine in the province of Ontario that uses propane. However, in Manitoba, electrical and propane heating is used in the mines visited. Therefore, in the financial and environmental analysis the price and CO_2 emissions of the source of heating were compared to that of the geothermal heating system. It is also worth mentioning that the names of the mines were labelled with alphanumerical letters rather than their actual names due to a confidentiality agreement between the author and the companies that own of these mining operations. The only information mentioned regarding the visited mining operations are those necessary for the calculations such as the province in which a mine is located, the amount of water ejected from the mine and the temperature of the water.

4. Results and Discussion

In this section the results and calculations will be placed followed by a brief discussion. The financial evaluation of replacing electrical heating or thermal heating is followed by the environmental savings for each of the fifteen mine visited. As mentioned earlier the mines will be labelled alphanumerically starting with the mines in Manitoba, then the ones in Ontario and finally the ones in Quebec. The quality of the water in these mines are very good in general with most mines treating the water before ejecting them. After discussing the possibility of using heat pumps, an example using a custom designed chiller will be provided. The custom designed chiller gives a real life example of the equipment that can be used in an active underground mine to extract the geothermal energy from the ejected water

4.1. Utilizing Florida Heat Pump WW-420

4.1.1. Manitoba Mines

Two of the mines that were visited are located in Manitoba. As mentioned earlier, the mines in the province of Manitoba use propane instead of natural gas for thermal heating. And so, the price and CO_2 emissions of both electrical heating and propane heating systems were compared to those of the geothermal heat pump. The mines will be labelled as Mine M1 and Mine M2. The following section will discuss the data obtained from the mines with the financial and environmental analysis of each mine. Then a small discussion about the results will follow.

Manitoba Mine M1

Mine M1 has a reported pumping rate of 719 gpm on average with peaks of 807 gpm. The ejected mine water temperature is measured between 13.6 °C and 14.0 °C with an average of 13.8 °C. Using the FHP WW-420, the heat gain per unit would be 121.98 kW. Since each pump has intake capacity of 84.20 GPM, then 9 units are needed for Mine M1 with total cost of heat pumps of $266,670 (price of unit is $29,630). Table 6 gives a summary of the FHP WW-420 performance and capital cost.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
13.8 °C	84.20	31.79	3.84	121.98	9	29,630	266,670

Table 6. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine M1

The potential savings if electrical heating system was used is estimated to be around $135,856 per year. Carbon dioxide emissions can be reduced by 154 tonnes per year if geothermal heat pumps replaced the electrical heating system. On the other hand, replacing a propane heating system will give an estimated savings of $288,098 and reduction in carbon dioxide reduction of 1048 tonnes annually. Table 7 below depicts the economic and environmental results of utilizing geothermal energy in Mine M1, as well as the payback periods associated with replacing electrical heating or propane heating systems.

Mine M1	**Annual Savings ($/yr)**		**Payback Period (yr)**		**Net CO2 Savings (t/yr)**	
	Electrical Heating	Propane Heating	Electrical Heating	Propane Heating	Electrical Heating	Propane Heating
	135,856	288,098	2.0	0.9	154	1048

Table 7. Summary of the Results Calculated for Mine M1

Manitoba Mine M2

The second mine visited in Manitoba has water ejected at a rate of 116 gpm with peak flow of 163 gpm. The temperature of the water is recorded at 13.6 °C. From these data the calculated heat gain from each heat pump is 121.4 kW. From the ejected flow rate, 2 heat pumps are needed which result in a capital cost of $59,260. Table 8 is a summary of the heat pump performance and capital cost of Mine M2.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
13.6 °C	84.20	31.79	3.82	121.40	2	29,630	59,260

Table 8. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine M2

Potential savings with the geothermal system compared to electrical system is estimated at $21,776, and carbon dioxide reduction is estimated at 25 tonnes per year. When it comes to replacing a natural gas heating system, the savings are estimated at $46,220 with an estimated reduction in CO_2 emissions of 168 tonnes per year. Table 9 gives a summary of the economic and environmental results of utilizing a geothermal system in Mine M2 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

	Annual Savings ($/yr)		Payback Period (yr)		Net CO2 Savings (t/yr)	
Mine M2	Electrical Heating	Propane Heating	Electrical Heating	Propane Heating	Electrical Heating	Propane Heating
	21,776	46,220	2.7	1.3	25	168

Table 9. Summary of the Results Calculated for Mine M2

<u>Summary of Manitoba Mines</u>

From the results calculated from Manitoba mines it is clear that replacing a conventional electrical or thermal energy heating system is financially feasible. In addition, implementing geothermal energy shows reduction in CO_2 emission resulting in a more environmentally friendly operation. Appendix 3 and Appendix 4 are a summary of the data and results from Manitoba mines.

4.1.2. Ontario Mines

A total of ten mines were visited in the province of Ontario. These mines will be labelled Mine O1 through Mine O10. In the province of Ontario natural gas is used for thermal heating for all mines except Ontario Mine O1. Therefore, the prices of electricity, natural gas and propane and the greenhouse gasses emitted per kW of each source of heat were compared with the geothermal heat pumps for the financial and environmental analysis. After discussing the data obtained from each mine and carrying out the financial and environmental analysis, a brief discussion of the data will be provided.

<u>Ontario Mine O1</u>

As mentioned, Mine O1 uses propane as a thermal heat source. The mine has a reported water pumping rate of between 361 and 506 gpm with an average of 398 gpm. The pumped water temperature ranges from 16.3 °C to 17.1 °C with an average of 16.7 °C. Using the FHP WW-420, the heat gain per unit would be 130.46 kW. Since each pump has intake capacity of 84.20 GPM, then 5 units are needed for Mine O1 with total cost of heat pumps of $148,150 (price of unit is $29,630). Table 10 gives a summary of the FHP WW-420 performance and capital cost.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
16.7 °C	84.20	31.79	4.11	130.46	5	29,630	148,150

Table 10. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine O1

The potential savings if electrical heating system was used in the mine is estimated to be around $188,092 per year. While carbon dioxide emissions can be reduced by 305 tonnes per year if geothermal heat pumps replaced the electrical heating system. On the other hand, replacing a propane heating system has an estimated financial savings of $125,930 annually, and 554 tonnes per year reduction in CO_2 emissions. Table 11 below depicts the economic and environmental results of utilizing geothermal energy in Mine O1, as well as the payback periods associated with replacing electrical heating or natural gas heating systems.

Mine O1	**Annual Savings ($/yr)**		**Payback Period (yr)**		**Net CO2 Savings (t/yr)**	
	Electrical Heating	Propane Heating	Electrical Heating	Propane Heating	Electrical Heating	Propane Heating
	188,092	125,930	0.8	1.2	305	554

Table 11. Summary of the Results Calculated for Mine O1

Ontario Mine O2

Mine O2, like the rest of Ontario mines, uses either electrical or natural gas sources of heating. The mine has water ejected at a rate of 950 gpm with peak flow of 1200 gpm. The temperature of the water recorded at a range between 20.3 °C and 21.4 °C with an average water temperature of 20.9 °C. From these data the calculated heat gain from each heat pump is 181.68 kW. From the ejected flow rate, 12 heat pumps are needed which result in a capital cost of $355,560. Table 12 is a summary of the heat pump performance and capital cost of Mine O2.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
20.0 °C	84.20	31.79	4.40	181.68	12	29,630	355,560

Table 12. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine O2

Potential savings with the geothermal system compared to electrical system is estimated at $415,116 annually and carbon dioxide reduction is estimated at 2080 tonnes per year. When it comes to replacing a natural gas heating system, the annual savings are estimated to be $167,173 while the reduction of carbon dioxide emission is approximately 1246 tonnes annually. Table 13 gives a summary of the economic and environmental results of utilizing a geothermal system in Mine O2 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

Mine O2	Annual Savings ($/yr)		Payback Period (yr)		Net CO2 Savings (t/yr)	
	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	415,116	167,173	0.9	2.1	2080	1246

Table 13. Summary of the Results Calculated for Mine O2

<u>Ontario Mine O3</u>

Mine O3 has an ejected water pumping rate average of 290 gpm but there are periods when the water flow can reach up to 1000 gpm. The measured mine water temperature is between 18.6 °C and 19.2 °C with an average of 18.9 °C. Therefore, the heat gain per heat pump unit is 136.89

kW and 4 heat pumps are needed for Mine O3, which leads to a capital cost of $118,520. Table 14 gives a summary of the heat pump performance and capital cost for Mine O3.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
18.9 °C	84.20	31.79	4.31	136.89	4	29,630	118,520

Table 14. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine O3

Potential savings associated with replacing electrical heating system is estimated to be $205,171 annually, while carbon dioxide reduction is estimated to be approximately 476 tonnes per year. Replacing natural gas heating system can result in annual savings of $21,326, and a reduction in CO_2 gas emission by approximately 270 tonnes per year. Table 15 gives a summary of the economic and environmental results of utilizing a geothermal system in Mine O3 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

Mine O3	**Annual Savings ($/yr)**		**Payback Period (yr)**		**Net CO2 Savings (t/yr)**	
	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	205,171	21,326	0.6	5.6	476	270

Table 15. Summary of the Results Calculated for Mine O3

Ontario Mine O4

Another mine visited in Ontario has a water ejected at an average rate of 133 gpm with occasions of maximum flow of 146 gpm. The temperature of water ranges from 16.3 °C to 16.8 °C with an average of 16.6 °C. From this, the calculated data per pump is estimated at 130.17 kW and from the ejected water flow rate 2 heat pumps are needed that give a capital cost of $59,260. Table 16 is a summary of the heat pump performance and capital cost of Mine O4.

Entering Source Fluid	**Nominal Source Fluid Flow (GPM)**	**Power Input ($W_{net, in}$) (kW)**	**COP**	**Heat Gain Per Unit (kW)**	**Number of Units**	**Cost of Unit ($CAD)**	**Cost of Heat Pumps ($CAD)**
16.6 °C	84.20	31.79	4.10	130.17	2	29,630	59,260

Table 16. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine O4

If a geothermal heat pump system is to replace an electrical heating system the potential savings are estimated at $87,892, while the carbon dioxide reduction would be approximately 204 tonnes per year. If the geothermal heat pump system replaces a natural gas heating system, the savings are estimated at $7,889 and the carbon dioxide reduction would be about 124 tonnes per year. Table 17 Table 35gives a summary of the economic and environmental results of utilizing a geothermal system in Mine O4 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

Mine O4	**Annual Savings ($/yr)**		**Payback Period (yr)**		**Net CO2 Savings (t/yr)**	
	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	87,892	7,889	0.7	7.5	204	124

Table 17. Summary of the Results Calculated for Mine O4

Ontario Mine O5

Mine O5 has water ejected pumped out at a rate of 515 gpm with peak flow that can reach up to 740 gpm. The temperature of the water is recorded at 16.7 °C. From these data the calculated heat gain from each heat pump is 130.46 kW. From the ejected water flow rate, 7 heat pumps are needed which result in a capital cost of $207,410. Table 18 is a summary of the heat pump performance and capital cost of Mine O5.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
16.7 °C	84.20	31.79	4.11	130.46	7	29,630	207,410

Table 18. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine O5

Potential savings with the geothermal system compared to electrical system is estimated at $341,347 annually and carbon dioxide reduction is estimated at 793 tonnes per year. On the other hand, replacing a natural gas heating system with a geothermal heating one, the annual savings are estimated to be $30,865 while the reduction of carbon dioxide emission is approximately 483 tonnes annually. Table 19 gives a summary of the economic and environmental results of utilizing a geothermal system in Mine O5 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

Mine O5	Annual Savings ($/yr)		Payback Period (yr)		Net CO2 Savings (t/yr)	
	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	341,347	30,865	0.6	6.7	793	483

Table 19. Summary of the Results Calculated for Mine O5

Ontario Mine O6

Mine O6 has water pumped at 700 gpm with occasions of peak flow of 1200. The temperature of that water ranges from 14.3 °C to 15.8 °C with an average of 15.1 °C. Using the average water flow rate and temperature, a WW-420 heat pump can generate 125.64 kW, and from the ejected water flow rate 9 heat pumps are needed that would cost of $266,670. Table 20 is a summary of the heat pump performance and capital cost of Mine O6.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
15.1 °C	84.20	31.79	3.95	125.64	9	29,630	266,670

Table 20. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine O6

Replacing an electrical heating system with a geothermal one can result in potential savings of approximately $441,231 and can reduce carbon dioxide emissions by an estimated 1025 tonnes per year. If the geothermal heat pump system replaces a natural gas heating system, the savings are estimated at $34,831 and the carbon dioxide reduction would be about 620 tonnes per year. Table 21 gives a summary of the economic and environmental results of utilizing a geothermal system in Mine O6 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

Mine O6	Annual Savings ($/yr)		Payback Period (yr)		Net CO2 Savings (t/yr)	
	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	441,231	34,831	0.6	7.7	1025	620

Table 21. Summary of the Results Calculated for Mine O6

Ontario Mine O7

This mine has water ejected at a rate of 500 gpm with occasional peak flow of 1400 gpm. The temperature of the water recorded at a range between 14.5 °C and 14.7 °C with an average water temperature of 14.6 °C. From the average data, the calculated heat gain from each heat pump is 124.32 kW. The average water flow rate indicates 6 heat pumps are needed which result in a capital cost of $177,780. Table 22 is a summary of the heat pump performance and capital cost.

Entering Source Fluid	**Nominal Source Fluid Flow (GPM)**	**Power Input ($W_{net, in}$) (kW)**	**COP**	**Heat Gain Per Unit (kW)**	**Number of Units**	**Cost of Unit ($CAD)**	**Cost of Heat Pumps ($CAD)**
14.6 °C	84.20	31.79	3.91	124.32	6	29,630	177,780

Table 22. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine O7

The potential savings with the geothermal system compared to electrical system is estimated at $310,736 annually and carbon dioxide reduction is estimated at 722 tonnes per year. When it comes to replacing a natural gas heating system, the annual savings are estimated to be $23,492 while the reduction of carbon dioxide emission is approximately 435 tonnes annually. Table 23 gives a summary of the economic and environmental results of utilizing a geothermal system in Mine O7 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

	Annual Savings ($/yr)		**Payback Period (yr)**		**Net CO2 Savings (t/yr)**	
Mine O7	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	310,736	23,492	0.6	7.6	722	435

Table 23. Summary of the Results Calculated for Mine O7

Ontario Mine O8

Water is pumped out of Mine O8 out at a rate of 675 gpm with occasional peak flow that can reach up to 1350 gpm. The temperature of the water is recorded at 14.0 °C. From this, the calculated heat gain from each heat pump is 123.09 kW. From the ejected water flow rate, 9 heat pumps can be applied which result in a capital cost of $266,670. Table 24 is a summary of the heat pump performance and capital cost of Mine O8.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
14.0 °C	84.20	31.79	3.87	123.09	9	29,630	266,670

Table 24. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine O8

Potential savings with the geothermal system compared to electrical system is estimated at $413,845 annually and carbon dioxide reduction is estimated at 961 tonnes per year. On the other hand, replacing a natural gas heating system with a geothermal heating one, the annual savings are estimated to be $29,916 while the reduction of carbon dioxide emission is approximately 578 tonnes annually. Table 25 gives a summary of the economic and environmental results of utilizing a geothermal system in Mine O8 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

	Annual Savings ($/yr)		Payback Period (yr)		Net CO2 Savings (t/yr)	
Mine O8	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	413,845	29,916	0.6	8.9	961	578

Table 25. Summary of the Results Calculated for Mine O8

Ontario Mine O9

Mine O9 has water pumped at 560 gpm with peaks that can reach 840 gpm. The ejected water temperature ranges from 15.6 °C to 15.9 °C with an average of 15.8 °C. Using the average values, a WW-420 heat pump can generate 127.83 kW. From the ejected water flow rate 7 heat pumps can be used which will cost a total of $207,410. Table 26. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine O9 is a summary of the heat pump performance and capital cost of Mine O9.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
15.8 °C	84.20	31.79	4.02	127.83	7	29,630	207,410

Table 26. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine O9

Replacing an electrical heating system with a geothermal one can result in potential savings of approximately $361,252 and can reduce CO_2 emissions by an estimated 839 tonnes per year. If the geothermal heat pump system replaces a natural gas heating system, the savings are estimated at $30,455 and the CO_2 reduction would be about 509 tonnes per year. Table 27 gives a summary of the economic and environmental results of utilizing a geothermal system in Mine O9 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

Mine O9	Annual Savings ($/yr)		Payback Period (yr)		Net CO2 Savings (t/yr)	
	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	361,252	30,455	0.6	6.8	839	509

Table 27. Summary of the Results Calculated for Mine O9

Ontario Mine O10

This mine has water pumped at an average rate of 800 gpm with a possibility of maximum flow of 3500 gpm. The temperature of the pumped water ranges from 9.7 °C to 13.2 °C with an average of 11.5 °C. From the average values, the WW-420 heat pump can produce 116.61 kW and from the average water flow rate 10 heat pumps can be applied to give a capital cost of $296,300. Table 28 is a summary of the heat pump performance and capital cost of Mine O10.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
11.5 °C	84.20	31.79	3.66	116.61	10	29,630	296,300

Table 28. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine O10

If a geothermal heat pump system is to replace an electrical heating system the potential savings are estimated at $455,540, while the carbon dioxide reduction would be approximately 1058 tonnes per year. If the geothermal heat pump system replaces a natural gas heating system, the savings are estimated at $24,456 and the carbon dioxide reduction would be about 628 tonnes per year. Table 29 gives a summary of the economic and environmental results of utilizing a geothermal system in Mine O10 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

	Annual Savings ($/yr)		**Payback Period (yr)**		**Net CO2 Savings (t/yr)**	
Mine O10	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	455,540	24,456	0.7	12.1	1058	628

Table 29. Summary of the Results Calculated for Mine O10

Summary of Ontario Mines

From the results obtained from the ten mines in Ontario, we can conclude that replacing conventional or thermal energy heating systems is financially sound. In addition, implementing geothermal energy reduces carbon dioxide emissions leading to a more environmental heating solution. Furthermore, it geothermal energy makes an operation even more economical if carbon tax regulations were implemented by the government. Appendix 5 and Appendix 6 are a summary of the data and calculations from Ontario mines.

4.1.3. Quebec Mines

Three mines in Quebec were visited. These mines will be labelled Mine Q1, Mine Q2 and Mine Q3. As the case of Ontario mines, the mines in the province of Quebec also use natural gas for thermal heating. Therefore, the prices of electricity and natural gas, as well as, the greenhouse gasses emitted per kW of each source of heat were compared with the geothermal heat pumps for the financial and environmental analysis. The following section will discuss the data obtained from each mine with the financial and environmental analysis of each mine. Then a summary of the data will be provided for all three mines.

Quebec Mine Q1

Mine Q1 has a reported pumping rate of 1000 gpm with peaks of 1,200 gpm. In addition, the mine has water temperature that ranges from 14.8 °C to 18.2 °C with an average temperature of 16.5 °C. Using the FHP WW-420, the heat gain per unit would be 129.88 kW. Since each pump has intake capacity of 84.20 GPM, then 12 units are needed for Mine Q1 with total cost of heat pumps of $355,560 (price of unit is $29,630). Table 30 gives a summary of the FHP WW-420 performance and capital cost.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
16.5 °C	84.20	31.79	4.09	129.88	12	29,630	355,560

Table 30. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine Q1

The potential savings if electrical heating system was used is estimated to be around $305,360 per year. Carbon dioxide emissions can be reduced by 190 tonnes per year if geothermal heat pumps replaced the electrical heating system. On the other hand, replacing a natural gas heating system does not lead to any annual savings but would rather lead to a loss of $3,186. This is because the price of natural gas in Quebec is very low that it will cost more money from the electricity needed to run the heat pumps compared to the price of natural gas. However, an increase in the natural gas price can result in having the geothermal system feasible. In addition, if carbon taxes were mandated by the government into mines it can make the geothermal system feasible. Moreover, if the purpose of the geothermal system is to have an environmentally friendly mine switching to a geothermal heating system can reduce CO_2 emissions by approximately 1366 tonnes per year. Table 31 below depicts the economic and environmental results of utilizing geothermal energy in Mine Q1, as well as the payback periods associated with replacing electrical heating or natural gas heating systems.

Mine Q1	Annual Savings ($/yr)		Payback Period (yr)		Net CO2 Savings (t/yr)	
	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	305,360	NA	1.2	NA	190	1366

Table 31. Summary of the Results Calculated for Mine Q1

Quebec Mine Q2

Mine Q2 has a pumping rate average of 375 gpm with peak periods of 420 gpm. The measured mine water temperature is between 13.3 °C and 20.0 °C with an average of 16.7 °C. Therefore, the heat gain per heat pump unit is 127.12 kW and 5 heat pumps are needed for Mine Q2, which result in capital cost of $148,150. Table 32 gives a summary of the heat pump performance and capital cost for Mine Q2.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
16.7 °C	84.20	31.79	4.10	130.32	5	29,630	148,150

Table 32. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine Q2

Potential savings associated with replacing electrical heating system is estimated to be approximately $115,023, while carbon dioxide reduction is estimated to be 72 tonnes per year. Similar to the case of Mine Q1, replacing natural gas heating system does not yield any savings but rather can lead to a loss of $1073 due to the low price of natural gas in Quebec. Still, if a geothermal system used instead of natural gas heating system CO_2 emissions can be reduced by almost 514 tonnes per year. Table 33 gives a summary of the economic and environmental results of utilizing a geothermal system in Mine Q2 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

Mine Q2	**Annual Savings ($/yr)**		**Payback Period (yr)**		**Net CO2 Savings (t/yr)**	
	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	115,023	NA	1.3	NA	72	514

Table 33. Summary of the Results Calculated for Mine Q2

Quebec Mine Q3

The third mine visited in Quebec has water ejected at a rate of 320 gpm with peak flow of 350 gpm. The temperature of the water is recorded at 22.0 °C. From these data the calculated heat gain from each heat pump is 145.97 kW. From the ejected flow rate 4 heat pumps are needed which result in a capital cost of $118,520. Table 34 is a summary of the heat pump performance and capital cost of Mine Q3.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)	Cost of Heat Pumps ($CAD)
22.0 °C	84.20	31.79	4.60	145.97	4	29,630	118,520

Table 34. Summary of the WW-420 Heat Pump Performance and Capital Cost for Mine Q3

Potential savings with the geothermal system compared to electrical system is estimated at $113,772 and carbon dioxide reduction is estimated at 71 tonnes per year. When it comes to replacing a natural gas heating system, the savings are very small at $2,805 annually. In the case of Mine Q3 there is a small savings (compared to a loss in the other mines) because the water ejected from the mine is at a higher temperature which results in a higher heat gain from the heat pumps. Still, the payback period of the geothermal system equipment is calculated at almost 43 years which makes installing geothermal heat pumps economically unfeasible. Having an increase in the price of natural gas in Quebec can change the feasibility outcome of installing a geothermal heating system. If the geothermal system is intended to be used for the purpose of reducing CO_2 emissions, the reduction in the greenhouse gas emission is estimated to be about 494 tonnes per year. Table 35 gives a summary of the economic and environmental results of utilizing a geothermal system in Mine Q3 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

Mine Q3	**Annual Savings ($/yr)**		**Payback Period (yr)**		**Net CO2 Savings (t/yr)**	
	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	113,772	2,805	1.0	42.3	71	494

Table 35. Summary of the Results Calculated for Mine Q3

Summary of Quebec Mines

From the results calculated from Quebec mines it is clear that if a geothermal energy system to be installed instead of an electrical system the financial benefits makes it feasible. This is not the case if the geothermal system is to replace a natural gas heating system due to the very low price of natural gas. However, if carbon taxes were mandated by the government into mines it can make the geothermal system feasible. Moreover, if the purpose of the geothermal heating system is to have an environmentally friendly heating system then geothermal energy is a sound solution. Appendix 7 and Appendix 8 are a summary of the data and calculations from Quebec mines.

4.2. Utilizing Trane's Custom Designed Chiller RTWD Series R

Compared to the Florida Heat Pump WW-420, the RTWD Series R chiller is a larger machine that can handle higher flow of water. In addition, the designed chiller has higher COP which makes it capable of providing more heat from the ejected mine water. In addition, it is more practical since only one unit can handle the average ejected water flow rate at the mine compared to multiple units in the case of a heat pump. The RTWD Series R chiller was custom designed for one of the mines (Ontario Mine O9) during one of the meetings with a Trane's representative. The purpose of this is to obtain a real life scenario where the expertise of an engineer technical representative is put into the design of a geothermal heat pump or chiller system. Appendix 2 contains the data sheet of the RTWD Series R chiller.

The reason Ontario Mine O9 was selected between all the other mines in this study is because it has ejected water flow rate and temperature that represent the overall average water flow rate and average temperature of all mines. When looking at the values of the overall ejected water pumping rates and temperature averages of all mines, Ontario Mine O5 and Ontario Mine O9 water flow rates and temperatures are the closest. However, due to the constraint availability of the representative at Trane, only one of these two mines were chosen, which is Mine O9. This is because Ontario Mine O9 has water flow rate and temperature that is the closest compared to

Ontario mines' averages. Therefore, Mine O9 was favored and was selected for the custom designed chiller. In addition, Mine O9 is within the vicinity of a small town. This would open the possibility for using excess heating generated from the mine into the town schools and municipal buildings. Moreover, having a town at a close proximity from the mine enables the use of the geothermal energy and geothermal equipment even when the mining activities come to an end.

The RTWD Series R chiller, which is designed for an inflow water of 560 gpm at a temperature of 15.8 °C, can produce 774.19 kW of heat. The chiller needs 129.4 kW to operate which result in a Coefficient of Performance (COP) of 5.98. The cost of the chiller is $125,000 and, unlike the situation with the WW-420 heat pump, only one chiller is needed for the mine. Table 36 is a summary of the RTWD Series R Chiller performance and capital cost of Mine O9. When compared to using the WW-420 system, it is clear that the cost of operation is lower which can be observed by the higher COP of the chiller. In addition, the capital cost to handle all the ejected water is also lower since only one RTWD Series R chiller is sufficient for 560 gpm inlet water flow compared to 7 WW-420 heat pumps, which makes the total equipment cost cheaper. Therefore, if a mine operation is looking to get the maximum geothermal energy potential from the ejected mine water, a custom built chiller would be the more economical option. However, if only a specific heating capacity is needed, implementing a heat pump can be the more economical option.

Entering Source Fluid	Nominal Source Fluid Flow (GPM)	Electric Power Input ($W_{net, in}$) (kW)	COP	Heat Gain Per Unit (kW)	Number of Units	Cost of Unit ($CAD)
15.8 °C	560	129.4 kW	5.98	774.19	1	125,000

Table 36.Summary of the RTWD Series R Chiller Performance and Capital Cost for Mine O9

If a geothermal chiller is designed to replace an electrical heating system the potential savings can be approximately $364,621, while reducing carbon dioxide emissions by 847 tonnes per year. On the other hand, if the geothermal chiller is designed to replace a natural gas heating system, the potential financial savings are approximately $63,393 and the carbon dioxide emissions can be reduced by 546 tonnes annually. Table 37 gives a summary of the economic and environmental results of utilizing the RTWD Series R chiller system in Mine O9 in addition to the associated payback period of replacing electrical heating or natural gas heating systems.

Mine O9 using RTWD Series R Chiller	**Annual Savings ($/yr)**		**Payback Period (yr)**		**Net CO2 Savings (t/yr)**	
	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating	Electrical Heating	N.G. Heating
	364,621	63,393	0.3	2.0	847	546

Table 37. Summary of the Results Calculated for Mine O9 Using the RTWD Series R Chiller

Looking at the results obtained from the chiller, it is clear the RTWD Series R chiller is more economical and environmentally friendly compared to using 7 WW-420 heat pumps for the 560 gpm ejected water rate. This can be further shown by the higher COP value of the RTWD Series R unit. However, if the mine does not plan to use the entire 560 gpm for the maximum heat gain possible, but rather has a limited heat gain goal, then the use of the WW-420 heat pump can be more economical.

5. Recommendations

In this study, 15 mines were visited within the province of Manitoba, Ontario and Quebec. After conducting the financial and environmental analysis of the possible outcome from implementing geothermal heat energy into the mines, the author's recommendations are given for future research or applications of this study. Eventually, there are hopes of implementing this geothermal energy harvesting technology into active mines, a concept that has not been implemented thus far into active mines.

The ejected water flow rate was given by mine personnel as it is constantly monitored and recorded by the mines visited. However, the temperature data collected from the mines were measured during the mine visits. Measuring the temperature was carried out at numerous sump levels when possible. Still, to obtain a more conclusive water temperature data of these mines it is recommended to record the temperature values periodically throughout the year. This can be done on a weekly or bi-weekly basis which can give more accurate values of the water temperatures in the mines. In addition, recording water temperature can show any variations in the water temperature throughout the year. The result of close monitoring of water temperature can result in better calculations of the heat gain from a heat pump or chiller.

During our visit to the mine operations, the heating information was not known by the mine personnel. This was one of the reasons for comparing the geothermal energy with both electrical heating and thermal heating systems. In addition, heating requirements of the mines visited were not known, which resulted in calculating the maximum possible heat gain from the ejected water instead of assessing the geothermal heat gain based on what is needed by the mine operation. Knowing the type of heating used in the visited mines, as well as the amount of heating would give better parameters to assess the finances and environmental benefits of applying geothermal energy in active underground mines. It can also influence the design of the geothermal heating system. Knowing the amount of heat energy needed for the mine shaft during the winter months compared to the mine's facilities is essential to design the location of the heating system. This is since depending on the heating requirement, the geothermal heating system can be designed to heat the mine shaft, the facilities on the mine's surface, or both. Still, since the mines visited did not have such information it was not possible to assign the location of the geothermal system.

Water quality studies can also expand the scope of this project. While visiting the mines, scarce information was obtained about the quality of the water ejected from the mines. Water quality can play an essential role in maintenance costs of the heat pumps. Moreover, the build up of minerals or debris in the heat pumps or chiller can affect their performance. Therefore, studying the quality of the mine water and their affects on the geothermal heat pumps or chillers could be proposed for a future geothermal study.

It is also possible to obtain more real life geothermal heating scenarios from heat pump suppliers. When meeting the heat pump suppliers, the author was given the chance to obtain a custom built chiller for only one mine. Having similar custom built equipment from the heat pump suppliers can expand this study by illustrating the most ideal equipment for each mine. This can be further extended if a mine allows for field testing of the geothermal equipment in an active mine.

This study was conducted on active mines that already have their heating systems installed. While the potential of installing geothermal energy systems indicated in this study seems feasible economically and environmentally, the mining companies were not found of buying and installing new equipment on their mine sites. Therefore, a study to examine the possibility of retrofitting the old heating equipment can encourage mining companies to implement the geothermal energy technology. Another possibility is to perform the same study for mines that are still in the developmental stage. This can result in the mining companies investing in geothermal heating equipment instead of conventional electrical or thermal heating systems at an early stage of the mine's life. These studies can result in the ultimate goal of carrying out this study, which is to implement geothermal heating into active mine sites.

6. Conclusion

This part of the thesis illustrates the potential financial and environmental benefits of implementing geothermal energy in active underground mining operations. This part had four objectives that were successfully met. The first step was to gather literature information about geothermal energy and study successful projects. Before conducting a study, it is important to learn about the previous work done in the field to be studied in order to expand the research on a certain topic. The information gathered about the applications of geothermal energy was a point to begin this study. Learning about geothermal energy showed several successful examples of utilizing geothermal energy and heat pump systems around the world. Although the similarity of equipment and finances of these successful projects, there is yet to be any implementation of geothermal energy in an active underground mine. This part of the thesis is a step towards applying geothermal energy within an active underground mining operation.

The second goal was to gather information about several underground mining operations. This was achieved through visiting mines and obtaining the desired data needed for the geothermal energy calculations. The third goal was to use the field data to calculate the possible economic and environmental gains in using geothermal energy in active mines. Some information such as the type of heating used in a mine and the amount of heat needed by the mine were not known and so when performing the calculations, the maximum possible geothermal heat gain was calculated and compared to both electrical and thermal heating systems. The mines visited were in different provinces which diversified the price of electricity, as well as the source and price of the thermal heating source. After finishing the third objective, the financial analysis using custom designed chiller from a heat pump manufacturer (Trane) was conducted. This illustrates the equipment needed for an active mine operation, its capacity and heat gain potential. It also gives an insight on the equipment that could be used in a real life situation if geothermal heating is implemented in an active mine.

This part of the report ends with few recommendations to further expand the topic of geothermal energy in active underground mines. With the current concerns about global warming, along with the increasing of carbon taxes mandated by governments, alternative sources of energy such as geothermal energy can be a key solution. In addition, the potential increase in fossil fuel prices can give a further push to explore alternative sources of energy. It is therefore important to continue the research in this topic. The suggested next step could be to perform a field case study by applying heat pump or chiller samples in active underground mines. This can give a further evaluation of a new possible implementation of geothermal energy.

Part II

Peliminary Assessment of Deep Lake Cooling Systems for Deep Underground Mines

7. Introduction

Continuing with geothermal energy, deep lake cooling is another way to access renewable energy. It is a system that is aimed to decrease the dependence on fossil fuel and minimize the environmental impact associated with conventional cooling systems. As the case of geothermal heating, deep lake cooling has also shown successful implementations globally but so far was never applied into the mining industry. Considering in Canada the mining industry contributes to a great deal of the nation's greenhouse gasses, new environmentally friendly solutions are constantly being investigated.

Deep lake cooling is a method of cooling that utilizes the cold water located in deep surface bodies of water. It can be used for cooling residential and industrial buildings. In underground mining, cooling the mine is one of the most energy intensive processes that is required to be done. Considering numerous active underground mines within Canada are in close proximity to deep surface bodies of waters, implementing deep water cooling can be more economical and more environmentally friendly than conventional cooling systems. Still, very few studies were carried out for implementing deep water cooling systems in active underground mining operations.

In this project there were three objectives to accomplish. The first objective is to gather data about surface water cooling and examine successful implementation of deep surface water geothermal cooling. This is an important step as it gives knowledge about the principal of deep surface water cooling and the logistics of this cooling method. Afterwards, the second objective is to find a suitable lake that is deep enough to be used for a cooling system and in close proximity of an active mine. This also consisted of a field visit of a candidate lake to examine the temperature of water along the depth of the lake. The third objective is to examine a method to apply geothermal deep lake cooling into an active mine and study the economic and environmental benefits of applying the deep lake cooling system.

Part II of the thesis follow the same structure as the first part. It contains six chapters with chapter 7 being the introduction. This is followed by chapter 8 which contains literature review of deep surface water cooing including the major component for an open loop deep surface water cooling system and successful implementation of such systems. Chapter 9 includes the methods, steps and calculations of this study. Followed by chapter 10 which contains the obtained results and a brief discussion. Chapter 11 lists some recommendations made by the authors in the hopes to further expand the broad of this research topic. Lastly, chapter 12 contains a conclusion regarding the work done in this study.

8. Literature Review

In the mining industry, particularly in underground mines, air conditioning imposes a great operational cost. Air conditioning in underground mines is needed even in cool regions as active areas of the mines produce great amount of heat from equipment such as haul trucks, as well as, from activities such as drilling and blasting. Cooling in underground mines can also be a challenge in deep underground mines and often requires constructing a cooling station at deep levels. In addition, cooling can create a great load on electrical grids and can have a great environmental impact especially in regions were electricity is generated with non-renewable energy. Therefore, developing a cheaper and more environmentally friendly alternative cooling solutions is of a great interest for any mining operation.

Cooling in a conventional air conditioner is performed by transferring the heat from the air to a refrigerant. A refrigerant is maintained as the colder medium by the compressor and the motor that runs it, which is an energy intensive process [17]. Therefore, great economic and environmental savings are possible if heat is transferred to a chilled medium with high specific heat capacity such as water. A simple way of using water as a heat sink involves pumping water from large surface bodies of water such as lakes. In fact, this is not only ideal because water is a good heat sink but also because large water bodies have significant amount of cool water mass at their lower depth. This results in having a permanent reservoir of cold water to be used in cooling. In addition, large water bodies usually show thermal stratifications where the hypolimnion water is isolated from surface radiation or wind mixing making it constantly cold during warm weather periods (Figure 8). Therefore, pumping deep surface water into an underground mining operation in order to use the cold water as a heat sink could be of a great economic and environmental benefit.

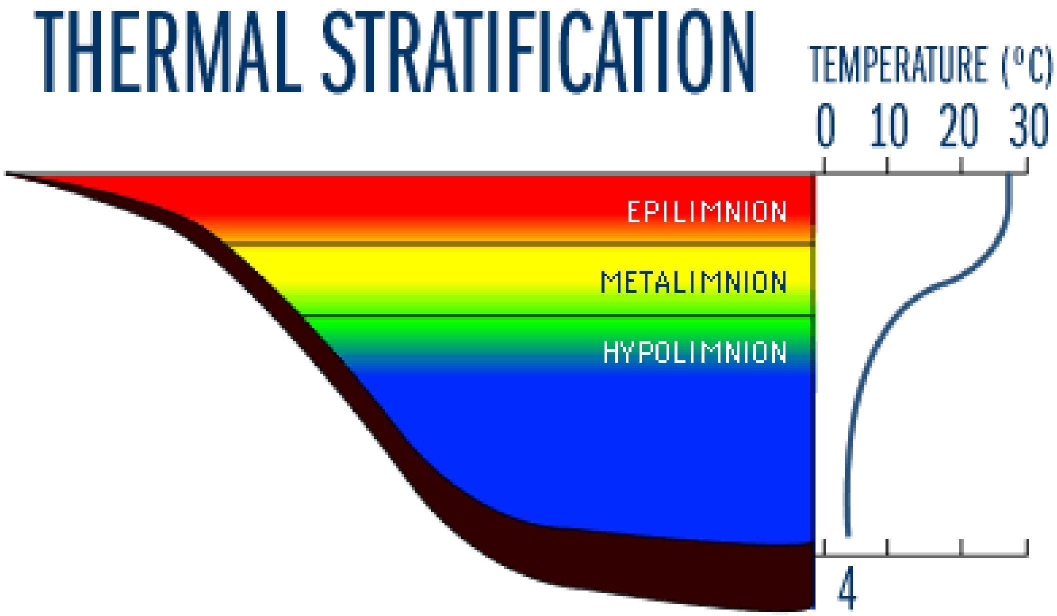


Figure 8. Thermal Stratification of Surface Water Bodies During Summer. Figure Taken From (http://www.lakeaccess.org/ecology/lakeecologyprim4.html)

A system where the source water is pumped to directly connects with the heat exchanger where it is used for heating or cooling is termed an open loop system. In general, open loop systems can be used in almost any application such as residential, commercial and institutional buildings. Because open loop systems require ample source of water as a requirement, they are in general less common [18]. As a result, before installing an open loop system it is important to ensure that the water source contains the necessary amount of water needed to fulfill the heating or cooling requirements. In addition, the method of disposing the water after it is used by the heat pump generates a challenge in open loop systems. If water is re-injected back into the water source, it is important to ensure that no pollutants are introduced into the water source [19]. There are several other methods to dispose of the water such as through surface drainage where the water is deposited to a low area towards a pond or a river.

Since open loops obtains water from a lake there are measures that must done in order to ensure the quality of the water used is suitable for the heat exchangers. As a result, the lake water should be tested for hardness, acidity and mineral contents. In addition, it is important to ensure dirt organic matter or other particles don't get into the system. This can lead to fouling of the heat pumps or clogging of the pipes which affects the operation of the system. Compared to a closed loop system which circulate its own fluid, an open loop would require more frequent maintenance to ensure there is no blockage or fouling of the system [19]. Therefore, it is important to examine the surface water source prior to initiating a deep surface water geothermal system. The following sections will describe the major system components needed for open loop systems which includes:

- **Intake Piping and screening:**
    - Intake piping: The piping needed to bring the water from the source to the heat pump.
    - Screening: Prevents fouling of the system by preventing suspended materials and biological entities from entering the pipes.
- **Pumps and Pump Sumps:** The equipment and their configuration that pump water from the water source to the heat exchangers.
- **Isolation of Heat Exchangers:** Equipment that prevents the water source from contaminating or corroding the distribution piping, heat pump condenser and/or evaporator, and building fan-coil units.
- **Heat Pumps, Chillers, or Heat Exchangers:** The heat exchangers needed for the system.
- **Returning Piping and diffusers:** Piping, nozzles and mixing equipment that seamlessly mix the return water with the water source.

8.1. Intake Piping and Screening

The intake piping size and design depends on several important factors including surface water bathymetry and depth, water temperature, peak cooling and/or heating load, and screening requirement. The source water bathymetry and temperature for example will determine the location where the pipeline will travel and the area where the pipe inlet is located [19]. Therefore, knowing the source water temperature profile is important not only to place the inlet of the pipe, but also to ensure very little rise in temperature will occur when pumping the cold water up through the warmer layers in a stratified surface water source. It is not economical to pump cold water from deep surface water source if the warmer layer of the source water will increase the temperature significantly.

During the past, numerous piping material such as steel or concreate were utilized for under water applications. These materials were considered to be the standard until the mid 1970's when high density polyethylene (HDPE) became widely used as a piping material. HDPE is chemically inert, fusible, flexible and strong. In addition, it will float in water which aids in pipeline installation [20]. Moreover, the material has low thermal conductivity which helps in sustaining the temperature of cold water as it passes through the warmer upper layers of a stratified surface water source. Furthermore, HDPE is smoother than steel or concrete which decreases the friction between the water and the pipe walls. As a result, HDPE is currently the most used material for underwater piping [20].

In order to prevent debris, biological organisms and other suspended particles from entering the cooling/heating system, a screen or filter is implemented at the intake. This plays a crucial role in maintaining pipes and heat pumps from fouling [21]. A typical design for the intake structure with the primary screening are shown in Figure 9 and Figure 10 [19, 22]. This design ensures that water is drawn from a specific horizontal stratum deep underwater while leaving the warmer water layers above undisturbed. In addition, the design prevents the sea or lake bed from being disturbed to avoid entraining sediment particles. The screen should be designed to allow the needed amount of water to enter the system while limiting the maximum face water velocity [19]. This is to ensure suspended sediments or biological organisms such as fish or fish larvae are not entrained which can foul the piping or pumps of the system.

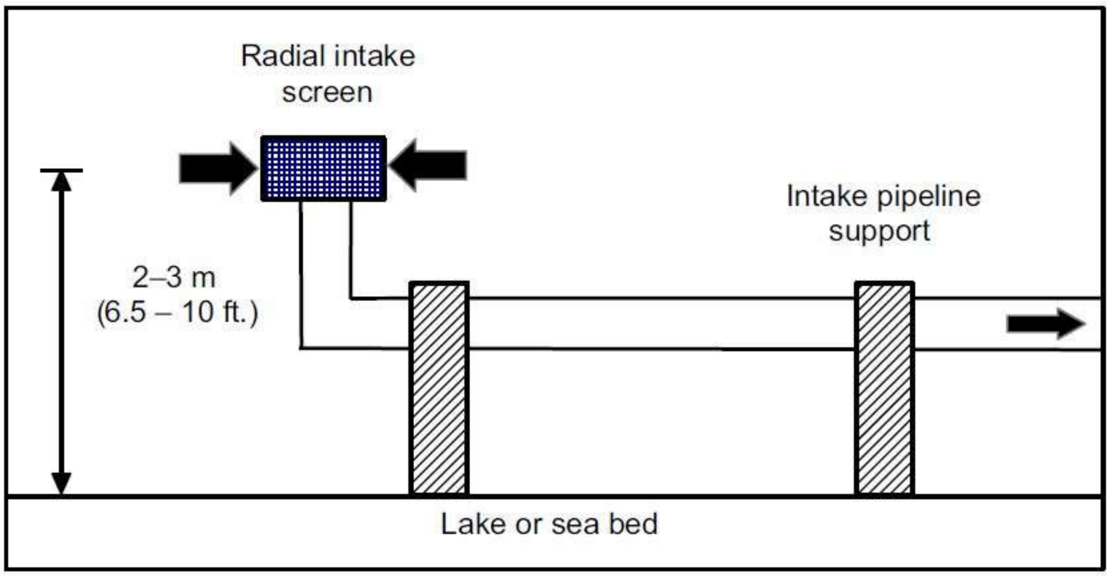


Figure 9. Typical Design for water intake. Figure Taken From [19]

Figure 10. Actual structure of a water intake. Figure Taken From [22]

The characteristics of screen or filter used varies depending on the system. For example, the J.H. Campbell power plant screen consists of wedge wires with 9.5mm openings [23]. On the other hand, the Cornell University system consists of a 2mm wide wedge wire screen [24]. For smaller open-loop systems used in residential application a sand filter has been shown to be sufficient. The sand function by passing the intake water only through the pores of the sand medium. Similar to the sand filter, another approach was designed by using the sea or lake bed itself as the filter. This is done by horizontally drilling beneath the lake or sea floor and then installing a perforated drill casing [23].

8.2. Pumps and Pump Sumps

For a surface water heat pump system, the surface water pump is the primary energy consumer. Thus, the design and the selection of these pumps is very important for the success of the system. There are two main design strategies for the surface water pump, wet sump and dry sump configuration [23].

In wet sump pumping system, the surface water pump is situated in a wet sump pumping pit as illustrated by Figure 11a. When the heating/cooling system is not operating, the water level in the well increases to the same level as the water source. As the system is activated, water is pumped from the wet well and the water level decrease. This will result in an elevation difference between the wet well and the source water which will be the driving force for water to flow into the wet well through the inlet and intake pipeline. This pumping configuration is limited by the depth of which the intake pipe outlet can be installed. In addition, wet sump pumping may require additional offshore dredging or trenching to install the pipeline inlet at a sufficient depth below the source water level. Furthermore, the design of the sump pit must evaluate the possibility of vortex formation at the pump inlet.

On the other hand, dry sump pumping configuration is designed so that the pump is directly connected to the intake pipeline as shown in Figure 11b. In this configuration, the pump can be located at or below the source body water level as long as the net positive suction head available is greater than the net positive suction head required. Placing the pump below sea level will help preventing pump cavitation as long as the net positive suction head available is always higher than the net positive suction head required.

An important aspect to consider when designing the surface water pump is the material used. Similar to the case of pipe material selection, the characteristics of the source water will determine the material which the pump is made from. Source water parameters such as salt content, suspended solids, temperature and pH are examined in order to determine the source water pump material. This is important as high salt content can lead to corrosion of the pump components by electrochemical corrosion process which will be accelerated at higher water temperatures. On the other hand, suspended solids can accelerate erosion of the high velocity pump components such as impellers, shrouds and casing, which affects the performance of the water pump [25].

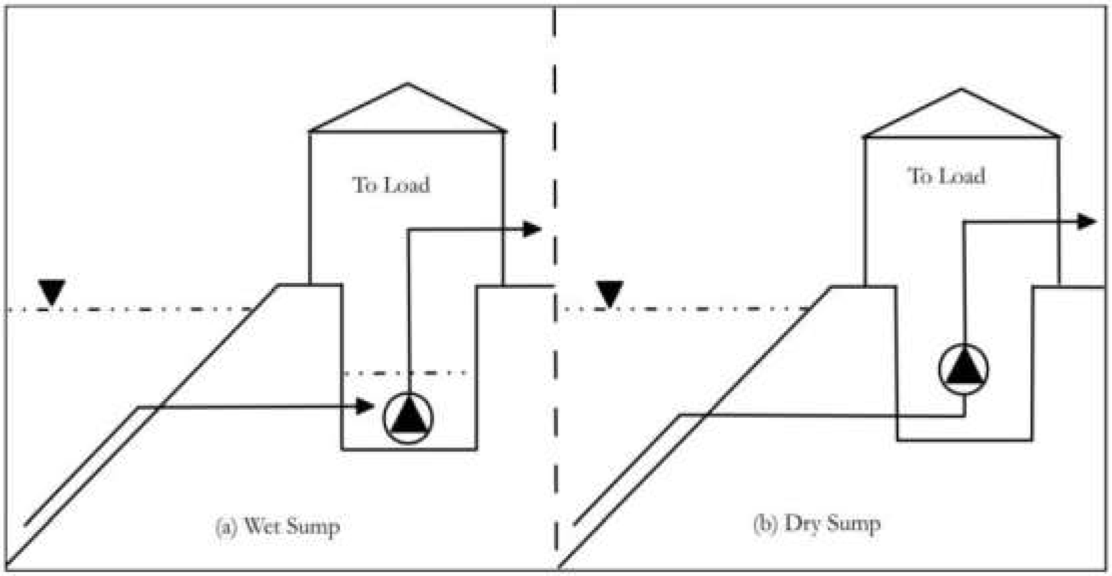


Figure 11. Comparing Pumping Configuration (a) Wet Sump to (b) Dry Sump. Figure Taken From [23]

8.3. Isolation of Heat Exchangers

Just as in the case of intake piping and the pump, the selection of isolation heat exchangers is an important step that is influenced by several factors. These include the surface water characteristics, desired heat transfer rate, planned cost, fouling resistance needed, maintenance requirements, pressure drop, and space requirements [19]. For example, for systems that uses brackish or saltwater surface water sources electrochemical corrosion is of a concern. Therefore, for surface water cooling systems that use seawater, it is recommended to use titanium in order to protect the heat exchangers [26]. For systems that use fresh surface water, high alloy steel is the advised material choice [27]. It is important to utilize material at the heat exchangers that are resistant to the water utilized in a surface water cooling or heating system.

Also as in the case with intake pipping, biological fouling is one of the challenges faced for open loop surface water cooling or heating systems. If proper precautions were not taken into consideration when designing a system biological film, algae, slime, and/or mollusks could form in the cooling system [28, 29]. This as a result will have an affect on the heat exchangers by increasing the thermal resistance. In addition, it will lead to an increase in the pumping requirement of the system. In order to prevent heat exchangers fouling due to the growth of biological organisms, it is recommended to implement biocides into the freshwater or seawater cooling system. It is also possible to have heat exchangers that contains brushing system installed within the heat exchangers in order to prevent fouling of the heat exchangers. Furthermore, having a scheduled maintenance of the heat exchangers where disassembly and cleaning of the heat exchangers is performed is another option to mitigate fouling of the heat exchangers [28, 29].

8.4. Heat Pumps, Chillers, or Heat Exchangers

If needed, heat pumps or chillers are usually custom designed for surface water heat pump systems in order to fit the requirements needed for the site. This is because of the wide range of temperature and conditions in which the system operates. In regard to the heat exchangers, there are two types: Open loop heat exchangers and closed loop heat exchangers. This report will focus on open loop heat exchangers.

8.5. Open Loop Heat Exchangers

Heat exchangers in an open loop cooling system can be classified into two types:

- Direct Contact heat exchangers which includes spray cooling
- Indirect heat exchangers such as a coil and fan system

In the coming sections, a brief literature review of each type of heat exchangers will be discussed, then will give an example of the finances associated with a coil and fan cooling system.

8.5.1. Direct Contact Heat Exchangers

These systems involved direct contact between the two fluids. The category includes systems such as cooling tower which is designed to reject heat from a system and other types such as spraying chambers which provide coolness into the system. Direct contact heat exchangers are characterized with their high efficiency of heat transfer which made it the preferred choice, especially for big projects, when compared to indirect heat exchangers [9]. This thesis literature will focus on cooling towers and spraying chambers when it comes to direct contact heat exchangers. Although there is a difference between the designs of cooling towers and cooling chambers there are common parameters that affects the amount and efficiency of the heat exchange. These include water mass flow rate, the supply temperature of water, air mass flow rate, psychrometric condition of the air at inlet, and the duration and intimacy of contact between the air and the water droplets. The contact characteristics between air and water droplets depends on the design of the heat exchanger such as the relative velocity between the air and water droplets, and the size and concentration of the water droplets. Water droplet size and concentration can be controlled by the flow and pressure of the water, the presence of packing within the heat exchanger, and the type and configuration of spray nozzles [9].

In the case of a cooling tower, the direct contact occurs between air and water media. Cooling towers are used to remove heat from the condenser which results in reducing water temperature. Inside the cooling tower, hot water is sprayed within the tower and descends as shower droplets through an ascending airstream. This results in heat transfer from the water droplets to the air via a combination of convection (sensible heat) and evaporation (latent heat). The cooled water then falls and is collected at the base of the cooling tower to be returned to the condenser (Figure 12). Air velocities through a packed cooling tower is typically in the range of 1.5 to 3.6 m/s [9].

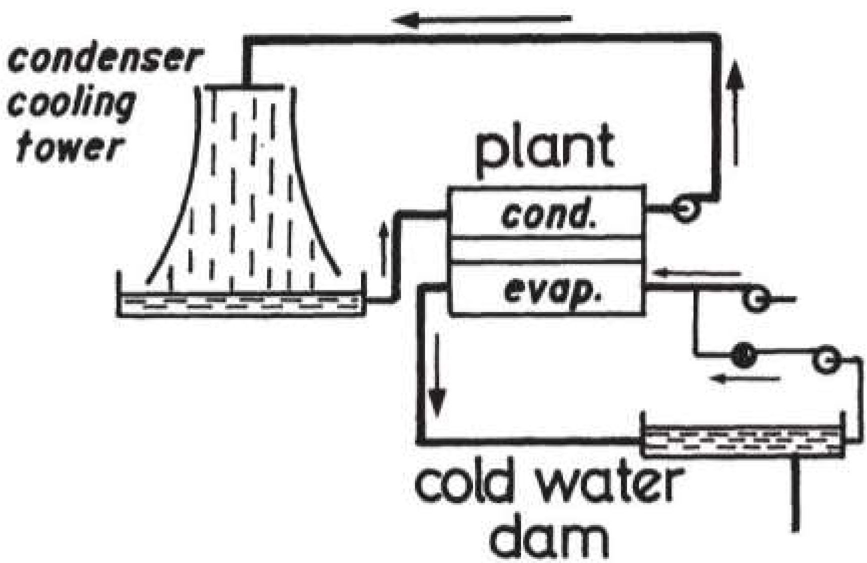


Figure 12. Schematic Illustrating a typical cooling tower. Figure Taken From [9]

Figure 13 illustrates how cooling towers work. In a cooling tower, hot water that is needed to be cooled down is sprayed into the cooling tower downwards against the flow of the rising air current. The water droplets pass through the packing which is designed to distribute the water and air flows uniformly through the cross section of the cooling tower. This will result in maximizing the total area of contact between the two media which leads to a faster and more efficient cooling. The packing can be designed as simple splash bars or riffles arranged in staggered rows, or egg-crate geometrics or wavy surfaces located in vertical configurations. The packing can be made of treated fir or redwood timber, galvanized steel, metals with plastic coatings, or injection moulded PVC or polypropylene. On the other hand, concrete is used primarily for the casing, structural reinforcements and water sumps or dams in a cooling tower. When air leaves the cooling tower it is normally saturated which can be observed by the formation of a fog plume. The surrounding environmental effects of the plume must be examined as design changes can be required to avoid any negative environmental effects.

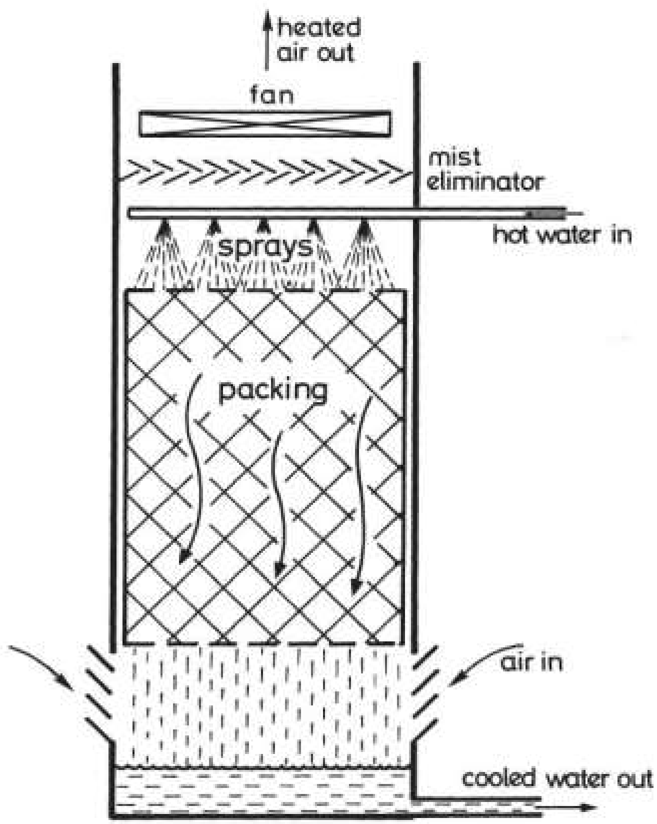


Figure 13. Direct Contact Cooling Tower. Figure Taken From [9]

For underground implementation, a cooling tower can be between 10 to 20 meters in height and around 3 to 8 meters in diameter, with a heat load as high as 30MW [9]. The airflow through the cooling tower is induced via the mine ventilation pressure or via the booster fans in the return airways rather than fans connected to the cooling tower. In addition, pressure drop is further reduced through cooling towers by replacing the mist eliminator screens with an enlarged cross-sectional area. This results in a lower air velocity which prevents the carry over of water droplets.

The ideal air velocity for air passing through a cooling tower is between 4 to 6 m/s and the maximum is 8 m/s [9].

On the other hand, spray chambers are designed to perform the opposite and cool the air using cold water. The cold water is sprayed in vertical or horizontal chambers. In a spray chamber, heat is transferred from air to water by a combination of convection and condensation. This requires that the air which enters the chamber to have a higher wet bulb temperature than the temperature of water. Vertical spray air coolers can be employed on the surface or underground for cooling the intake air. This type of coolers have heat transfer capacity of up to 20MW [9].

Unlike vertical spray chambers, horizontal spray chambers have more limited capacity within the 3.5MW range [9]. They can, however, be utilized without additional excavation making them more convenient for underground applications (Figure 14). The sprays can be designed in a direction against or across the airflow with the nozzles distributed over the cross section, at the sides, or near the base of the chamber. It is essential that the sprays and the airflow are distributed uniformly over the cross section. The contact area between the liquid-air interface affects the heat exchange efficiency which increases as the size of the droplets decrease. However, excessive decrease in droplet size can lead to water droplets carry over which would require highly constrictive mist eliminators. Horizontal spray chambers can also have a single stage or multi staged design (Figure 15). The cross-sectional area of a spray chamber should be designed to give air velocity of 4 to 6 m/s and not more than 7 m/s. Higher air velocities will reduce the efficiency of the heat exchanging spray chamber [9].

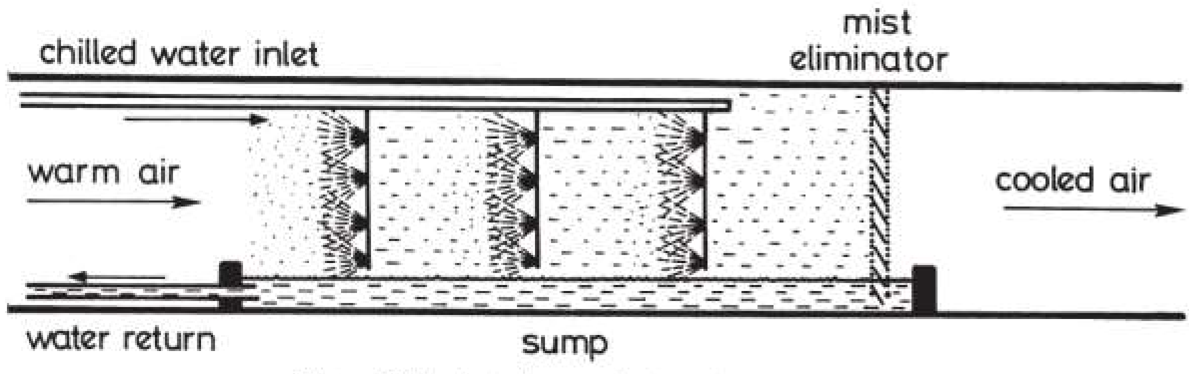


Figure 14. Horizontal Spraying Chamber. Figure Taken From [9]

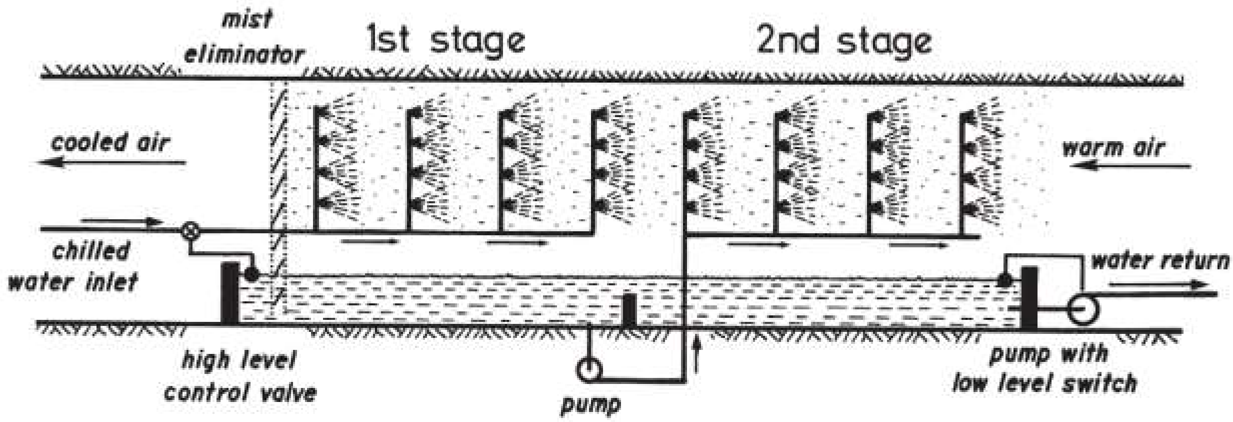


Figure 15. Multistage Horizontal Spraying Chamber. Figure Taken From [9]

In addition to cooling, spray chambers can help in reducing dust concentration. Still, dust particles build up can occur in the recirculating water which can result in fouling of the pipes and other spray chamber components [9]. This can be prevented by adding water filters or sedimentation areas within the spray chamber design. Spray chambers can also be designed to only reduce the dry bulb temperature of air by utilizing unchilled water. This type of spray chamber where no heat is removed from the air is termed evaporative cooler. This type of systems is utilized in very dry climates. Enclosed and portable direct spray coolers, which are mounted on wheels or sleds, have also been developed [9].

8.5.2. Indirect Heat Exchangers

An indirect heat exchanger is a system were heat is transferred between two fluids across a solid medium without any direct contact between the fluids (Figure 16). This solid medium can be a tube or a tubular coil [9]. Therefore, it is important to select the solid medium to be of material with high thermal conductivity as well as high resistance to corrosion and scale deposit buildup. It is also possible to apply chemical additives to the system to prevent fouling within the tubes or coils. If the heat exchanger is not maintained the efficiency of the system can be affected dramatically [9]. As a result, brushing of the tubes can be performed periodically to prevent any fouling or scale build up. In the case of air to water tube coils caking by mine dust deposits can form and so periodic cleaning is required.

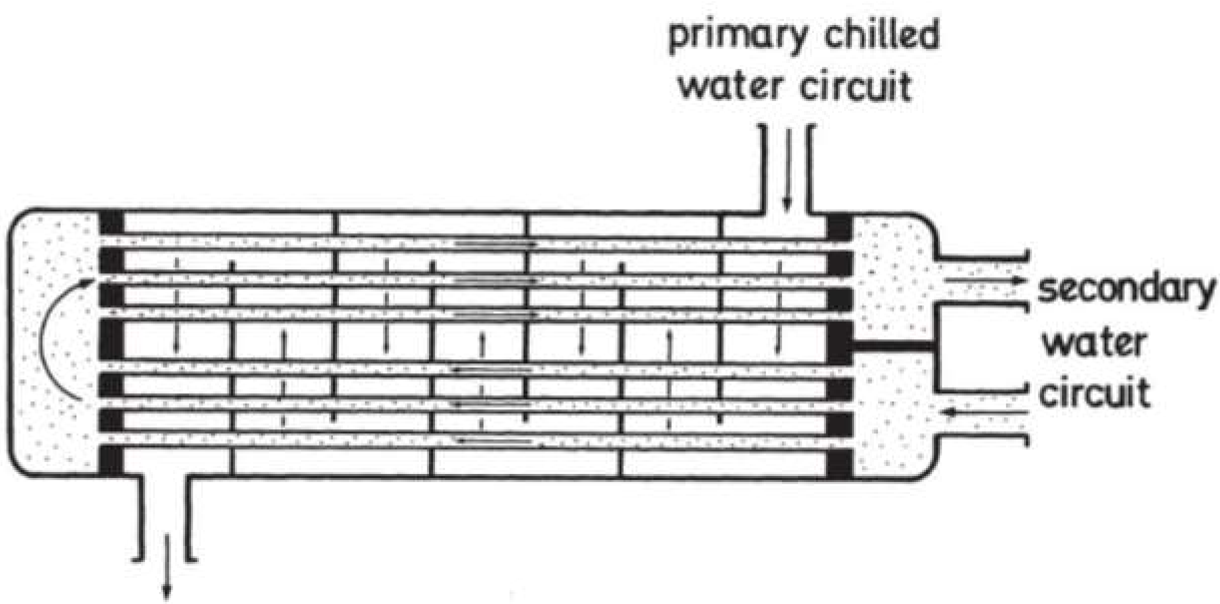


Figure 16. Indirect Heat Exchanger. Figure Taken From [9]

For indirect heat exchangers, the effective area available for thermal transfer is an essential factor to control the capacity of the heat exchanger. As a result, spiral fins welded to the tubes can be used to increase the effective thermal transfer area [9]. However, designing fins or other methods of thermal transfer area enlargement should be done carefully to ensure minimum resistance of the flow over the heat exchanger.

8.6. Returning Piping and diffusers

In an open loop surface water heat exchanger system, it is important to return the water that is warmed up or cooled down without creating a concentrated pocket of water that is significantly different in temperature than the water source. This is because water taken from deep surface water generally more nutrient rich compared to shallow surface water [19]. And so, if not considered it can promote the growth of biological entities like algae at shallow surface water. Thus, outfall systems are commonly designed with the purpose of mixing the water from heat exchanger system with the source water body over a large enough area that will ensure temperature gradients are minimal. This can be done by implementing a discharge pipe that has multiples holes that spreads along the pipe in order to gradually discharge the water back into the lake or sea (Figure 17) [23]. In addition, outfall systems are typically built so that they discharge the water near the lake or sea bed instead of discharging the water at the surface or directly into the water column.

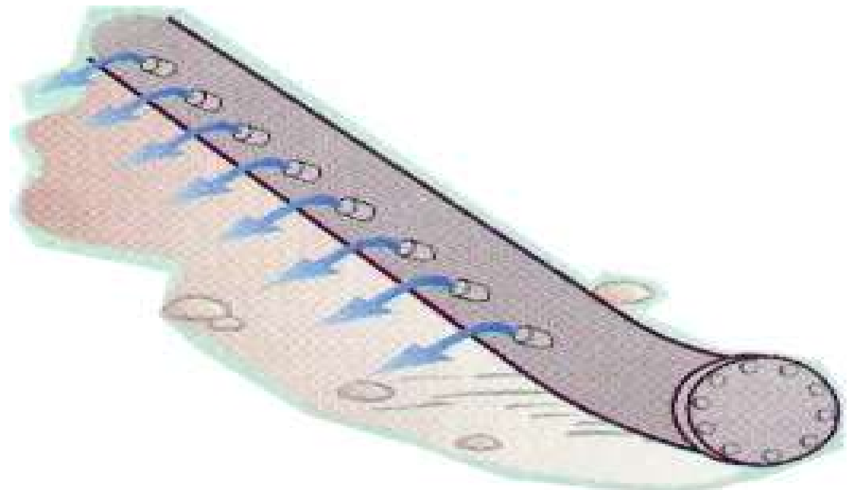


Figure 17. Discharging Water to Surface Water Source. Figure Taken From (https://energyandsustainability.fs.cornell.edu/util/cooling/production/lsc/works.cfm)

8.7. Open Loop Implementation Examples

8.7.1. Enwave

The project which is owned by Enwave began operation in July of 2004 in the city of Toronto. The system is designed to take water from Lake Ontario to air condition nearly 3.2 million cubic meters of space which has led to a significant decrease in electrical consumption in Toronto. The system utilizes 3 intake pipes reaching 5 meters into Lake Ontario and water is withdrawn from 83 meters below the surface as shown in Figure 18. Coldness is transferred from the cold water, estimated at 4 degrees Celsius, to Enwave's closed-loop network by using 18 pairs of stainless steel heat exchangers with over 800 sandwiched plates per heat exchanger [17]. The pipes used are made of HDPE plastic and are held in place in the bottom of the lake by concrete collars. At shore, these pipes are buried by beach sand to protect the land from erosion. After using the water for the heat exchanger system, the water is directed to the city's water treatment plant where it is treated to be used as drinking water for the city. The system currently withdraw water at a rate of 5 m^3/s from the lake and the system is considered sustainable at extractions rates up to 10,000 m^3/s [30].

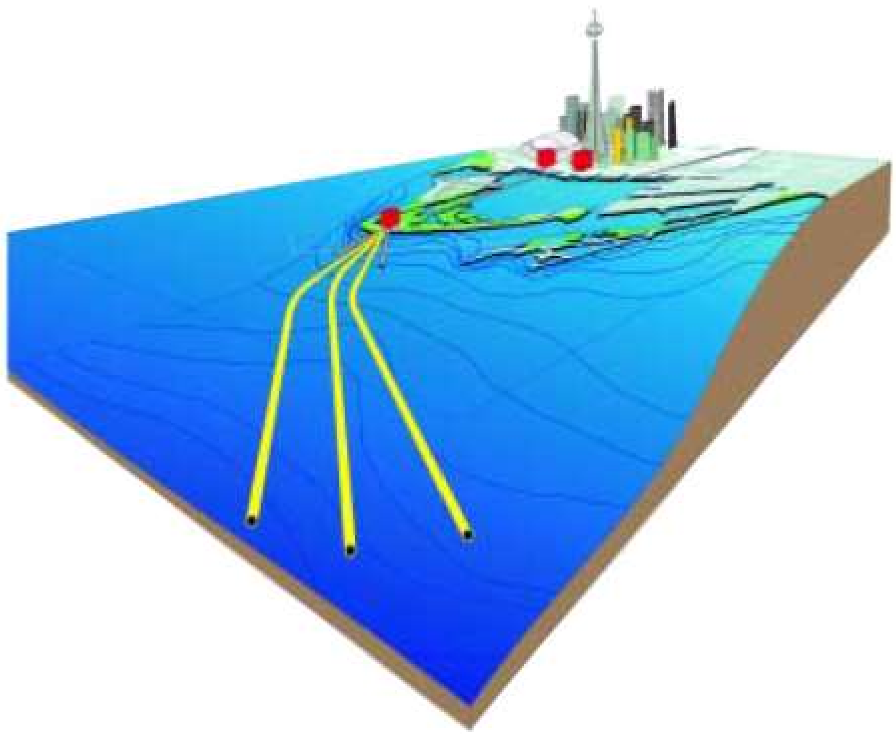


Figure 18. Lake Ontario Cooling Project. Figure Taken from [30]

Lake Ontario project has numerous environmental benefits as it illustrated a 90% reduction in electricity usage compared with utilizing conventional cooling system. This is because the system utilizes 10% of the electricity used of a standard air conditioning system, which freed approximately 61 MW of electricity from Ontario's electricity infrastructure and transmission grids. It also decreased carbon dioxide emissions by 79,000 tonnes annually [17, 30], which is equivalent to removing 15,800 cars from the roads. It also eliminated the emission of 145 tonnes of nitrogen oxide and 318 tonnes of sulphur dioxide which is produced with coal-fired electricity. In addition, the project also has economic benefits including the generation of 1,000 jobs annually. Furthermore, it provides lower costs for air conditioning for consumers [17].

8.7.2. Cornell University and Ithaca High School

The Cornell University lake cooling project is one of most important examples of sustainable cooling that is also environmentally friendly. The system utilizes water from Cayuga Lake (Figure 19) and is estimated to save 80% of the cooling energy compared to conventional cooling methods [24]. The cooling system is divided into two sections, an open loop where lake water intake occurs and a closed loop which transfer the coldness to the building. The intake occur within the open loop circuit happens through a screen located at depth of approximately 76 meters (3 meters above the bottom of the lake) and at 3.2 Kilometers into the center of the lake. The water temperature is about 3.89 ^{0}C all year around. The cold water then travels to a heat exchanger which transfers the heat from the returning closed loop coming from the school to the open loop incoming water from the lake as illustrated by Figure 20. Once heat transfer is complete, water returns gradually back to the lake upper levels via small holes at the outfall [19]. This open loop design is important to reduce

Figure 19. Cayuga Lake. Figure Taken from (https://en.wikipedia.org/wiki/Cayuga_Lake)

the impact of the returning water on the lake higher levels. Gradually dispersing the returning water will prevent the generation of water pocket of different temperature at the outfall area, and therefore prevent any changes in the biological flora at the outfall. Monitoring of the water condition of the lake and the cooling system occurs periodically at eight points including the outfall area [24].

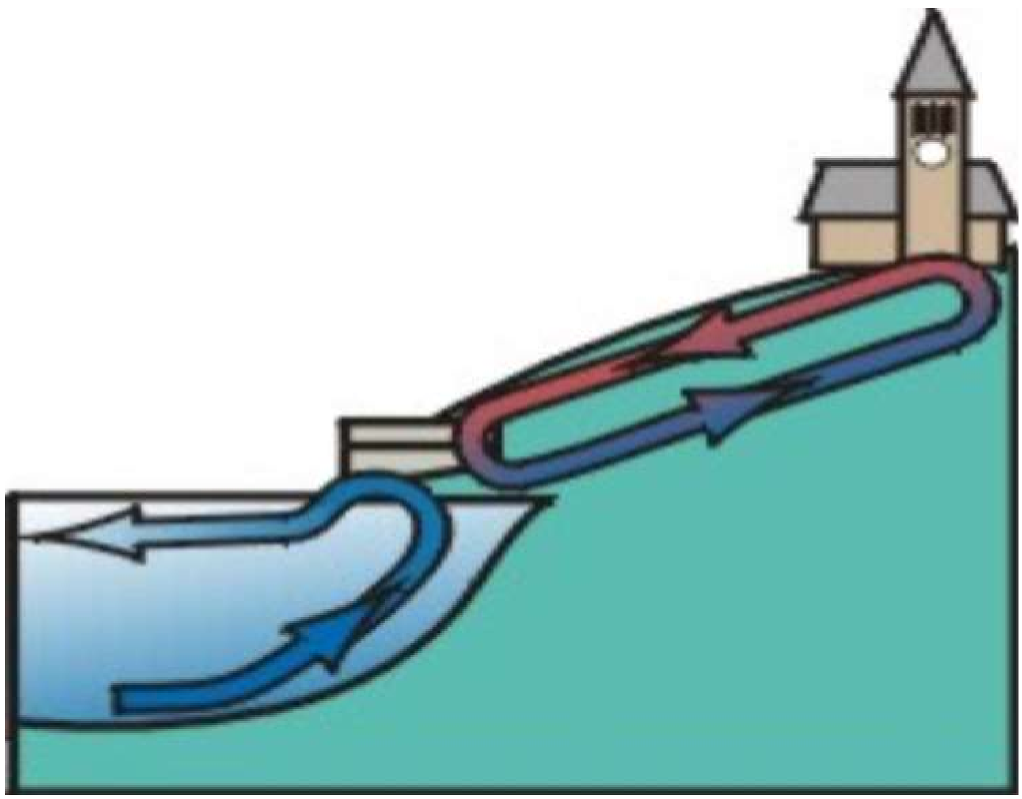


Figure 20. Diagram of Cornell University Cooling System. Figure Taken From [24]

The closed loop circuit, on the other hand, was designed to minimize the energy required to impel the cooled water from the shore to the campus and back. This is done by using large pipes which reduce friction and a closed circuit design that enables the hot water coming from the school to push the cooled water going back. There are seven heat exchangers that transfers the heat from the warm water coming from Cornell University to the cold water coming from the lake. These heat exchangers are arranged in parallel which facilitate controlling the number of heat exchangers to be activated based on demand. In addition, the seventh unit is designed as a backup if maintenance or repair is needed for one of the other exchangers [24]. It is important to note that the open loop lake water and the closed loop water that goes through Cornell University never mix.

The Cornell University lake cooling project is one of most important environmental projects to promote sustainability. It eliminated the use of conventional cooling systems which in turn eliminated the energy used by cooling equipment, the environmental impact, and possible future problems that can be caused by refrigerants that has been designed to replace CFC's. In addition, cooling using lake water resulted in an average power savings of 25,000 MWh annually when compared to conventional cooling. Moreover, the lake cooling that Cornell University uses is designed to last 75 to 100 years which is more than twice of the typical life of conventional cooling equipment [31]. This illustrates the huge potential of lake cooling for a long term clean sustainable source of energy.

9. Methodology

As illustrated in the previous section, there are several successful deep lake cooling projects across the world. While surface water cooling has been extensively studies, very little research has been carried out when it comes to its application in active underground mining operations. In addition, the concept has never been applied to an underground mine operation even though it is an economical and environmentally friendly method of cooling. This study gives a brief insight to the mining industry about the possible financial and economical benefits of utilizing deep surface water cooling systems.

Implementing deep surface water cooling into the mining industry can have several financial and environmental benefits. This is especially the case if new strict carbon taxes were mandated in Canada on the mining industry, since deep surface water cooling would reduce greenhouse gas emissions. In order to study the finances of deep surface water cooling, a mine that is of close proximity to a lake was selected for this study. The mine was visited to obtain the necessary data such as the distance of the lake from the mine, the temperature of the water of that lake, and the quality of the lake water. From the gathered data, a heat exchanger was selected in order to obtain a preliminary estimation of the cost benefits of installing a deep lake cooling system into an active underground mine.

An open loop cooling system was the method of choice due to its higher efficiency compared to a closed loop cooling system. However, the method of cooling that is discussed in this report is an open loop indirect contact cooling system rather than an open loop direct contact cooling system. The reason of this selection is because cooling a mine would require pumping a big amount of water from the lake into the mine and then back into the lake. Having lake water coming into contact with the air within the mine in direct contact heat exchange systems (in spray cooling) can trap elements from the mine, such as dust, debris and oils, into the water. Since the water needs to be returned back into the lake in order to ensure sustainability of the cooling system, the water in the case of direct contact cooling needs to be treated first and examined before being returned to the lake. This may add extra cost into the cooling system that renders it economically unfeasible. As a result, an indirect contact open loop heat exchanger was chosen for this preliminary assessment of deep surface water cooling.

9.1. Data Gathering

Gathering data about deep surface water cooling is an important first step. This was done by gathering literature about the cooling process and available methods, as well as studying about successful implementations of deep surface water cooling. In addition, gathering information about underground mines that have a deep water body in close proximity from them was done. Then after locating a mine that is in close proximity to a lake, the mine was contacted to gain information about the cooling requirements. A field visit was also carried out to measure the temperature of the lake. Afterwards, a heat exchanger supplier was contacted to obtain information about the heat exchanger units that can be utilized for the purpose of this assessment. The heat exchanger selected was then compared a conventional cooling system to assess the financial and environmental benefits of a deep lake cooling system.

The mine selected for this study has a lake, which is deep enough to be utilized for surface water cooling, approximately 3.5km away. The mine is located in the province of Ontario. It is still in the developing stage, therefore, while the mine engineers have designed the cooling and ventilation system, the equipment for cooling were not installed at the time this report was written. A key factor to consider in this study is the cooling demand of the mine. For the selected mine, cooling is needed between the months of May to September. If the refrigeration plan is located on the surface of the mine, the cooling required is estimated to be 16.4 MW. On the other hand, if the decision is made to install the refrigeration plant underground within the mine, the cooling required is 7.5 MW.

The cooling requirement increases significantly if the refrigeration plant is assembled on the surface due to the cooling loss of the ventilated air that needs to travel 2.6 km from the surface of the mine to the deepest planned operating levels of the mine. While an underground refrigeration plant results in less cooling demand, the ease of access of the surface refrigeration plant may result in cheaper maintenance and operational cost, which can make the surface refrigeration plant a more financially feasible option. In addition, an underground refrigeration plant will require equipment to reduce the downstream pressure such as a dissipater or pressure reducing valves which can add more cost. Moreover, pumping cost will be higher in an underground refrigeration scenario since water needs to be pumped back from the mine back into the lake. Furthermore, as water travels at high velocity through the pipes going into the mine it will generate heat through friction or turbulence. This will increase the water temperature by 2.34 °C for each 1000m [9]. Therefore, a deeper cost analysis comparison between a surface refrigeration plant and an underground one is required to determine the ideal location of a refrigeration plant.

An Air Handling Unit (AHU) is a metallic box in which air passes through. A typical AHU contains dampers, filters, a blower as well as the indirect heat exchangers [32]. Dampers play a role in modulating the airflow going to the cooling coil sections. If needed, dampers can divert the entire airflow completely towards a bypass section. Filters on the other hand are placed upstream from the heat exchanging coils and are designed to reduce dust going to the coils, which in turns reduces dust from settling on the coils. They are made of synthetic laminated fiber and coated with water repellent adhesive. The heat exchanging coils are usually made with the seamless tubes with fins that increases the heat exchanger's active surface area [32].

9.2. Calculations

In an indirect heat exchanger it is important to understand that, at equilibrium, the heat gained by one fluid in a heat exchanger must equal the heat lost by the other fluid [9]. Therefore, in the application of lake cooling with an indirect heat exchanger, heat transferred from air should be equal to heat absorbed by the water. This can be expressed by Equation (9).

$$q = Q \times C_w \times \rho_w \times \Delta T = m_a \times \Delta S \qquad (9)$$

Where: Q = the flow of water into the heat exchanger (m^3/s), C_w = specific heat of water (4187 J/(kg ^{0}C), ρ_w is the density of water (1000 kg/m^3), Δt_w = rise in temperature of the water (^{0}C), m_a = mass flow of air (kg/s) and ΔS = fall in sigma heat of the air (J/(kg ^{0}C)). The middle part of the equation is the same as Equation (2), which is the heat gain equation discussed in Part I of this thesis. The right part of this equation does not consider the heat removed from the system by the condensate in situations where condensation occurs on the outside of the heat exchange coils. This is because that removed heat is usually very small and can be neglected. From this equation it can be observed that the amount of water provided to the heat exchange system is proportional to the amount of cooling capacity.

When it comes to calculating the performance of a cooling system, the same principal of geothermal heat pump or chiller can be applied. Therefore, the Coefficient of Performance of cooling system is a relationship between the total cooling effect and the total energy input to run the cooling system. This can be illustrated as follow:

$$COP = \frac{Total\ Cooling\ Capacity\ of\ a\ Cooling\ System}{Electrical\ Energy\ Input} \qquad (10)$$

The economic assessment was carried out by comparing an AUH to a conventional refrigeration plant in terms of the capital and operational cost. Cooling is required when wet bulb temperature reaches 26.5^0C or above. Therefore, gathered data estimates that this temperature occur between the months April to September. Therefore, the cooling plant is estimated to operate 4,416 hours per year as shown by Table 38. The electricity cost for that mine is $0.097 per kWh. Just as the first study, the name of the mine will remain confidential due to a confidentiality agreement between the author and the company that owns the mine operation. The only information mentioned regarding the mine are those necessary for the calculations and comparison, such as the cooling requirement.

Number of Operating Months	6 Months
Number of Operating Hours per Day	24 hours
Number of Operating Days	184 Days
Total Number of Operating Hours Per Year	4,416 hours

Table 38. Cooling Plant Annual Operating Hours

When it comes to estimate the environmental benefits of incorporating a deep lake cooling system it is possible to examine the difference in CO_2 emission between a deep lake cooling and a conventional cooling system based on the required power input for each scenario. Since the mine is in the province of Ontario, we can refer to Table 5 to calculate the overall CO_2 emission per kWh of energy used ($kgCO_2/kWh$) using Equation (11).

$$Annul\ CO_2\ Emission = W_{net} \times Number\ of\ Units \times hrs \times CO_2\ Emission \qquad (11)$$

Where W_{net} is the electrical power input needed to operate the AHU or conventional cooling unit, hrs is the annual operating hours, and CO_2 Emission is the carbon dioxide emissions from electricity. Once CO_2 emission for each case is calculated it is possible to compare the carbon savings from utilizing a geothermal deep surface water cooling system.

10. Results and Discussion

The mine that is considered for this study has a lake approximately 3.5km away. The first step is to ensure the lake is deep enough to be utilized for surface water cooling. After several measurements of temperature at numerous depths, it was concluded that the lake is indeed stratified Figure 21. As can be seen by the obtained data, at great depths it is possible to obtain temperatures close to 5 °C. This cold water can therefore be pumped into the mine and passed by a heat exchanger to be used as a heat sink.

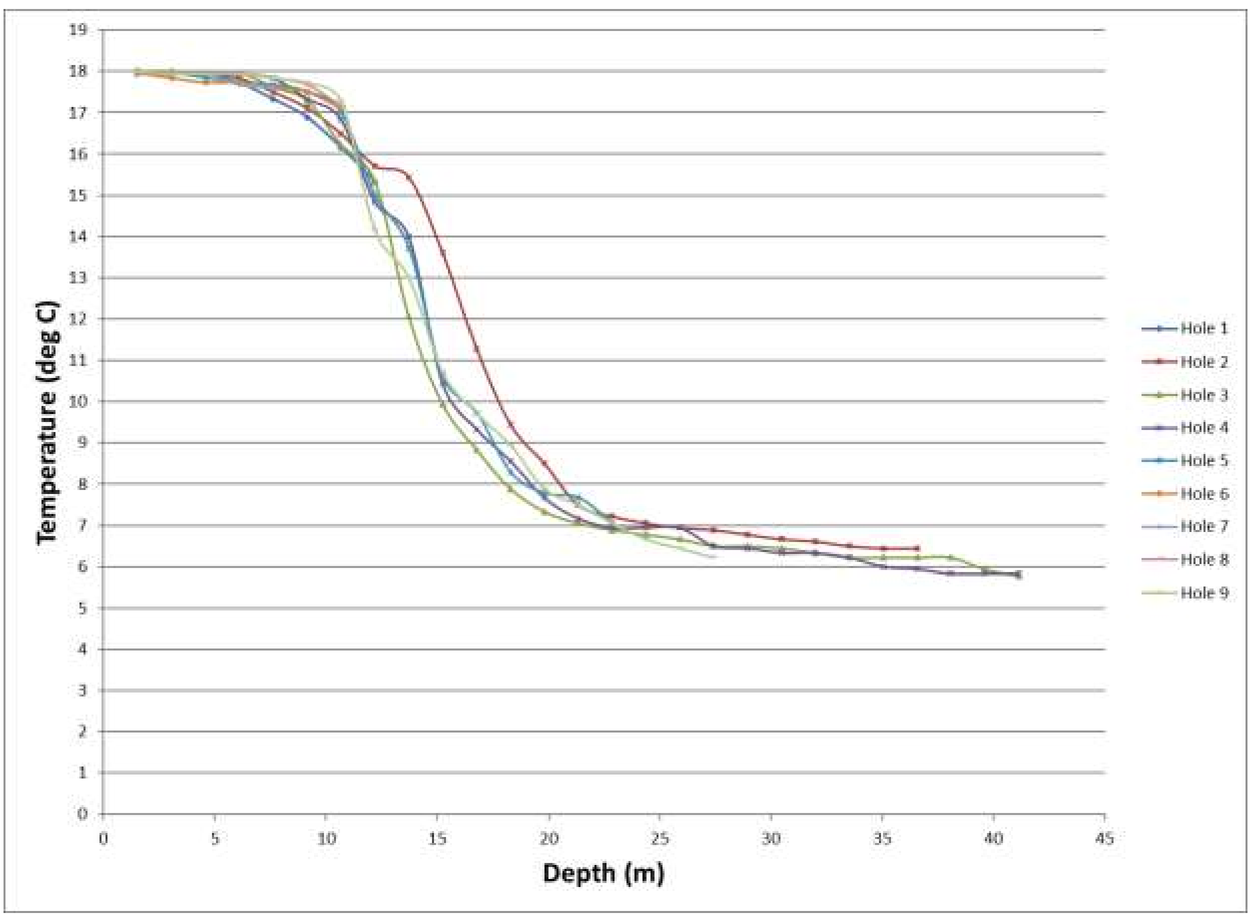


Figure 21. Water Temperature at Different Depths and Locations

The AHU of choice for the active mine lake cooling project is provided by Trane and has physical dimensions of 4.6 meters in width, 7.2 meters length, and 3 meters height. The heat exchanging coils are made of 5/8 inch seamless copper tubes and aluminum fins, which have collars drawn, belled and firmly bonded to the tubes by mechanical expansion. The heat exchanging coils are tested to 300 psi and leak tested under water for 200 psi. The AHU is designed with a double inlet, multi blade airfoil fan that can handle 70000 cfm. The fan is driven by a belt that is connected to a 57kW premium efficiency squirrel cage induction motor. It is assembled in the factory with a complete static and dynamic balance. The selected AHU capital and operational cost was compared to that of a conventional cooling plant. The conventional cooling plant data was obtained from SIBISI, 2014 who listed the cost of a 1 MW refrigeration plant [33]. Table 39 below is a summary comparison between the AHU of choice and a conventional 1 MW cooling plant.

Type of Cooling Plant	**Lake Cooling Air Handling Unit (AHU)**	**Conventional Cooling Plant (1 MW Capacity)**
Total Input Power	57.79 kW	381 kW
Total Cooling Capacity	605.97 kW	1000 kW
Coefficient of Performance (COP)	3.17	3.5
Total Unit Price	**$225,594**	**$774,220**

Table 39. Summary of AHU Performance and Price Compared to Conventional Cooling

Since the active mine cooling requirement has been estimated to be 16,000 kW if the cooling plant is on surface and 7,500 kW if the cooling plant is underground, the next step is to compare the capital cost and operational cost of the lake cooling system with the conventional cooling system. Table 40 shows the estimated capital and operational cost of each cooling system if the cooling plant is built on the surface of the mine.

Cooling Plant on Surface		
Type of Cooling Plant	**Lake Cooling Air Handling Unit (AHU)**	**Conventional Cooling Plant**
Cooling Required	16,400 kW	
Capacity	605.97 kW	1000 kW
Number of Units Needed	27.1 → 28	16.4 → 17
Cost Per Unit	$225,594	$774,220
Total Capital Cost	**$6,316,632**	**$13,161,740**
Operating Hours Per Year	4,416 hours	
Electricity Price	0.097 CAD per kWh	
Total Input Power	57.79 kW	381 kW
Annual Operating Cost Per Unit	$24,755	$163,202
Total Annual Operating Cost	**$693,140**	**$2,774,434**

Table 40. Comparison Between Lake Cooling and Conventional Cooling With Cooling Plant Assembled on Surface of the Mine

As can be observed from Table 40, there is a great economical benefit from utilizing a deep lake cooling instead of a conventional cooling system. This can be observed by both the capital cost of the needed units and the operational cost to run the cooling systems. The capital cost is lower for the lake cooling system is attributed to the lower cost per unit compared to a conventional cooling system. Therefore, even though more units are needed with the lake cooling system to fulfill the mine's requirement, the cost per unit difference keeps the overall capital cost advantage towards using a deep lake cooling system. Similar trend follows when considering the operating cost with the deep lake cooling system which has significantly lower operating cost compared to conventional cooling system. This is because conventional cooling system requires significantly higher input power to operate. Having significantly higher input power with conventional cooling can be explained by the need for more power with conventional cooling to run the compressor which keeps the cooling liquid at low temperature. On the other hand, an AHU depends on the naturally low temperature of the lake water and does not require a compressor during its operation.

Looking at the scenario where the cooling plant is built inside the mine, a similar comparison between a deep lake cooling system and a conventional cooling system can be done. Table 41 shows the estimated capital and operational cost of each cooling system if the cooling plant is built inside the mine. The estimated capital and operational cost for an underground cooling plant show similar savings patterns when compared to a surface cooling plant. Just as in the case of surface cooling plant, the higher price per unit of a conventional cooling system gives the financial advantage to the deep lake cooing system. In addition, due to the higher required power input for conventional cooling, the operation cost is significantly lower with a lake cooling AHU system. From these preliminary results, deep lake geothermal cooling system shows great potential for a more economical solution for cooling underground mines whether the cooling plant is designed on the surface of the mine or underground.

Cooling Plant Underground		
Type of Cooling Plant	**Lake Cooling Air Handling Unit (AHU)**	**Conventional Cooling Plant**
Cooling Required	7,500 kW	
Capacity	605.97 kW	1000 kW
Number of Units Needed	12.4 → 13	7.5 → 8
Cost Per Unit	$225,594	$774,220
Total Capital Cost	**$2,932,722**	**$6,193,760**
Operating Hours Per Year	4,416 hours	
Electricity Price	0.097 CAD per kWh	
Total Input Power	57.79 kW	381 kW
Annual Operating Cost Per Unit	$24,755	$163,202
Total Annual Operating Cost	**$321,815**	**$1,305,616**

Table 41. Comparison Between Lake Cooling and Conventional Cooling With Cooling Plant Assembled Inside the Mine

When it comes to estimate the environmental benefits of incorporating a deep lake cooling system, CO_2 emissions were calculated following Equation (11). From the difference in power input needed between the two systems, it is clear that a lake cooling AHU system would be more environmentally friendly. As can be seen from Table 42, the overall annual carbon savings from utilizing a geothermal deep lake cooling system on the surface of a mine is 5,589.5 tonnes. On the other hand, the overall annual carbon savings from implementing a deep lake cooling system inside the mine is 2,642.04 tonnes. The complete CO_2 emission comparison is summarized in Table 42.

Type of Cooling Plant	Lake Cooling Air Handling Unit (AHU)	Conventional Cooling Plant
Annual Operating Hours	4,416 hours	
Total Input Power Per Unit	57.79 kW	381 kW
Annual CO_2 Emission Per Unit	66.48 tonnes	438.29 tonnes
Cooling Plant on Surface		
Number of Units Needed	28	17
Total Annual CO_2 Emission	1,861.43 tonnes	7,450.93 tonnes
Cooling Plant Underground		
Number of Units Needed	13	8
Total Annual CO_2 Emission	864.28 tonnes	3,506.32 tonnes

Table 42. CO2 Emission Comparison Between Lake Cooling System and Conventional Cooling System

When carrying out the financial and environmental analysis, these preliminary result show promising reduction in cooling cost and CO_2 emissions. Whether the cooling plant is built on the surface of the mine or underground inside the mine, the geothermal deep surface cooling system showed reduction in both capital and operational costs, as well as, carbon emissions.

11. Recommendations

In this study, a mine within the province of Ontario was visited and a preliminary assessment of implementing a geothermal deep lake cooling system was carried out. This section contains the author’s recommendations for future research on this topic. The author hopes that one day deep surface water cooling systems are implemented into active mines, which is a concept that has never been applied in active mines.

Since this study took on only one mine for the preliminary analysis, it is possible to do similar studies with other mines that have lakes in their vicinity. This can give further understanding of the potential financial and environmental benefits of applying deep surface water cooling systems into underground mine operations. Having more mining operations examined for this study can broaden the scope of this study.

For the reason explained earlier in this study, the focused was only on lake cooling systems that are open loop with indirect heat exchange systems. Examining other methods of lake cooling techniques, such as closed loop systems and open loop direct heat exchange systems, can expand the scope of this study. Having different methods to use the cool water as a heat sink can give a deeper understanding of the advantages and disadvantages of each method. This can also result in finding the most economic and environmentally friendly technique for a deep surface water cooling system.

This preliminary assessment showed great financial and environmental potential of implementing deep lake cooling into underground mines. However, this study did not consider the capital cost associated with the pipes and pumps needed to transport the lake water from the lake to the mine. This is important considering the pipes to be used should be insulated to keep the water temperature cool. Adding the cost of piping and pumping of the lake water can reduce or offset the financial benefits of implementing deep water cooling systems in active underground mining operations. Moreover, pumping cost can also reduce or offset the operational cost as well as the environmental benefits of utilizing a deep lake cooling system in active underground mines. Therefore, further examining of piping and pumping costs are essential to further understand the potential of implementing surface water cooling for active underground mine operations.

In the scenario where the cooling plant is built inside the underground mine, it is possible install turbines that convert the potential energy of the water going into the mine into electricity. The turbines can absorb some or all pumping costs of a lake cooling system. In addition, these turbines can also function as dissipaters to reduce the downstream water pressure which is necessary in such scenario. Carrying out such analysis can be a step closer to the ultimate goal of this study, which is to implement geothermal deep surface water cooling into active underground mine sites.

12. Conclusion

This part of the thesis is a preliminary assessment of the financial and environmental benefits of utilizing geothermal deep lake cooling systems in active underground mining operations. The results illustrated show promising reduction in cooling cost and CO_2 emissions. This part of the thesis had three objectives that were successfully met. The first step was to obtain as much literature information as possible about deep surface water cooling and examine successful examples. This is a crucial step before conducting any study as it gives an understanding of previous work in a topic and help expand the research within that topic. There are several successful examples of utilizing deep surface water for cooling, still, there yet to be an implementation of geothermal deep surface water cooling in an active mine. This part of the thesis is a step in the direction of applying deep surface water cooling in an active underground mining operation.

The second goal was to investigate underground mining operations which are at close proximity from a deep surface water. Once a suitable mine was found a field visit was conducted to gather information about the mine and the lake. The third objective was to use the gathered data to calculate the potential financial and environmental benefits of utilizing a deep surface water cooling system instead of a conventional cooling system. This included selecting an Air Handling Unit manufactured by Trane and comparing its performance and cost to a conventional cooling system for the mine being investigated.

Part II of this report ends up with recommendations to go beyond what is discussed in this thesis about deep surface water cooling in an active underground mining operation. With a possibility for the Canadian government to implement new carbon taxes, as well as the increase concerns about global warming, alternative sources of energy can be a solution. And so, it is important to continue the research in this topic. This study is a crack on the surface when it comes to installing deep surface water cooling systems in active underground mining operations. Therefore, there are many possible steps to further broaden the scope of this study. It is possible to explore the potential pumping and piping costs associated with transferring the water from the lake to the mine. It is also possible to study other method heat exchange techniques such as direct heat exchange and closed loop heat exchange systems. In addition, looking into other mines that have deep bodies of surface water within close proximity is another possibility to expand the scope of this study. All of these can give further understanding about the financial and environmental aspects of implementing geothermal deep surface water cooling system into active underground mining operations.

Appendix

Appendix 1: FHP WW-420 Heat Pump Specification Sheet

WATER COOLED CHILLERS AND LOW TEMP BOILERS
SPECIFICATION DATA SHEET
FHP MANUFACTURING ENERGY WISE HVAC EQUIPMENT

WW420
AQUARIUS SERIES
R-410A

ELECTRICAL SPECIFICATIONS

Electrical Characteristics	Elect. Symbol	Compressor		Min. Circuit Ampacity	Max. Fuse Size
		RLA	LRA		
208/230-3-60	-3	59.1	425	133.0	190
460-3-60	-4	26.4	187	59.4	80
575-3-60	-5	26	148	58.5	80

FLUID FLOW & PRESSURE DROP

Chilled Fluid Side (@ 55°F)		Cond. Fluid Side (@ 85°F)	
Flow (GPM)	P (FOH)	Flow (GPM)	P (FOH)
50	5.8	50	5.0
60	8.0	60	7.0
70	10.6	70	9.3
80	13.5	80	11.8
90	16.8	90	14.7

UNIT WEIGHT

Unit Weight (lbs) 1550
Shipping Weight (lbs) 1570

CHILLER PERFORMANCE

Based on 68 GPM load and 84.2 GPM source fluid flow.

Leaving Load Fluid (F)	Entering Source Fluid (F)	Total Capacity (Tons)	Total Capacity (MBtuH)	Power Input (kW)	EER	Heat Rejection (MBtuH)
40°	75°	27.95	335.40	21.46	15.63	408.61
	80°	27.19	326.23	22.61	14.43	403.37
	85°	26.41	316.89	23.88	13.27	398.36
	90°	25.61	307.38	25.26	12.17	393.55
	95°	24.81	297.67	26.74	11.13	388.92
42°	75°	28.97	347.61	21.58	16.11	421.23
	80°	28.18	338.13	22.71	14.89	415.63
	85°	27.37	328.47	23.97	13.70	410.26
	90°	26.55	318.63	25.34	12.57	405.09
	95°	25.72	308.59	26.83	11.50	400.12
44°	75°	29.49	353.85	21.64	16.35	427.69
	80°	28.68	344.21	22.77	15.12	421.90
	85°	27.87	334.38	24.02	13.92	416.34
	90°	27.03	324.37	25.39	12.78	411.00
	95°	26.18	314.16	26.87	11.69	405.84
45°	75°	30.01	360.17	21.71	16.59	434.25
	80°	29.20	350.37	22.83	15.35	428.27
	85°	28.37	340.38	24.07	14.14	422.52
	90°	27.52	330.20	25.44	12.98	416.99
	95°	26.65	319.81	26.92	11.88	411.65
46°	75°	31.09	373.10	21.85	17.07	447.67
	80°	30.25	362.96	22.96	15.81	441.29
	85°	29.39	352.63	24.19	14.58	435.15
	90°	28.51	342.10	25.54	13.40	429.24
	95°	27.61	331.36	27.01	12.27	423.52
48°	75°	31.64	379.71	21.93	17.31	454.53
	80°	30.78	369.39	23.02	16.04	447.95
	85°	29.91	358.89	24.25	14.80	441.6
	90°	29.01	348.18	25.59	13.61	435.50
	95°	28.10	337.26	27.06	12.46	429.59
50°	75°	32.77	393.19	22.10	17.80	468.58
	80°	31.88	382.53	23.17	16.51	461.58
	85°	30.97	371.67	24.37	15.25	454.83
	90°	30.05	360.59	25.71	14.03	448.30
	95°	29.11	349.30	27.17	12.86	441.99

c UL US

HEATING PERFORMANCE

Based on 68 GPM load and 84.2 GPM source fluid flow

Leaving Load Fluid (F)	Entering Source Fluid (F)	Heating Capacity (MBtuH)	Power Input (kW)	COP	Heat of Absorb. (MBtuH)
100°	35°	328.13	25.18	3.82	242.21
	40°	350.02	25.16	4.08	264.18
	50°	398.09	25.12	4.64	312.39
	60°	452.59	25.17	5.27	366.72
	70°	514.34	25.40	5.94	427.69
110°	35°	324.39	28.31	3.36	227.78
	40°	345.32	28.31	3.57	248.72
	50°	391.12	28.26	4.06	294.71
	60°	442.89	28.22	4.60	346.61
	70°	501.46	28.28	5.20	404.95
120°	35°	321.01	31.78	2.96	212.58
	40°	341.02	31.83	3.14	232.41
	50°	384.63	31.84	3.54	276.01
	60°	433.74	31.78	4.00	325.32
	70°	489.20	31.75	4.52	380.86
125°	35°	317.86	35.57	2.62	196.48
	40°	336.98	35.72	2.77	215.12
	50°	378.46	35.84	3.09	256.17
	60°	424.98	35.83	3.48	302.71
	70°	477.39	35.78	3.91	355.30

Units are complete packages featuring 1 stage operation and containing refrigeration compressor, reversing valve, expansion valve metering device and water to refrigerant heat exchangers. Also included are safety controls: Overload protection for compressor, high and low refrigerant pressure switches and a lock-out control circuit.

FHP MANUFACTURING COMPANY
601 N.W. 65th Court
Fort Lauderdale, FL 33309
Phone: (954) 776-5471 Fax: (800) 776-5529
http://www.fhp-mfg.com

As a result of continuing research and development, specifications are subject to change without notice. WW420IP6.P65 Rev:10-04

Appendix 2: RTWD Series R Chiller Specification Sheet

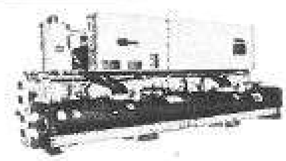
RTWD Series R(TM) 70-250 Ton Water-Cooled Chiller

Job Information

TRANE

McGill University mining recovery project
Montreal Main Office
(D88)Luc Tremblay

Tag	RTWD-1
Model Number	RTWD 160 HE
Quantity	1
Product Version	185
Unit nominal tonnage	160
Unit type	High efficiency



General Information

Cooling capacity	644.83 kW	Refrigerant	R134a
		Sound reduction package	None
Cooling efficiency	0.201 kW/kW	Sound pressure	79 dBA
IPLV	0.170 kW/kW	Heating capacity	774.19 kW
NPLV	0.156 kW/kW	Heating efficiency	5.98 COP

* At 1 meter in free field.

Evaporator Information

Evaporator application	Std cooling	Evap fouling factor	0.044025 m2-deg C/kW
Entering temperature	15.8 C	Number of evap passes	2 pass evap
Leaving temperature	11.4 C	Saturated evap temp-ckt 1	9.0 C
Fluid flow rate	554.00 gpm	Saturated evap temp-ckt 2	8.8 C
Pressure drop	113.9 kPa	Minimum flow rate	9.54 L/s
Evap fluid type	Water	Pressure drop at min flow rate	11.7 kPa
Evap fluid freeze point	0.0 C	Maximum flow rate	34.98 L/s
Evap fluid concentration	--	Pressure drop at max flow rate	113.9 kPa

Condenser Information

Unit application	High ent cond >95F/35C	Cond fouling factor	0.017610 m2-deg C/kW
Cond entering temp	30.0 C	Saturated cond temp-ckt 1	38.6 C
Cond leaving temp	35.8 C	Saturated cond temp-ckt 2	38.8 C
Cond flow rate	560.00 gpm	Min cond flow rate	10.91 L/s
Cond pressure drop	96.5 kPa	Press drop at min cond flow	9.6 kPa
Cond fluid type	Ethylene glycol	Max cond flow rate	40.01 L/s
Cond fluid concentration	40.00 %	Press drop at max cond flow	120.4 kPa
Cond tubes	Enhanced fin - copper		

Compressor Information

			RLA	LRA
Number of compressors	2	Comp A	84.00 A	172.00 A
Number of circuits	2	Comp B	84.00 A	172.00 A

Electrical Information

Unit voltage	575 volt 3 phase	Unit power	129.40 kW
Incoming power line conn	Single point	Compressor starter type	Wye-delta
Single point power MCA	191.00 A	Single point power MOP	250.00 A
Short circuit rating	25000.00 A		

3/11/2016 Product Version 185

Page 1 of 2

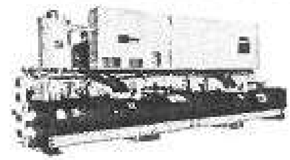
RTWD Series R(TM) 70-250 Ton Water-Cooled Chiller

Job Information

TRANE

McGill University mining recovery project
Montreal Main Office
(D88)Luc Tremblay

Tag	**RTWD-1**
Model Number	**RTWD 160 HE**
Quantity	**1**
Product Version	**185**
Unit nominal tonnage	**160**
Unit type	**High efficiency**



Physical Information

Length	**3660 mm**	Refrigerant charge circuit 1	**64 kg**
Width	**1202 mm**	Refrigerant charge circuit 2	**64 kg**
Height	**1920 mm**	Oil charge circuit 1	**11.73 L**
Operating weight	**3808 kg**	Oil charge circuit 2	**11.73 L**
Shipping weight	**3645 kg**	Water connections evap	**127 mm**
		Water connections cond	**152 mm**

Notes: All weights +- 3%. Operating weights include refrigerant, oil, and water charges.

Sound pressure measured in accordance with AHRI Standard 575-94.
Water connections are not reversible.

Certified in accordance with the AHRI Water-Cooled Water-Chilling and Heat Pump Water-Heating Packages Using Vapor Compression Cycle Certification Program, which is based on AHRI Standard 550/590 (I-P) and AHRI Standard 551/591 (SI). Certified units may be found in the AHRI Directory at www.ahridirectory.org.

AHRI CERTIFIED

This unit does NOT comply with the efficiency requirements of ASHRAE Standard 90.1 or CAN/CSA C743.

Appendix 3: Summary of the Performance Analysis for Manitoba Mines

Mine Operation	Average Water Flow (GPM)	Average Water Temp (^0C)	Heat Gain per Unit (kW)	Number of Heat Pumps	Cost of Heat Pumps ($CAD)
Mine M1	719	13.8	121.98	9	266.670
Mine M2	116	13.6	121.40	2	59.260

Appendix 4: Summary of the Financial and Environmental Analysis for Manitoba Mines

Mine Operation	Annual Savings ($/yr)		Payback Period (yr)		Net CO2 Savings (t/yr)	
	Electrical Heating	Propane Heating	Electrical Heating	Propane Heating	Electrical Heating	Propane Heating
Mine M1	135,856	288,098	2.0	0.9	154	1048
Mine M2	21,776	46,220	2.7	1.3	25	168

Appendix 5: Summary of the Performance Analysis for Ontario Mines

Mine Operation	Water Flow (GPM)	Average Water Temp (^{0}C)	Heat Gain per Unit (kW)	Number of Heat Pumps	Cost of Heat Pumps ($CAD)
Mine O1	398	16.7	130.46	5	148,150
Mine O2	950	20.9	181.68	12	355,560
Mine O3	290	18.9	136.89	4	118,520
Mine O4	133	16.6	130.17	2	59,260
Mine O5	515	16.7	130.46	7	207,410
Mine O6	700	15.1	125.65	9	266,670
Mine O7	500	14.6	124.32	6	177,780
Mine O8	675	14	123.09	9	266,670
Mine O9	560	15.8	127.83	7	207,410
Mine O10	800	11.5	116.61	10	296,300

Appendix 6: Summary of the Financial and Environmental Analysis for Ontario Mines

Mine Operation	Annual Savings ($/yr)		Payback Period (yr)		Net CO2 Savings (t/yr)	
	Electrical Heating	Natural Gas Heating	Electrical Heating	Natural Gas Heating	Electrical Heating	Natural Gas Heating
Mine O1	188,092	125,930	0.8	1.2	305	554
Mine O2	415,116	167,173	0.9	2.1	2080	1246
Mine O3	205,171	21,326	0.6	5.6	476	270
Mine O4	87,892	7,889	0.7	7.5	204	124
Mine O5	341,347	30,865	0.6	6.7	793	483
Mine O6	441,231	34,831	0.6	7.7	1025	620
Mine O7	310,736	23,492	0.6	7.6	722	435
Mine O8	413,845	29,916	0.6	8.9	961	578
Mine O9	361,252	30,455	0.6	6.8	839	509
Mine O10	455,540	24,456	0.7	12.1	1058	628

Appendix 7: Summary of the Performance Analysis for Quebec Mines

Mine Operation	Average Water Flow (GPM)	Average Water Temp (^{0}C)	Heat Gain per Unit (kW)	Number of Heat Pumps	Cost of Heat Pumps ($CAD)
Mine Q1	1000	16.5	129.88	12	355,560
Mine Q2	375	16.7	130.32	5	148,150
Mine Q1	320	22.0	145.97	4	118,520

Appendix 8: Summary of the Financial and Environmental Analysis for Quebec Mines

Mine Operation	Annual Savings ($/yr)		Payback Period (yr)		Net CO2 Savings (t/yr)	
	Electrical Heating	Natural Gas Heating	Electrical Heating	Natural Gas Heating	Electrical Heating	Natural Gas Heating
Mine Q1	305,360	(3,186)	1.2	NA	190	1366
Mine Q2	115,023	(1,073)	1.3	NA	72	514
Mine Q3	113,772	2,805	1.0	42.3	71	494

Appendix 9: Air Handling Unit Performance Data Specification Sheet

Length	7.2 m	**Fluid type**	Water
Width	4.6 m	**Water entering temp**	10 °C
Installed weight	7.2 ton	**Water leaving temp**	17.5 °C
Actual airflow	70000 cfm	**Water flow rate**	1083 L/min
Fan Total static pressure	4.74 (inch water)	**Fluid pressure drop**	19.39 (ft. water)
Fan pressure drop	2.00 (inch water)	**Sensible cooling Capacity**	93 tons
Fan outlet velocity	13 m/s	**Total cooling Capacity**	172 Tons ~ 605 kW
Fan speed	805 rpm	**Bypass damper airflow**	70000 cfm
Fan Power	57 kW	**Bypass damper pressure drop**	1.805 (inch water)
Coil air flow	70000 cfm	**Face damper pressure drop**	0.098 (inch water)
Coil face are	11 sq. m	**Filter pressure drop**	0.558 (inch water)
Coil face velocity	3 m/s	**Approximate cost of 1 Unit**	225,000 CAD
Air pressure drop	0.28 (inch water)		
Coil weight	273 kg		
Air entering DBT	36 °C		
Air entering WBT	28 °C		
Air leaving DBT	28 °C		
Air leaving WBT	25 °C		

References

1. Hochstein, M., *Classification and assessment of geothermal resources*. 1990. 31-59.
2. DiPippo, R., *Chapter 8 - Geothermal Energy: – electricity generation and environmental impact A2 - Jackson, Tim*, in *Renewable Energy*. 1993, Butterworth-Heinemann. p. 113-122.
3. Barbier, E., *Nature and technology of geothermal energy: A review.* Renewable and Sustainable Energy Reviews, 1997. **1**(1): p. 1-69.
4. De Giorgi, L. and G. Leucci, *Study of Shallow Low-Enthalpy Geothermal Resources Using Integrated Geophysical Methods.* Acta Geophysica, 2015. **63**(1): p. 125-153.
5. Council, W.E. *World Energy Resources*. 2016; Available from: https://www.worldenergy.org/wp-content/uploads/2017/03/WEResources_Geothermal_2016.pdf.
6. M. M. Ghomshei, K., MacLeod, T.L Sadlier-Brown, J.A. Meech, R.A. Dakin, *Canadian Geothermal Energy Poised for Takeoff.* presented at the World Geothermal Congress, Antalya, Turkey,, 2005.
7. Jessop, A., *Geothermal energy in Canada*. Vol. 25. 1998. 33-41.
8. S.E. Grasby, D.M.A., S. Bell, Z. Chen, G. Ferguson, A. Jessop, M. Kelman, M. Ko, J. Majorowicz, M. Moore, J. Raymond, R. Therrien, *Geothermal Energy Resource Potential of Canada.* GEOLOGICAL SURVEY OF CANADA OPEN FILE 6914, 2012.
9. McPherson, M.J., *Subsurface ventilation and environmental engineering*. 1st ed. 1993, London ; New York: Chapman & Hall. xvi, 905 p.
10. Self, S.J., B.V. Reddy, and M.A. Rosen, *Geothermal heat pump systems: Status review and comparison with other heating options.* Applied Energy, 2013. **101**: p. 341-348.
11. Louis Hiddes, J.S., René Verhoeven, Marlie Dix, Herman Eijdems, *SMART ENERGY REGIONS - THE NETHERLANDS*, in *SMART ENERGY REGIONS*, W.L. Phil Jones, Jo Patterson, Philipp Geyer, Editor. 2014, The Welsh School of Architecture, Cardiff University: United Kingdom. p. 169 – 180.
12. Verhoeven, R., et al., *Minewater 2.0 Project in Heerlen the Netherlands: Transformation of a Geothermal Mine Water Pilot Project into a Full Scale Hybrid Sustainable Energy Infrastructure for Heating and Cooling.* Energy Procedia, 2014. **46**: p. 58-67.
13. Jessop, A., J. K. Macdonald, and H. Spence, *Clean Energy from Abandoned Mines at Springhill, Nova Scotia*. Vol. 17. 1995.
14. Jessop, A. *Geothermal energy from old mines at Springhill, Nova Scotia, Canada*.
15. 23rd day of October, A.D., N.S.R.C.a.t.i.i.t.u.o.f.o.o.d.s.r.t.a.a.B.i.N.M.a.S.o.t. and D. McInnes, *Report*. 1959.
16. CADDET, *Geothermal mine water as an energy source for heat pumps.* Centre for Analysis and Dissemination of Demonstrated Energy Technologies. Result 112 (CA 91.003/3D.H03), 1992.
17. Newman, L. and Y. Herbert, *The use of deep water cooling systems: Two Canadian examples.* Renewable Energy, 2009. **34**(3): p. 727-730.
18. http://www.geothermalgenius.org. *Are You in the Loop? Open vs. Closed Loop Systems in Geothermal*. Available from: http://www.geothermalgenius.org/blog/are-you-in-the-loop-open-vs-closed-loop-systems-in-geothermal.
19. Spitler, J.D. and M.S. Mitchell, *8 - Surface water heat pump systems A2 - Rees, Simon J*, in *Advances in Ground-Source Heat Pump Systems*. 2016, Woodhead Publishing. p. 225-246.
20. Hirshman, J., D. A. Whithaus, and I. H. Brooks, *Feasibility of a district cooling system utilizing cold seawater. Phase I: final report*. 2017.
21. Iso, S., *Problems on sea water intake and discharge facilities in coastal region.* Desalination, 1977. **22**(1): p. 159-168.

22. Viquerat, P.-A., et al., *Utilization of a Deep Lake Water Direct Cooling Network (DLWDC) for cooling of a large administrative district. Energy and Environmental demonstration and follow-up*. 2018.
23. Mitchell, M. and J. Spitler, *Open-loop direct surface water cooling and surface water heat pump systems—A review*. Vol. 19. 2013.
24. University, C. *How Lake Source Cooling Works*. 2005; Available from: https://energyandsustainability.fs.cornell.edu/util/cooling/production/lsc/works.cfm.
25. Maehara, T., *Materials technology for seawater pumps.* World Pumps, 2007. **2007**(490): p. 38-39.
26. Leraand, T.K. and J.C.V. Ryzin. *Air conditioning with deep seawater: a cost-effective alternative for West Beach, Oahu, Hawaii*. in *OCEANS '95. MTS/IEEE. Challenges of Our Changing Global Environment. Conference Proceedings.* 1995.
27. Janikowski, D.S., *Selecting Tubing Materials for Power Generation Heat Exchangers.* Power-Gen International Conference at New Orleans, Dec 12, 2007 2007.
28. Pugh, S., G. F. Hewitt, and H. Müller-Steinhagen, *Fouling During the Use of "Fresh" Water as Coolant - The Development of a "User Guide"*. Vol. 30. 2009. 851-858.
29. Pugh, S.J., G.F. Hewitt, and H. Müller-Steinhagen, *Fouling During the Use of Seawater as Coolant—the Development of a User Guide.* Heat Transfer Engineering, 2005. **26**(1): p. 35-43.
30. Eliadis, C., *Deep Lake Water Cooling A Renewable Technology.* electrical line, 2003. **9**(3): p. 26-8.
31. University, C. *Lake Source Coolig*. 2005; Available from: https://energyandsustainability.fs.cornell.edu/util/cooling/production/lsc/default.cfm.
32. *Carrier System Design Manual. Part 2, Air Distribution*. 1972: Carrier Air Conditioning Company.
33. SIBISI, *Effects of surface ambient temperature on refrigeration plant design*, in *The 6th International Platinum Conference, 'Platinum–Metal for the Future'*. 2014, The Southern African Institute of Mining and Metallurgy.