

University of Nevada, Reno

**Evaluating Mine Cooling Systems and Mine Ventilation Strategies to be Applied in
Deep and Hot US Mines**

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

by

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Abstract

Metal production in the United States contributes significantly to the national and global economies due to resource demands. As mineral reserves are becoming scarce, demand has driven mining companies to operate at increasing depths underground. Along with this, production has continued to increase year after year, as lower grade ores are excavated economically. However, the increased mining depths and increased production have resulted in enlarged heat loads in the underground mine environment. Increased heat loads can result in temperatures which are too high for mine workers to safely work. This may cause heat related illness, injuries, or even death. Mine operators must pursue heat reduction strategies in order to maintain safe temperatures to protect mine workers.

There are a number of heat mitigation methods and strategies which mine operators can implement. The most common means is through the use of ventilation to provide cool air volumes to reduce the heat load and dilute the contaminants generated in the production workings below their threshold limit values (TLV). This can be done by increasing the fresh air volumes through surface accesses such as shafts, raises, adits, ramps, or other mine entrances. When ventilation alone cannot provide acceptable climatic conditions in the production workings and throughout the mine, artificial cooling methods need to be used. These methods can be very effective, however, they require large capital investments, continuous maintenance, and additional operating costs. This includes central cooling, spot cooling, and micro-climate cooling systems. Though reducing the heat load is effective, another strategy is to reduce the source of the heat generation. One such source is the heat generated by diesel engine equipment fleet. This

can be decreased by switching to a battery powered equipment fleet. All of these strategies can be compared based off their heat reduction, temperatures, and operating costs. This study does exactly this by using an underground metal mine's ventilation system to compare various scenarios and identify the most effective cooling method or system that can be used in deep and hot US mines.

Dedication

This thesis is dedicated to Dr. Karoly (Charles) Kocsis and Eniko (Annie) Kocsis for encouraging me to pursue my graduate degree, advising me on career decisions, and providing the support I needed for success academically and professionally.

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Introduction

Underground mines in the United States and across the world continue to become deeper and more mechanized as the occurrence of near-surface ore deposits decreases and the world demand for minerals continues to drive increasing production rates. A consequence of these changes in the underground mine environment is increasing heat generation. This is directly a result of increasing mining depths and increased production resulting in greater mechanization.

While the underground mine environment is experiencing these changes, mine workers are still present in these worsening climatic conditions, which expose them to a wide risk of dangers. In regards to heat, it results in the temperatures underground becoming high enough to risk illness, injury, or even death. The sources of this heat must be meticulously identified, measured, and calculated. Doing so allows mine operators to properly counter the heat load with heat reduction strategies to meet their safety and economic goals.

To examine and compare heat reduction and control methods, a partner mine provided its mine design and ventilation models to be used to compare different mine operating scenarios. The partner mine is located in northern Nevada, which puts it in a high desert climate. It is an underground, precious metal mine, which utilizes longhole stoping as well as the drift and fill variation of the cut and fill (C &F) mining method. In its current state it consists of an intake shaft and an exhaust shaft in an exhausting configuration. A diesel fleet of equipment is used which includes LHDs and haul trucks for materials handling. Nevada is known for experiencing high temperatures underground

as a result of the high surface temperatures in the summer and high geothermal gradient. These heat issues are wide spread across Nevada and recorded in history back to the Silver Rush in Virginia City, Nevada (Lord, 1883). As expected, the partner mine has continued to experience heat problems as the mine has expanded deeper, and production rate increased, resulting in greater equipment usage. In order to maintain safe temperature and humidity levels for the mine workers, solutions must be investigated to reduce the heat load.

Traditionally, ventilation is the primary means to reduce the heat load. This is done by increasing cooler airflow and/or introducing surface air through shafts, raises, adits, ramps, or other mine entrances/exits. An alternative to this is applying artificial cooling in the form of either centralized cooling, spot cooling, and/or micro-climate cooling. Both pose different heat reduction abilities and costs which mine operators should consider. Other strategies involve reducing the heat generation at the source. One notable source is heat generation from diesel engines. By switching to a battery powered equipment fleet this heat generation can be drastically reduced. All of these scenarios should be considered when planning heat reduction at an underground mine.

This study does this exact comparison using the mine ventilation model of a partner mine. Five scenarios were generated based on different ventilation and cooling strategies such as: (1) baseline, (2) a new shaft, (3) increased airflow, (4) artificial cooling by surface bulk air cooling (BAC), and (5) switching from a diesel engine fleet to a battery powered equipment fleet. The scenarios were compared based on their heat reduction capabilities, temperatures in the production workings, and operating costs. Performing a tradeoff study such as this to investigate heat reduction strategies is of

utmost importance to ensure not only the economic prosperity and success of the mine, but also to protect the health and safety of mine workers.

Literature Review

Heat Stress and Heat Sources

Heat is a significant concern in many underground metal mines. This is due to the fact that mine workers are exposed to extreme conditions found underground. The excess heat generated from sources underground and the high humidity may result in heat related illness, injury, or death. To address this problem, it is important to understand how heat affects the human body, what sources underground are generating heat and what mine operators can do to mitigate it.

The human body naturally controls its core temperature by means of conduction, convection, radiation and evaporation of sweat (Sunkpal, 2015). When exercise is performed and the heart rate increases, the human body is able to exhaust this increased metabolic heat load (Payne & Mitra, 2008). These natural processes give the human body its own effective cooling system. However, the human body's ability to cool itself is affected by the surrounding environment. When in the presence of excess heat and humidity, the human body transfers a reduced amount of heat to the mine air. This is further exasperated when work is performed at high intensity, as the core temperature of the human body is increased but its ability to transfer that heat to the mine air is decreased. This heat stress can result in heat related illness, injury, or potential death. The onset of heat stress begins with fatiguing, loss of concentration and slowed thinking.

Ultimately with continued exposure, heat stress will lead to more serious heat illnesses such as cramps, syncope, exhaustion, heat stroke and even death (Roghanchi, 2017).

The safety and health risks of excessive heat and humidity are a significant issue in underground mines. This is because mine workers can be exposed to unsafe temperatures and humidity when working that may result in accidents, injury or death. The onset of apparently minor issues due to heat stress such as loss of concentration, slow thinking and fatigue may also lead to actions which can indirectly harm mine workers particularly when operating heavy equipment. Fortunately, there are methods and systems which can be implemented by mine operators to reduce mine workers susceptibility to heat related illnesses and injury. Mine workers can be mandated to perform work-rest cycles in order to give their bodies time to lower their core temperatures during breaks. Hydration is also important as the core temperature will quickly rise if the human body is dehydrated and unable to sweat when in excess heat. Mine workers should also be equipped with appropriate clothing to allow for proper evaporative cooling from sweat. As for new mine workers, it is important that they become acclimatized to the working conditions of the mine before taking on the workload and exposure of current mine workers (Brake & Bates, 2002).

Though these practices can do a significant amount of work to reduce the effects of heat stress on mine workers, at a certain point the dry-bulb (T_d) and wet-bulb (T_w) temperatures can be too high for the mine workers to even be present. Because of this, mine operators need to quantify the heat generated by the sources in order to conceptualize the best means to reduce and remove the heat. The main sources of heat in underground metal mines include: (1) auto-compression as air descends through vertical

openings, (2) strata heat (geothermic gradient), (3) machinery, (4) mine water influx, (5) explosive detonations, (6) friction between falling rock, (7) human metabolism, (8) pipelines, and (9) oxidation (Carpenter, Roghanchi & Kocsis, 2015).

Regulations and recommendations for the maximum T_d and T_w mine workers can be exposed to and/or the maximum allowable temperature values underground can vastly vary world-wide. Whatever the case may be, there are multiple means to reduce the heat load and remove the heat being produced. This includes ventilation, artificial cooling, and reducing the magnitude of heat generation of a given source.

Primary Ventilation Planning

Ventilation is the primary means to remove heat from the underground mine environment. It allows for the movement of fresh air from the surface into underground airways through which fresh air is delivered to the development and production workings where contaminants such as dust, diesel particulate matter, gases, as well as heat are removed. This spent air, also known as return air or contaminated air is then directed to surface through the mine's exhausting system. Primary ventilation planning involves extensive development that is integrated with the mine design process and upgraded throughout the life of the mine. But the means of how this air is moved can vary drastically different from mine to mine due to the employed mining method and ore body geometry, size, and shape (McPherson 2009).

Though there is not a strict standard across the mining industry, primary mine ventilation design does conform to specific practices. In order to move air into the subsurface, fans are employed in specific configurations such as forcing, exhausting, or

push-pull to deliver fresh air into the mine through surface accesses such as shafts, raises, adits, ramps, or other mine entrances. A surface fan positioned at the top of an exhaust shaft or exhaust raise will pull the air thus producing a negative pressure throughout the mine. A fan positioned at the top of an intake shaft or intake raise will be forcing fresh air through vertical and horizontal airways thus producing positive pressure through the mine. Surface fans positioned at the top of an exhaust and an intake airway will both push and pull the air thus producing a neutral pressure at some locations in the mine (McPherson 2009). Other concerns include considering airflow direction for materials handling systems such as haulage, conveyance, or hoisting. An antitropical system involves moving material in intake airways while a homotropical system is in exhaust airways (Tien, 1999). Federal and state law requirements may dictate one system over another. Engineering considerations may include the heat, dust, and/or gas inflow into the ventilating air generated by mining equipment, blasting, ore oxidation, which will affect air quality.

A key topic of discussion for primary ventilation planning is major upgrades to account for significant changes in the mine design that deviate from the original plans. This may happen due to the discovery of new reserves which requires expansion beyond the previous mine life or an increase in the production rate, which requires more fresh air to dilute the heat load or remove other contaminants. An upgrade such as this creates a higher demand on the ventilation system. Sometimes this can be met by upgrading the fans to supply more air. This method is known as “flooding” and can be represented in Figure 1. The first part of the graph in Figure 1 represents this “flooding” strategy where airflow is increased to mitigate low to moderate heat generation. The downside to the

“flooding” strategy is that the efficiency decreases exponentially as the heat load increases (Brake, 2001). At this point other alternatives must be considered. In the case of underground mine expansion, the cooler intake air has to travel further distances to reach working areas. When heat is an issue in deep, hot underground mines this may result in the cooler air becoming heated before even reaching the working areas. In regards to airflow, this can be solved by creating a new source of airflow from the surface through an intake airway such as a shaft, raise, adit, ramp, or other mine entrance (Wallace, Tessier, Pahkala & Sletmoen, 2005).

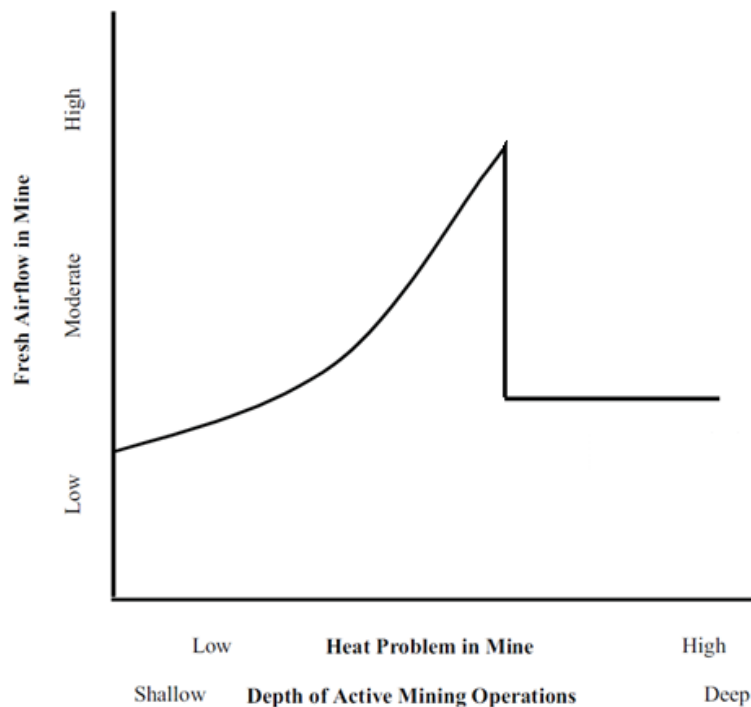


Figure 1: Appropriate airflow delivery strategy (Brake, 2001)

One huge benefit to introducing a new shaft is it can also be used for production hoisting. This can allow for reduced materials handling time and quicker shift changes. However, the downside of introducing new airways is not only the substantial cost of construction for a new surface access such as a shaft, raise, adit, ramp, or other mine

entrance, but also the required upgrades to ventilation infrastructure such as regulators, stoppings, fans, and more due to the potential change in airflow direction or volume. In regards to airway reversal, this costs not only money but time as mine workers must perform these upgrades. Production may be lost as man power is diverted and areas of the mine are idled (Carter, 2016). Yet, even with a new shaft, the airflow alone may still not be enough to reduce the temperature to appropriate levels. Ultimately, a point is reached where an artificial cooling system must be introduced, as the heat mitigation is not achievable by ventilation on its own (Brake, 2001).

Cooling Systems

Mine ventilation has been traditionally used as the primary method to remove the heat and the moisture that was transferred to the ventilating air from linear/spot heat sources and diesel/electrical mining equipment. Fresh air is delivered into the mine environment to remove heat and to benefit evaporative cooling off the body of mine workers. In some cases, artificial mine cooling systems are incorporated with the ventilation when the ventilation alone cannot adequately provide acceptable work conditions in the production and development workings and throughout the mine. This can be seen in Figure 1 (Brake, 2001).

The first part of the graph in Figure 1 represents a “flooding” strategy where airflow is increased to mitigate low to moderate heat generation. The downside to the “flooding” strategy is that the efficiency decreases exponentially as the heat load increases. Eventually ventilation loses its economic advantage and must be replaced by artificial cooling. The horizontal portion of the graph represents the phase when artificial

cooling is introduced while the airflow velocity is lowered to minimum airflow velocity requirements (Brake, 2001). There is a large tradeoff as mine cooling systems are a significant expense, but the capital and operating costs to install and operate these systems are necessary to ensure the safety of the mine worker.

The United States has a long history of using natural and artificial cooling to combat excessive heat problems. In the 1860's, mines in Virginia City, Nevada used naturally formed blocks of ice shipped in from the mountains to cool the workings and the miners. In 1878, there was an average daily consumption of 95 pounds of ice per miner (Lord, 1883). The first mechanical heat exchangers in the United States were used in 1937 for artificial cooling at the Magma Copper mine in Superior, Arizona (Biddle, 1976). Today, only a few mines in the United States use cooling systems and many rely solely on ventilation. Other countries such as Australia and South America have extensively invested in research and development for underground cooling systems.

Currently used underground cooling practices are broken down into different categories based on the scale of the systems. This includes three wide ranging categories: central cooling, spot cooling and micro-climate cooling. These categories can each be divided further into different cooling methods which vary based on design and heat exchange techniques.

Centralized Cooling Systems

Centralized cooling is often referred to as bulk air cooling or primary cooling. These systems are used in mines where heat issues are widespread (McPherson, 2009). They provide cooling throughout the mine workings in order to reduce the heat load to

safe levels. This cooling system consists of two non-mobile heat exchange systems. One is the bulk air cooler (BAC), which acts as an evaporator that cools the surrounding air. The BAC system includes a cooling tower that sprays chilled water over the air which is drawn through the BAC. The other system includes the refrigeration plant, which acts as a condenser where heat is rejected in the form of air or water to the surrounding area. If heat is rejected through water then a condenser cooling tower (CCT) is required. Unlike a BAC, a CCT rejects the heat from water to the air (Brake, 2012).

Centralized cooling systems can be broken down into two categories based on the location of the BAC: surface or underground. Many of the surface BAC and underground BAC design features are similar; however, the configuration of the systems varies based on a variety of factors (Hooman, Webber-Youngman, Plessis, & Marx, 2015).

A conventional surface BAC is commonly the primary means of artificial cooling used by a mine. This is due to the complexity and cost of implementing underground artificial cooling on a central scale (Mackay, Bluhm, & Van Rensburg., 2010). A surface BAC is positioned on the surface where the ventilation system can draw air through the chamber of the BAC. The positional efficiency of a surface BAC can be the smallest compared to other methods as it is located so far away from the mine's production workings. At mine sites where the geothermal flow of heat emanating from the earth's core is significantly higher due to an anomalous geothermal activity, the temperature of the ventilating air will significantly increase by the time it arrives from the surface BAC system to the production workings. This can be further amplified as cool air entering the intake shaft will draw an increased amount of heat from the surrounding strata. However, this can be compensated by the fact that the surface BAC has no size limit and therefore

can cool larger amounts of air. Multiple surface BACs can be used in different configurations at the same location to maximize air cooling (Brake, 2012). Two different surface BAC configurations are shown in Figure 2.

A limiting factor for the conventional surface BAC is that there is a boundary to how low the temperatures can drop in the intake shaft as mine personnel use it for transport and hoisting. The solution to this is the use of a dedicated downcast airshaft which utilizes ultra-cold surface bulk cooling. This ultra-cold air will reach safe limits by the time it reaches the bottom of the shaft due to auto-compression and strata heat. It will also require upgrading the BACs and refrigeration plant infrastructure (Ramsden, Branch, & Wilson, 2007). However, at some point the mining depth will be too large for any surface BAC to be cost effective. This depth will vary between mine sites as the heat load experienced at a given mine at a given depth differs greatly. When the mine reaches this depth it must utilize underground artificial cooling in order to continue to mitigate the mine's heat load (Mackay, et al., 2010).



Figure 2: A vertical fill-packed tower BAC and a multi-stage horizontal spray chamber BAC (Roman, Glehn, & Marx, 2013)

An underground BAC is usually positioned where large quantities of intake air can be directly passed through the BAC chamber. This can be aided by air locks and/or auxiliary fans (Kamyar, Aminossadati, Leonardi, & Sasmito, 2016). The primary underground BAC is generally placed in the main intake. Secondary underground BACs may be placed deeper in the mine and used to re-cool fresh intake air or to re-cool recirculated air. This is known as secondary cooling (Roman et al, 2013). Cooling-coil heat exchangers may be used in place of BAC's for secondary cooling if the cooling requirements are low (less than 1.5 MW). Unlike BACs, a cooling-coil heat exchanger can be moved, but they also require a washing system as the coils can become dirty and less efficient. An example can be seen in Figure 3 (Mackay, et al., 2010).

Underground BACs can utilize either an underground or surface refrigeration plant. Underground refrigeration plants perform at a higher efficiency over surface plants as they are closer to where cooling is required underground. A surface refrigeration plant providing cold water to an underground BAC requires a large system of insulated pipes, pumps, and water dams. At the same time, there are other disadvantages to having an underground refrigeration plant. The coefficient of performance (COP) is lower as vapor condensing temperatures are increased due to limited air quantities and because the air used for the condenser heat rejection has a higher T_w (Castillo, Baard, & Pieters, 2005). Fouling may be more common in underground refrigeration plants if the water source is not directly from the surface due to the inferior quality of underground water. Also, maintenance on underground refrigeration plants is burdensome due to the confined areas underground (Castillo et al., 2005). On the top of this, the most significant disadvantage is that underground refrigeration plants can only dispense so much heat into the return air

for heat rejection. In some cases, heat rejection in a return airway is limited in order to comply with regulatory requirements regarding the mine climate and maximum airflow velocities. Otherwise, if the return air temperature is relatively high then the refrigeration plants will only be able to dispense a fraction of the heat needed for rejection. As a result, the cooling power will decrease thus resulting in an unsafe and uneconomic installation. For these reasons, refrigeration plants are most often placed on the surface (McPherson, 2009).



Figure 3: A closed-circuit cooling-coil heat exchanger bank (Mackay, et al., 2010)

Although a surface refrigeration plant may provide chilled water, at greater depths, the chilled water may heat up drastically due to the pressure differential. As water is pumped underground the potential energy is converted directly to heat thus warming the water. For example, at the Vall Reefs mine in South Africa this temperature rise was 2.34 °C per 1,000 meters of elevation change when pumped underground. An immediate solution is to use ice from the surface in the form of an ice slurry. Ice is produced on the surface, mixed with water to form an ice slurry and then piped underground. This ice slurry provides cold water for the underground BACs, spot coolers and other general

mine operating purposes. Ice slurries are highly advantageous as there is little to no temperature change as the increase in temperature due to potential energy is largely compensated by the latent heat used to melt the ice. Pumping costs are also low as gravity is used to move the ice slurry down the shaft and a pneumatic pumping system is used to move the ice slurry throughout the levels (Bellas & Tassou, 2005). Yet, the energy cost associated with an ice plant capable of servicing a mine makes it the most expensive artificial cooling method due to the ice generation. For this reason, ice slurries are only used for deep mines as a last resort.

A less common natural cooling method in underground mines is the use of ice storage. In climates with seasonal freezing conditions, ice can be created and stored in either a single stope or multiple stopes during colder months and then used during warmer months to cool the mine's intake air. This is known as a "cold stope" or an "ice stope". The system also provides heating during winter by raising the intake air temperature due to the formation of ice in the cold stope. Air is forced through the cold stope and either becomes chilled during warmer months or becomes heated during colder months due to heat exchange processes (Howes & Horton, 2005). In 2012, a prototype portable surface ice stope, called the Modular Thermal Transfer Unit (MMTU), was designed to emulate an ice stope. It consists of stacked shipping containers with the tops and bottoms removed to generate and store the ice on surface. Water sprays were used to accumulate ice. This allows for easier maintenance and greater control over heating and cooling. Though it is only in the prototype stage, the MMTU has a high potential to be employed in mines with large heat loads in areas which see cold winters (Allen, Morgan, & Rantanen, 2012).

Spot Cooling Systems

Spot cooling systems are often referred to as decentralized, tertiary, face, or in-stope air cooling systems. These spot cooling systems are used in areas where heat problems are localized and often are away from main airways (McPherson, 2009). Most often these localized areas include actively mined faces as heat is produced from equipment operation and from the freshly mined rock/ore. If these areas are not active for a long period of time, then a mobile spot cooler would be ideal as they can be designed to be portable and thus used in other active production workings. The mobility of spot coolers and their location underground gives them a high positional efficiency. The disadvantage of a spot cooler is that its size limits its cooling capacity (Brake, 2001). Spot cooling systems are often used in conjunction with central cooling. However, if the overall mine heat load is low and highly localized it may in some cases be used exclusively (Schlotte & Walasiak, 2005).

The two types of spot coolers which are actively used are: (1) spray chambers, and (2) closed circuit cooling-coil heat exchangers. An example of a portable spot cooler is shown in Figure 4. The evaporator portion of the spot cooler can be installed in an air duct, while the condenser portion is positioned outside of the duct in the return air way where the spot cooler rejects its heat. Another option is to use an underground refrigeration plant to provide chilled water to spot coolers. In this situation, the refrigeration plant is set up in an area where it can directly reject heat into a return airway. Chilled water is then pumped to where the spot cooler is situated. This can be referred to as district cooling. Both of these situations are not always ideal as new airways are not always close to return airways (Brake, 2001).



Figure 4: An experimental cooling-coil spot cooler (Biffi, Plessis, & Marx, 2005)

Micro-Climate Cooling Systems

Micro-climate cooling is the cooling of the area directly surrounding the mine worker. This is ideally the most efficient way to keep the mine workers cool in a hot underground mine environment as the positional efficiency can be close to 100% (Brake, 2001). This method is not often mentioned in underground mine cooling literature as micro-climate cooling systems don't cool the mine environment. Nevertheless, an example of this is utilizing air conditioned cabins on mining equipment, which allows mine workers to stay out of the heat. This has resulted in a reduction of heat related injuries and increased productivity. The issue of heat stress is not completely eliminated as not all tasks can be completed from inside of an air conditioned cabin, as many operations underground may not be fully mechanized, or the mining equipment may not be equipped with an air conditioned cabin (Brake, 2001).

A less common micro-climate cooling system is the use of cooling garments that a mine worker would wear. In the 1970's, the U.S. Bureau of Mines investigated ice-cooled vests and liquid-cooled clothing for mine workers. The ice-cooled vest, seen in

Figure 5, consisted of pouches of ice that could be refrozen after use (U.S. Bureau of Mines “Ice Cooled”, 1979). The liquid-cooled clothing consists of a vest, hood, and a heat sink which pumps liquid coolant through the clothing to cool the mine worker (U.S. Bureau of Mines “Liquid Cooled”, 1979). Today we have significantly more advanced cooling garments which can cool the worker through air cooling, water circulation, gas expansion and more. A study in 2016 (Sayed, Vinches, & Hallé, 2016) investigated these garments specifically for use in underground mines. They concluded that no current cooling garment technology alone can protect a mine worker from excess heat exposure underground. These, like other cooling methods, can be used to mitigate heat exposure.

Cooling System Comparative Analysis

Mine cooling systems are difficult to compare and contrast as there are not only many different cooling systems, but each system varies wildly by cooling capacity, operating cost, capital investment, efficiency, and more. How effective these systems are will also vary between different mine sites based on a variety of factors such as mine design, mining method, material handling, heat load, and more. Table 1 shows a comparison of different cooling systems with respect to cooling capacity, mobility, positional efficiency, and cost. Table 2 highlights the advantages and disadvantages of current cooling system strategies.

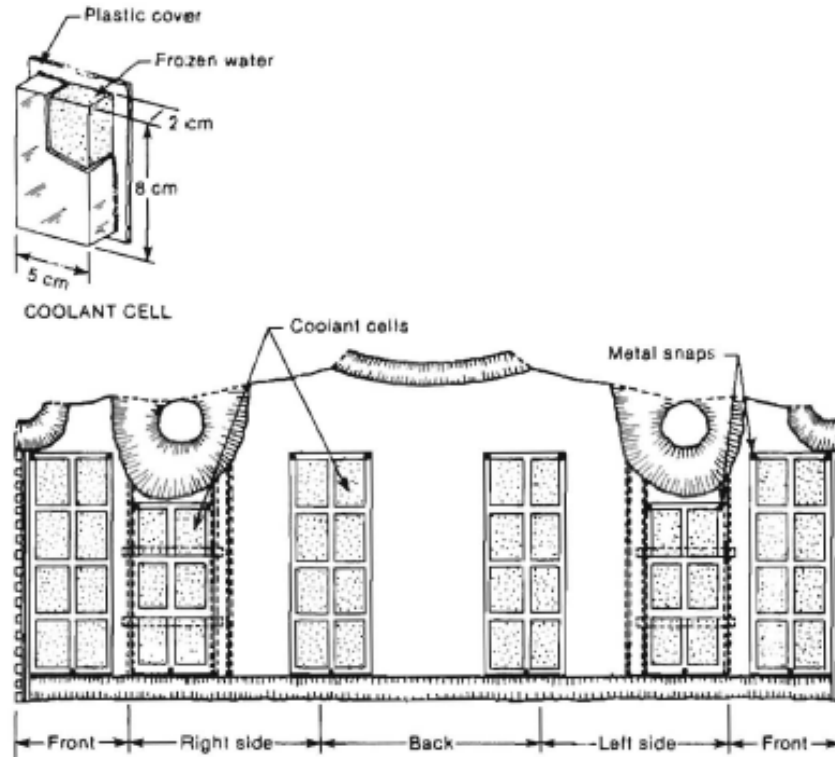


Figure 5: USBM prototype ice jacket (U.S. Bureau of Mines “Ice Cooled”, 1979)

Cooling System	Cooling Capacity	Mobility	Positional Efficiency	Cost
Surface Bulk Cooling	High	Stationary	Low	High
Underground Bulk Cooling	Medium-High	Stationary	Low-Medium	High
Ice Storage	Medium-High	Stationary	Low-Medium	Medium-Low
Spot	Low-Medium	Partially Mobile	Medium-High	Medium-Low
Micro-Climate	Low	Fully Mobile	Maximum	Low

Table 1: Cooling system ability comparison

Cooling System	Advantages	Disadvantages
Surface Bulk Cooling	Provides the greatest amount of cooling	Limited by the depth of the mine
Underground Bulk Cooling	Generates the largest amount of cooling capable underground	Must reject heat to a return airway or through return waterlines to the surface
Ice Storage	Utilizes natural cooling processes to reduce operating costs	Limited to cold climates
Spot	Mitigates heat in localized areas	Must reject heat to a return airway or through return waterlines to the surface
Micro-Climate	Cools area directly around the mine worker	Workers are unable to always remain in air conditioned cabs Current cooling garments aren't optimal for use in the mine environment

Table 2: Cooling systems - advantages and disadvantages

As shown in Table 1 and Table 2, each cooling system provides a unique set of capabilities which can be utilized by a mine in order to reduce its heat load. Though a single system may be able to reduce the heat load to appropriate levels, a cooling system strategy is often developed based on multiple systems. As the mine continues to deepen and becomes increasingly mechanized, more cooling is implemented by upgrading the current cooling infrastructure and/or by implementing more or other cooling systems. Most often, surface bulk air cooling is utilized solely or first when implementing cooling due to its large cooling capacity, ease of maintenance, and lower installation costs relative to underground cooling infrastructure (van den Berg, Funnell, & Bluhm, 2013). This is only the case when the mine design allows for the chilled air to be directly moved

to specific areas underground experiencing excess heat. Other cooling methods would need to be employed if the chilled air from the surface BAC system is unable to reach these regions or the mining depth and associated geothermic gradient is too large for a surface BAC system to be efficient (Brake, 2001).

In 1998 in South Africa, a hierarchy of cooling systems was established to provide a basic structure for the phases of implementation of cooling methods as a mine's depth increases (Ramsden et al., 2007). This hierarchy, which is shown in Figure 6, has been referenced and revisited multiple times in various publications (Brake, 2012; Hooman et al., 2015; Mackay et al., 2010; Ramsden et al., 2007; Roman et al., 2013; Kamyar et al., 2016).

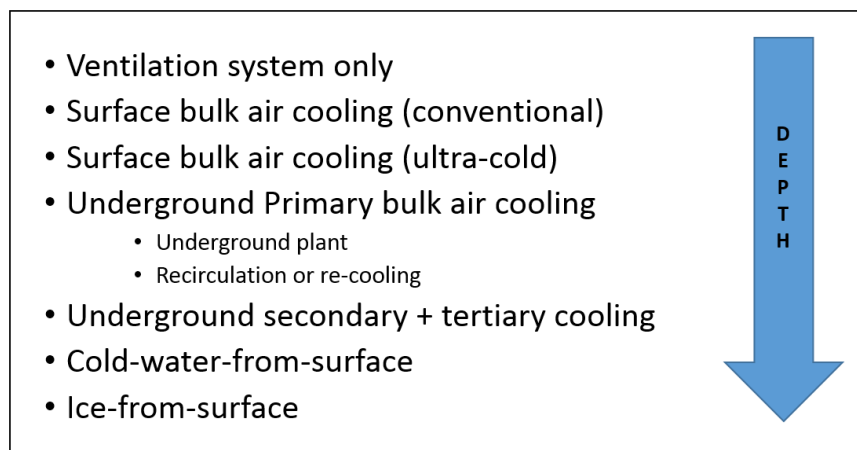


Figure 6: Hierarchy of mine air cooling at depth (Ramsden et al., 2007)

Figure 6 shows a broad chart outlining the phases of cooling methods which can be employed as the mining depth increases. This starts with the ventilation system alone and transitions through both central cooling and spot cooling systems. For example, as the mining depth increases, this chart recommends the use of an underground primary bulk air cooling system before employing a “cold-water- from-surface” cooling system.

Furthermore, a revised version of this generic hierarchy chart recommends the use of “cold-water- from-surface” cooling systems before installing an underground refrigeration plant in deep mines (Mackay et al., 2010). The generic hierarchy of cooling systems as function of depth is not perfectly valid for all mine sites as other important parameters may call for a different order of implementation. However, this hierarchy chart provides a very useful blueprint for how an underground mine may approach its cooling strategies and needs.

Ventilation and artificial cooling are both effective strategies used to reduce the heat load underground. However, these strategies may not always remove the heat that is being put in the system. To effectively reduce the heat load, means to regulate the sources of heat should also be investigated. One such source being heat generated from equipment engines.

Diesel Engines versus Battery Powered Equipment

The diesel engine generates a number of contaminants when operating in an underground mine due to the nature of the internal combustion engine. A report by the International Council on Clean Transportation found that heavy diesel engines used in the trucking industry are averaging 43% to 44% engine efficiency based on 2013-2014 certified engines of at least 400 horsepower or 298.28 KW (Delgado & Lutsey, 2015). Mining equipment such as LHDs and haul trucks use diesel engines that are comparable to those used in the trucking industry to meet material handling needs in underground mines. However, the trucking industry mainly operates on highways, which involve consistent high speeds with less accelerating and braking. Underground mining

equipment, on the other hand, sees a significant amount of accelerating, braking, and idling resulting in lower energy efficiencies for the diesel engines that power LHDs and haul trucks underground (Underground Mining Battery Electric Vehicles Working Group, 2016; Paraszczak, Svedlund, Fytas & Laflamme, 2014). As a consequence of the inefficiencies given such large diesel engines, a significant amount of heat is exhausted into the mine environment. Excessive heat can raise the ambient temperature above what is safe for the presence of mine workers. Additional ventilation or artificial cooling must be provided in order to reduce the heat load and maintain appropriate climatic conditions.

Another disadvantage of the diesel engine is its production of diesel particulate matter (DPM). When diesel fuel completely combusts it yields carbon dioxide and water vapor. However, engine combustion efficiency isn't 100% (Ristovski et al., 2012). Because of this, diesel engines also emit nitrogen, carbon monoxide, oxides of nitrogen, sulphur dioxide and DPM. Unused fuel, soot, and aldehydes make up DPM. These particles are a mixture of both liquid and solid particles suspended in a gas. The composition, concentration and size of particles vary based on the type of fuel used, lubricants used, atmospheric conditions, engine specifications, particle filters used, maintenance, and fuel to air injection ratio (McPherson, 2009). Because the particles are often less than 1 micron (.0000394 inches) in diameter, they are able to diffuse themselves through the walls of the alveoli. Lung inflammation is the body's immune response to these toxins in its attempt to remove them. As the DPM cannot be removed, the lungs suffer from chronic inflammation. Because of this failure of the immune system, continued lung inflammation allows other pathogens access to sites in the lungs where they would otherwise not be found (Ristovski et al., 2012). To combat this, more

airflow must be supplied where diesel engines are present in order to dilute the DPM and remove it from the mine environment.

The continued mechanization of mines has led to increased adoption of larger diesel engines underground. As a consequence, ventilation demands have increased and so have operating costs to meet this demand. Safety has also been stressed as a concern as higher temperatures and increased DPM concentrations pose a threat to mine workers. Because of this, we should explore safer and more economic alternatives in respect to material handling underground, while reducing DPM. One such option which would relieve the mine environment of DPM and reduce the heat load dramatically is the battery powered mining equipment (Bétournay et al, 2005). Underground haul trucks and LHDs can run off of an electric engine powered by a rechargeable battery. Commercially available batteries currently on the market last four hours before requiring a recharge. A battery recharge takes two hours, but this can be alleviated by swapping out a spent battery for a fresh battery. This process takes less than 15 minutes (Atlas Copco, 2017).

Battery powered mining equipment have a higher mechanical power efficiency than diesel engines (Paraszczak et al., 2014; Bétournay et al., 2005). For example, electric LHDs require reduced powered engines to obtain the same output as a higher powered diesel engine. As a result, electric LHDs consume less energy (Salama, Greberg, Skawina & Gustafson, 2015). The internal combustion engines of diesel equipment have an overall efficiency of one-third of that achieved by electrical units. Hence, diesels will produce approximately 3 times as much heat as electrical equipment of the same mechanical output. Another important difference between diesel and electrical equipment is that diesels produce part of its heat output in the form of latent heat. Each liter of diesel

fuel that is consumed produces approximately 1.1 liter (0.29 gallons) of water (liquid equivalent) in the exhaust gases. This may be multiplied several times over by the evaporation of water from cooling systems and where water is employed in emission control systems. Underground tests have shown that the factor of 1 liter of diesel fuel consumed can generate as much as 3 - 10 liters (0.93 – 2.64 gallons) of water (liquid equivalent), depending on the design of the engine, exhaust treatment and maintenance schedule (McPherson, 2009)

For example, the Caterpillar R1600H is a 208 KW diesel LHD with a bucket capacity of 5.5 yds³ to 7.7 yds³ and loading capacity of 10,200 kg (22,487 lbs) (Caterpillar, n.d.). The RDH Muckmaster 600 EB is only a 149 KW battery electric LHD but its bucket capacity is 3.4 m³ to 5.4 m³ (4.4 yds³ to 7 yds³) and loading capacity of 11,000 kg (24,250 lbs) (RDH Equipment, n.d.). As a result of the higher mechanical power efficiency, significantly less heat is generated by the battery electric engine. Likewise, no internal combustion occurs with a battery electric engine meaning DPM isn't generated. These traits make battery powered mining equipment a viable alternative to diesel equipment.

Multiple studies have been done to compare cost savings of using a diesel engine fleet versus a battery/electric fleet. Salama (2015) analyzed energy consumption and gas emissions of electric versus LHDs underground. Righettini & Mousset-Jones (2004) as well as Bétournay et al. (2005) created simulations to determine the ventilation cost savings of removing DPM by switching from a diesel engine fleet to a fuelcell fleet at multiple mines. A more recent study, which was performed by Allen and Stachulak (2016) compared ventilation cost savings due to both heat load and DPM reduction. What

all these studies show is that there is a significant economic incentive for underground mine operators to switch to a battery powered equipment fleet in order to reduce the operating costs. For the sake of investigating strategies to reduce the heat load, this study also compared scenarios which used diesel and battery powered mining equipment.

Methodology

For this study, multiple cooling strategies and heat reduction practices were investigated. These strategies included: (1) baseline, (2) a new shaft, (3) increased airflow, (4) artificial cooling by surface bulk air cooling (BAC), and (5) switching from a diesel engine fleet to a battery powered equipment fleet. All of the strategies were investigated by generating different scenarios for the ventilation model at one of our partner mines. The scenarios were then run and compared in VenstimTM. VentsimTM is a 3D underground mine ventilation software produced by Chasm, which was acquired by Howden. It is used to model ventilation systems and simulate distribution of ventilation parameters such as airflows, pressures, humidity, temperature, contaminants, mire fire, and much more (Howden, 2017). For this study, VentsimTM was used to simulate ventilation parameters and compare various mine operation scenarios based on airflow distribution, climatic parameters, and ventilation operating costs.

The partner mine is an underground, metal mine located in northern Nevada. The dry climate and high elevation at 5,384 feet (1641 meters) give the intake air a wide seasonal variance. July, the hottest month of the year, sees highs on average of 93°F T_d (33.9°C T_d) during the day and lows on average of 52°F T_d (11.1°C T_d) during the night. December, the coldest month of the year, sees highs on average of 41°F (5.0°C) during

the day and lows on average of 17°F (-8.3°C) during the evening (“Climate Winnemucca - Nevada,” n.d.). For modeling purposes, an average was taken of the average high and low for July. The surface temperature is assumed to be 72.6°F T_d (22.6°C T_d) and 56.5°F T_w (13.6°C T_w) to simulate average conditions during the hotter summer months. The humidity is assumed to be 35.7% to reflect the dry air in northern Nevada.

The mine is accessed through two 20-foot (6 m) diameter shafts, which provide 533,500 cfm (252 m³/s) of air using an exhausting system. Two exhaust fans are located at the top of Shaft No. 1, while Shaft No. 2 is the intake production shaft. The network of airways includes drifts, ramps, shafts, and raises to deliver air to the working areas as far as 2,668 feet (813.2 m) below the surface. For the purposes of this study, the auxiliary system, which includes stope accesses, ducting, and auxiliary fans, is not included to simplify the model. There are 17 primary fans in the system, which range in size from 35.5 inches to 108 inches (0.90 m to 2.74 m) with input powers ranging from 6.3 HP to 465.9 HP (4.7 KW to 347.4 KW) as shown in the appendix. This ventilation network and fans are considered to be the “baseline” scenario. The baseline scenario is referred to as Scenario #1 for this study.

The baseline scenario was validated through previous work performed at the partner mine. This included ventilation and climatic data collection, continuous climatic monitoring and modeling. This data was used to quantify the heat loads and associated temperatures in the production workings and throughout the mine. These allowed for the amounts of heat generated from various heat sources to be quantified (Roghanchi, 2017). This data was used to ensure that the airflow distribution and temperature values in the baseline scenario were validated.

A total of five scenarios were modeled with varying parameters and layouts as illustrated in Table 3. The difference in layout comes from the employment of a new shaft. Scenario #2 and Scenario #3 involve implementing this new, 24-foot (7.3 m) diameter shaft referred to as Shaft No. 3. This new intake shaft is 1,929 feet (588.0 m) deep and includes a 3,924 foot (1196 m) long access ramp. Shaft No. 1 was kept as an exhaust airway, and Shaft No. 2 remained an intake airway in order to keep potential airflow reversals in the primary system to a minimum for Scenario #2 and Scenario #3. Scenario #2 and Scenario #3 have some fans turned off and some fan curves changed in order to at least meet the airflows in Scenario #1. These changes can be seen in the appendix.

The fans, their locations, configurations, and fan curves in Scenario #1 will be kept the same for Scenario #2 to show the effects of creating a new source of air to the underground mine workings but without increasing airflow through the top of Shaft No. 1. The exhausting airflow volume for Scenario #2 will increase due to reduced mine resistance caused by sinking the new shaft. The mine total air volumes are presented in Table 3. Any fans which are no longer needed for providing the required air volumes will be turned off as shown in the appendix. For Scenario #3, the amount of exhaust air out of Shaft No. 1 will be increased by 35% to 807,300 cfm (379.4 m³/s). This was done in order to show the effect a new shaft with increased airflows through the mine would exert in respect to the heat load. Fans were turned off or their fan curves were changed in order to accommodate this airflows. The results of this can be seen in the appendix.

Scenario #4 did not use a third ventilation shaft but instead used a surface BAC installed at the top of Shaft No. 2 for artificial cooling. This surface BAC provides

170,607 Btu/min (3,000 KW) cooling to reduce the effects of heat generation from mining equipment, fans, strata, and auto-compression. The 170,607 Btu/min (3,000 KW) BAC would reduce the intake air temperatures to decrease the temperature through the underground workings. This cooling system reduces the T_d from 72.6°F T_d (22.6°C T_d) and 56.5°F T_w (13.6°C T_w) to 54.8°F T_d (12.7°C T_d) and 49.0°F T_w (9.4°C T_w). Humidity increases from 35.7% to 66.7% due to the spray chambers within the surface BAC. Scenario #4 has the same fans and fan curves as the baseline scenario as the airflows remain the same. The operating costs of the artificial cooling system are included in the cost analysis along with fan operating costs.

Scenario	Fleet	Shafts	Airflow		Surface BAC
			kcfm	m ³ /s	
#1	Diesel	2	533.5	250.7	No
#2	Diesel	3	558.7	262.6	No
#3	Diesel	3	807.3	379.4	No
#4	Diesel	2	533.5	250.7	Yes
#5	Battery	2	346.8	163.0	No

Table 3: Model scenarios

The equipment included in the model comprises LHDs and haul trucks for materials handling which produce heat. Scenario #1, Scenario #2, Scenario #3, and Scenario #4 used diesel equipment fleets. Scenario #5 used battery powered equipment fleet. Scenario #5 reflects the baseline scenario with the initial ventilation design and fans. The diesel engine scenarios and battery powered equipment scenarios were each assigned two LHDs and two haul trucks with comparable capacities. The engine types, engine power, nominal payload capacities, bucket sizes for the LHDs can be seen in Table 4 and Table 5. Only production LHDs and haul trucks were considered as they

operate as scheduled, and they generate significantly more heat than other support equipment due to their larger engines. Other support equipment such as drill jumbos, man carriers, ANFO loaders, scissor lifts, etc. use smaller engines and significantly lower utilization factors as per their support capacities. As such, support equipment was not included in this model.

The Caterpillar AD30 haul truck and CAT R1600H LHD were selected for the diesel engine scenario (Caterpillar, n.d.; “R1600H Underground Mining Loader,” n.d.). Both were chosen to reflect the current engine fleet at the partner mine. The RDH Muckmaster 600 EB LHD and a “Conceptual” haul truck were chosen for the battery powered equipment scenario. The Conceptual haul truck was used as there are no 30 tonne (66,139 lb) battery powered underground haul trucks available on the market. Currently, there are only two with different specifications available on the global market: the RDH Haulmaster 800-20 EB and the Artisan Z40. These have a nominal payload of 20 tonnes (44,092 lbs) and 40 tonnes (88,185 lbs) respectively (RDH Equipment, n.d.; Mayhew, 2018). For this reason, an average was taken of the two battery powered haul trucks’ engine powers and nominal payloads to create the Conceptual haul truck.

Haul Truck	Engine	Nominal Payload		Power	
		lbs.	kg	HP	KW
CAT AD30	Diesel	66,139	30,000	409	305
RDH Haulmaster 800-20EB	Battery	44,092	20,000	300	224
Conceptual	Battery	66,139	30,000	450	336
Artisan Z40	Battery	88,185	40,000	600	447

Table 4: Haul truck fleet comparison

LHD	Bucket Volume		Nominal Payload		Power	
	yd ³	m ³	lbs.	kg	HP	KW
CAT R1600H	5.5 to 7.7	4.2 to 5.9	22,487	10,200	279	208
RDH Muckmaster 600 EB	4.4 to 7.1	3.4 to 5.4	24,251	11,000	149	111

Table 5: LHD fleet comparison

For each scenario, the haul trucks and LHDs were assigned to specific locations in the mine in respect to heat generation. The quantity of heat generation depended on whether the engine is diesel or electric. For battery powered equipment, a mechanical efficiency of 73% is assumed to account for losses from battery heat loss, power electronics losses, electric motor losses, the drop box and the axles. The 27% efficiency loss results in the energy being exhausted to the ventilating air as sensible heat. For diesel engines, a mechanical efficiency of 35% is assumed to account for losses from charge air cooling, exhaust gases, heat to coolant, engine friction, the torque converter, the gear box, and the axles. The 65% efficiency loss results in energy being exhausted to the ventilating air as both sensible heat and latent heat due to the moisture that is also produced from the combustion of diesel fuel (Conklin, 2017). This heat exhaust is accounted for in VentsimTM.

As Scenario #5 is utilizing a battery powered equipment fleet, the heat load will be reduced in comparison to the diesel equipment fleet used in the other scenarios. When using the same airflows as in the baseline scenario, the temperatures throughout the mine are reduced. To show the economic benefits of this, the airflow is reduced in Scenario #5 so underground mine temperatures are closer to that of Scenario #1. The amount of air exhausted through Shaft No. 1 was reduced by 35% to 346.8 kcfm (163.0 m³/s), as shown

in Table 3. The fan curves for other fans were adjusted to account for the reduction in airflow and can be seen in the appendix.

VentsimTM is used to create a thermodynamic model representing the heat sources from auto-compression, strata heat, the fans, and the equipment fleets. This can calculate the heat load as well as the T_d and T_w temperatures at any location in the mine. The thermodynamic model is run for each of the above mentioned scenarios in order to compare the effectiveness of the different heat management strategies. The scenarios are also compared based on the associated operating costs at \$0.07/KWh from the fans and surface bulk air cooling. Analyzing these results will show what the best practices are from the perspective of both cost and safety and health considerations.

Results

The engine heat was determined based on the number of specific equipment used in each scenario. The engine efficiencies, percent utilization, and VentsimTM heat calculator were used to determine a total heat load as shown in Table 6 and Table 7. The battery powered equipment scenarios have a lower total heat generation than the diesel equipment scenarios because of their superior engine efficiency. As a result, the battery powered equipment fleet produces 59,161 Btu/min (1,040 KW), while the diesel equipment fleet produces 141,742 Btu/min (2,492 KW). This is a reduction of 58%.

Equipment	Engine	Engine Efficiency	Max Rated Power		Utilization	Average Engine Output	
			HP	KW		HP	KW
CAT AD30 Haul Truck	Diesel	35%	409	305	85%	347.7	259.2
Conceptual Haul Truck	Battery/Electric	73%	450	336	85%	382.5	285.2
CAT R1600H LHD	Diesel	35%	279	208	85%	237.2	176.8
RDH Muckmaster 600 EB LHD	Battery/Electric	73%	149	111	85%	126.7	94.4

Table 6: Equipment parameters for determining total heat exhaust

Equipment	Sensible Heat		Latent Heat		Number of Equipment	Total Heat	
	Btu/min	KW	Btu/min	KW		Btu/min	KW
CAT AD30 Haul Truck	27,077	476	15,053	265	2	84,260	1,482
Conceptual Haul Truck	22,223	391	0	0	2	44,445	782
CAT R1600H LHD	18,472	325	10,269	181	2	57,482	1,011
RDH Muckmaster 600 EB LHD	7,358	129	0	0	2	14,716	259

Table 7: Equipment total heat exhaust

Primary and auxiliary fans also produce heat due to the electric motors which power them. The same fans were used for each of the scenarios. During simulation exercises the fans operating point (Q, P) were changed by varying the blade angles, which generated better characteristic curves in respect to airflow and pressure generation, or they were even turned off to maintain airflows similar to the baseline scenario. The fans, airflow quantities, fan curves, pressures and associated operating cost can be seen in the appendix. The subsequent total heat generation from these fans is shown in Table 8.

It should be noted that the surface exhausting fans are not included in the total fan heat generation for each scenario as this heat is exhausted directly to the atmosphere as the fans are located on the surface.

As previously mentioned, the artificial cooling scenario had no changes to the ventilation design, airflows, or fans. Because of this, Scenario #1 and Scenario #4 have the same fan heat generation of 5,929 Btu/min (104 KW). Scenario #2 involved a new shaft with similar airflows to the baseline scenarios. Without increasing airflow, fan heat generation dropped to 5,110 Btu/min (90 KW) as a result of the new shaft and two fans being turned off. This is a decrease of 13.8%. As for Scenario #3, the fan heat generation decreased to 4,873 Btu/min (86 KW) as the surface exhaust fans were pulling so much more air that additional fans were turned off in the ventilation system and fan curves were adjusted. Scenario #5 used underground fans generating 5,869 Btu/min (103 KW). This was a decrease in fan heat generation of 1% from the baseline scenario.

Fans	Scenario #1		Scenario #2		Scenarios #3		Scenario #4		Scenario #5	
	Btu/min	kW	Btu/min	kW	Btu/min	kW	Btu/min	kW	Btu/min	kW
Fan 02	937	16.5	963	16.9	1,154	20.3	937	16.5	937	16.5
Fan 03	267	4.7	OFF	OFF	OFF	OFF	267	4.7	369	6.5
Fan 04	517	9.1	458	8.1	377	6.6	517	9.1	517	9.1
Fan 05	1,845	32.4	1,624	28.6	1,395	24.5	1,845	32.4	1,951	34.3
Fan 06	267	4.7	297	5.2	318	5.6	267	4.7	267	4.7
Fan 07	687	12.1	670	11.8	941	16.6	687	12.1	653	11.5
Fan 08	288	5.1	OFF	OFF	OFF	OFF	288	5.1	424	7.5
Fan 09	441	7.8	424	7.5	OFF	OFF	441	7.8	293	5.1
Fan 10	679	11.9	674	11.9	687	12.1	679	11.9	458	8.1
	5,929	104	5,110	90	4,873	86	5,929	104	5,869	103

Table 8: Fan heat generation

The equipment and fan heat generation were used in the model to determine both the strata heat generation and heat from auto-compression. The rock properties used in the model to determine the strata heat generation can be found in the appendix. The VentsimTM results for total heat gain are shown in Table 9 and Table 10. The heat generation between the scenarios is visualized in the bar graphs located in the appendix. It should be noted that the exhaust fan heat generation is not included, as the exhaust fans are located on the surface.

The artificial cooling scenario which utilized a surface BAC has the second highest heat gains. This is Scenario #4. It is a result of increased strata heat generation due to the lower air temperatures entering the mine. Decreasing the temperature of the intake air will increase the heat flow from the strata (Brake, 2001). Had the air flows not been lowered in Scenario #5, the battery powered equipment scenario, similar effects would have also occurred, as heat would have been transferred from strata as a result of lower air temperatures underground, but at a lower rate as in Scenario #4.

The scenarios which incorporated a new shaft experienced greater heat generation due to auto-compression compared to the other scenarios. Scenario #2 only saw moderate increases of roughly 15,000 Btu/min (264 KW) from the baseline scenarios due to the third shaft with little additional exhaust airflow. Scenario #3 saw significantly higher increases of roughly 69,000 Btu/min (1,213 KW) more than the baseline scenarios due to the third shaft and increased exhaust airflow. The heat generation in Scenario #4 saw values higher than Scenario #2 but lower than Scenario #3. The artificial cooling scenario is different as no extra heat is generated from auto-compression as the fan powers and

mine design remain the same. However, the heat generation from strata is the largest for Scenario #4 due to high temperature differential between the wall rock and the intake air.

The battery powered equipment scenario, Scenario #5, had the lowest total heat gains. This is because of the reduction in heat generated by equipment and reduction of heat generated from auto-compression. The decrease in total heat generation is a direct result of the 58% decrease in heat generation between the equipment fleets and the reduced airflows. As a result, the heat generation in Scenario #5 is 31% lower than Scenario #1.

An important phenomenon to note is that the total heat gains in an underground mine don't exactly correlate to the total heat removed by ventilation or artificial cooling. For example, the installation of the new shaft will allow the movement of an increased air volume through the mine in order to remove the heat generated from various heat sources (e.g. auto-compression, strata, mining equipment). The total heat gain in Scenario #3 where the intake air volume was increased by 34% is deceiving due to the fact that intake air enters the shaft at 72.6°F T_d (22.6°C T_d). Surface climatic data shows that during the night the intake temperature of the air entering the shaft is 52°F T_d (11.1°C T_d) and during the day is 93°F T_d (33.9°C T_d). Based upon this intake air temperature, the heat gain in Scenario #3 would be significantly less (night-time) or more (day-time) than the base scenario when providing a 34% increased air volume throughout the mine. The phenomenon of storing and releasing heat into the mine air by the strata during day-time and night-time, as well as during spring, summer, fall and winter is called the "*thermal flywheel effect*" (TFE) or the "*thermal damping effect*" (TDE), as heat is transferred to the strata during the day when the temperature of the intake air is 93°F T_d (33.9°C T_d) and

some amount is released back into the mine air during the night when the intake air temperature is 52°F T_d (11.1°C T_d). A mine ventilation program which has the ability to take into account the TFE or the TDE would show the immense benefits of adding a new shaft to the ventilation model, which in turn would allow to increase the mine's total intake air volume.

Heat Gains (Btu/min)					
Scenario	#1	#2	#3	#4	#5
Fans	5,929	5,110	4,873	5,929	5,869
Engines	141,742	141,742	141,742	141,742	59,158
Strata	121,352	134,112	141,735	150,467	120,292
Auto-compression	123,473	132,188	183,852	123,418	86,333
Total	392,495	413,152	472,202	421,555	271,652

Table 9: Total heat gains (Btu/min)

Heat Gains (KW)					
Scenario	#1	#2	#3	#4	#5
Fans	104.2	89.9	85.7	104.2	103.2
Engines	2,492.4	2,492.4	2,492.4	2,492.4	1,040.3
Strata	2,133.9	2,358.3	2,492.3	2,645.9	2,115.3
Auto-compression	2,171.2	2,324.4	3,232.9	2,170.2	1,518.1
Total	6,901.7	7,265.0	8,303.3	7,412.7	4,776.8

Table 10: Total heat gains (KW)

The total heat removed from the mine environment is measured by calculating the total heat flux between the intake and exhaust airways. This can be summarized in Table 11. The heat flux was calculated by determining the sigma heat at the intake and exhaust and using it in conjunction with the airflow volume and air density to determine the heat flux. The heat flux determines the heat which needs to be removed from the underground mine environment.

The results presented in Table 11 show is that in Scenario #5 the least amount of heat was removed. This is due to the lower air volumes and lack of artificial cooling. Scenario #2 removed 31% less heat than scenario #1 because less heat is generated. Comparatively, the scenarios with a new shaft (Scenario #2 and Scenario #3) and a Surface BAC (Scenario #4) removed more heat than the baseline scenario, but these scenarios also generated more heat than the baseline scenario.

Table 11 shows that by increasing the total intake air volume by 34% in Scenario #3, the amount of heat removed increases by 29% compared to Scenario #1. It should be again mentioned that the ventilation simulator does not take into account the “*thermal flywheel effect*” (TFE), and consequently cannot quantify the amount of heat that is temporarily stored in the strata, which at some point in time will be released back into the mine air as a function of the temperature of the mine air and the wall temperature of the airway, as well as any moisture that might be present on the wall.

Scenario	Heat Flux		Change from Baseline
	Btu/min	KW	
#1	193,359	3,400.1	-
#2	226,657	3,985.6	17%
#3	248,582	4,371.1	29%
#4	227,971	4,008.7	18%
#5	132,501	2,329.9	-31%

Table 11: Total heat flux

Temperature measurements were recorded from the model at important locations and displayed in Table 12. This included the T_d and T_w for all scenarios. The locations included the top of the intake shaft, the bottom of the intake shaft, the lowest point, outby a production drift, bottom of the exhaust shaft, and the top of the exhaust shaft before the

exhaust fans. The temperatures at the locations vary between each scenario due to the different cooling strategies and parameters. It should be noted that the temperatures at the top of Shaft No. 1 were taken before the surface exhaust fans. For Scenario #4, the temperatures at the top of Shaft No. 2 were taken after the air was chilled by the BAC.

Scenario #2 and Scenario #3 benefit from a new shaft as areas of the mine which previously took longer to supply air to would now receive fresher air through the use of the new shaft. As a result, the lowest point in the mine saw temperatures lower than Scenario #1, Scenario #5, and close to Scenario #4. Scenario #4 sees a decrease in temperatures due to the surface BAC, especially at locations closer to the intake shaft. Scenario #5 would see some of the lowest temperatures when compared to the other scenarios, if its air volumes had not been reduced. However, because these temperatures are close to those in the baseline scenario, the benefits come from operating cost savings as a function of reduced air volumes, while still maintaining safety standards in the production workings and throughout the mine.

Scenarios	#1	#2	#3	#4	#5
Units	T_w °F	T_w °F	T_w °F	T_w °F	T_w °F
Top Shaft No. 2	56.5	56.5	56.5	49	56.5
Bottom Shaft No. 2	62.2	62.9	62.2	55.5	62.9
Lowest Point	72.9	65	64.6	68.4	72.7
Outby Prod. Drift	74.2	72.7	70.1	69.9	72.8
Bottom Shaft No. 1	70.8	70.8	68.3	66.3	71.4
Top Shaft No. 1	80.3	80.2	78.7	75.4	78.4
Scenarios	#1	#2	#3	#4	#5
Units	T_d °F	T_d °F	T_d °F	T_d °F	T_d °F
Top Shaft No. 2	72.6	72.6	72.6	54.8	72.6
Bottom Shaft No. 2	78.8	78.8	78.8	64.3	78.8
Lowest Point	83.9	75.6	75	78.2	83.4
Outby Prod. Drift	86.5	84	80	80.3	85.5
Bottom Shaft No. 1	78.7	78.1	75.2	72.4	79.5
Top Shaft No. 1	68.3	67.9	91.8	61.9	69.3
Scenarios	#1	#2	#3	#4	#5
Units	T_w °C	T_w °C	T_w °C	T_w °C	T_w °C
Top Shaft No. 2	13.61	13.61	13.61	9.44	13.61
Bottom Shaft No. 2	16.78	17.17	16.78	13.06	17.17
Lowest Point	22.72	18.33	18.11	20.22	22.61
Outby Prod. Drift	23.44	22.61	21.17	21.06	22.67
Bottom Shaft No. 1	21.56	21.56	20.17	19.06	21.89
Top Shaft No. 1	18.83	18.83	29.11	16.11	19.22
Scenarios	#1	#2	#3	#4	#5
Units	T_d °C	T_d °C	T_d °C	T_d °C	T_d °C
Top Shaft No. 2	22.6	22.6	22.6	12.7	22.6
Bottom Shaft No. 2	26.0	26.0	26.0	17.9	26.0
Lowest Point	28.8	24.2	23.9	25.7	28.6
Outby Prod. Drift	30.3	28.9	26.7	26.8	29.7
Bottom Shaft No. 1	25.9	25.6	24.0	22.4	26.4
Top Shaft No. 1	20.2	19.9	33.2	16.6	20.7

Table 12: Underground location temperatures

In the case of mine heat reductions strategies that were investigated, no benefit comes without a cost. The worst culprit of this is the artificial cooling scenarios as shown in Table 13 and Figure 7. Table 13 displays the power and corresponding yearly

operating costs for each scenario. Figure 7 has a visual representation of the yearly operating costs to assess the scale of the costs when compared. What the operating cost results show is that the surface BAC shows poor returns in comparison to all other scenarios. Scenario #3 has similar underground temperatures to Scenario #4 due to the new shaft and increased airflows, but the operating cost is 39% less than the artificial cooling scenario. For the mine considered in this study, it would be difficult to justify using artificial cooling when taking into account capital costs. This includes the cost of installing a surface BAC and a refrigeration plant. Nonetheless, the cost of artificial cooling may be justified for other mines and scenarios when ventilation alone cannot meet threshold temperatures.

Scenario #2 does have benefits over Scenario #1 and Scenario #3 due to its lower operating costs as a result of the lower mine air resistance. This is because the new shaft would reduce ventilation costs if the same exhausting fans as in the baseline scenario were utilized. However, this scenario sees the least amount of heat reduction benefits with the TFE not accounted throughout the heat transfer processes. The same can be said for Scenario #3 which saw the operating costs nearly double from the baseline scenario. For these scenarios, the increase in operating cost is also the result of an increased air volume which is handled by the surface fans, as there is a cubic relationship between the fan power and the air volume ($P \sim Q^3$). Also, like the artificial cooling scenarios, the capital costs are not included in this study. This includes the sinking and construction of a new shaft.

One of the most beneficial scenarios solely based on operating costs would be Scenario #5. As the air volumes were decreased, the operating costs were reduced by

50% or \$150,000 per year. This equates to significant cost savings over the life of the mine. Though, like in the other scenarios the capital costs were not considered. In this case that would be the cost of a battery powered equipment fleet. Although, this cost can be justified by quantifying the ventilation operating cost savings and employing the battery powered fleet the diesel equipment fleet needs replacing. Battery powered equipment fleets would also allow for lower mine air temperatures to be reached if required. However, one of the most important considerations that the costs based analysis leaves out are the health and safety benefits to mine workers. By reducing the heat load and removing DPM from the work place, battery powered equipment creates a healthier work environment in underground mines.

Scenario	Fan Power Input		Artificial Cooling Power Input		Ventilation Costs	Cooling Costs	Total Operating Costs
	HP	KW	HP	KW	USD/year	USD/year	USD/year
#1	630.2	469.9	0.0	0.0	\$300,596	-	\$300,596
#2	560.1	417.7	0.0	0.0	\$267,122	-	\$267,122
#3	1093	815.1	0.0	0.0	\$521,217	-	\$521,217
#4	630.2	469.9	4023.1	3000.0	\$300,596	\$548,322	\$848,918
#5	316.3	235.9	0.0	0.0	\$150,921	-	\$150,921

Table 13: Fan and artificial cooling operating costs

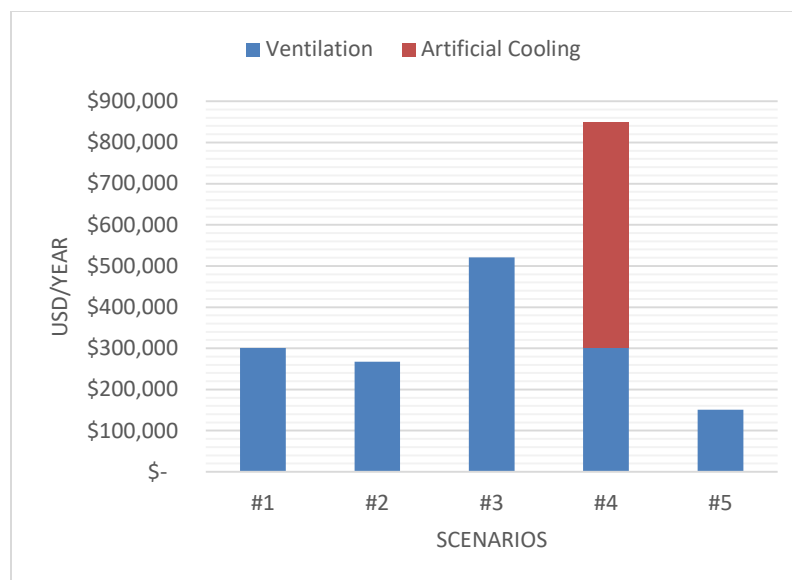


Figure 7: Scenario operating costs

Discussion

Though this research shows the effectiveness of different heat reduction strategies, a thermal management program should still be established for the mine workers. Such programs create T_w and T_d ranges which require specific actions in order to keep mine workers safe. At certain temperatures this may include work-rest cycles and mandated hydration requirements using water or sport drinks. At higher temperatures, mine personnel may be completely prevented from working in certain areas. For new employees, it is important that they become acclimated to the extreme conditions in the mine environment which they don't normally encounter. New miners are significantly more likely to succumb to heat related illness, injury, or death without proper acclimatization.

To create these thermal management policies, temperature thresholds must be established based on heat indices. Heat indices are used to assess the condition of a mine

worker in a work area based on environmental, physiological, and personal parameters. This is used to quantify the temperature thresholds for mine workers (Roghanchi & Kocsis, 2017). With a temperature threshold established, not only can thermal management practices be put in place but the mine can design the heat reduction strategies around meeting these threshold temperatures.

Though the operating costs are a great means of comparing the economic viability of the heat reduction strategies, an important consideration which this study did not investigate is capital costs. This is difficult to account for as the level of detail involved in estimating the cost of sinking a shaft and installation of a head frame, hoist house, ventilation fans, surface BAC, refrigeration plant, and more are tremendous. These capital costs can amount to millions of dollars and must be carefully considered as they can't be generalized. The estimation can be done, but mines that have done similar practices can also be compared.

For example, Newmont Mining Corporation's Leeville underground mine site is located in northern Nevada and recently began operating its new production shaft capable of moving 2,600,000 cfm (1,227 m³/s) of air. Construction began in 2012 and commissioned its new Turf No. 3 shaft in February 2016 at a total cost of \$360 million. These costs included special problems and designs such as using ground freezing techniques during shaft sinking and installing a special airlock at the top of the shaft to prevent conveyance from interrupting airflow. Other costs were associated with the planning, man power, and upgrades required accounting for the change in airflow direction within the mine while still maintaining production. Though it was a significant investment, the massive amount of fresh air being provided closer to active workings

reduced the heat load and DPM concentration allowing for increased production and expanded exploration (McKown, 2016; Carter, 2016). By installing a new shaft not only were the heat reduction needs met but many more benefits were gained.

Newmont Mining Corporation's new shaft is a recent, local example for what the partner mine in this study could be compared to. Unfortunately, such examples of artificial cooling such as a surface BAC are uncommon in the United States. The nearest, most recent example would be the Resolution Copper underground, block cave, copper mine in Superior, Arizona. Due to the mine's geothermal gradient and rock thermal properties, at 7,000 feet (2,133.6 m) depth, the virgin rock temperatures reaches over 176°F (80°C). To counteract this, there is an artificial cooling capacity of 187,743 HP (140 MW) onsite and 6,356,700 cfm (3,000 m³/s) of fresh air supplied underground, once the mine is fully operational (Bluhm, Moreby, von Glehn, & Pascoe, 2014). Currently the mine is in the process of extending the No. 9 shaft after having finished the No. 10 shaft. The current artificial cooling system consists of a 10,326 HP (7.7 MW) surface bulk air cooler cable of chilling air to 42.8°F T_w (6°C T_w) and a chilled service water system running at 63.4 gpm (4 liters/s) and chilled to temperatures of 49.2°F (4°C). The chilled service water is used for drilling, washing, and muck cooling during the initial development of the mine (BBE Morvent, 2012). Initially, the cost of installing the chilled service water system was \$10 million ("Resolution Copper Mine", n.d.). But issues with heat and mine worker safety required \$4 million in improvements ("Resolution Copper Awards", 2014). Costs of the surface BAC were unavailable.

Unfortunately, there is a lack of data available on the cost of currently existing artificial cooling infrastructure. This comes as little surprise, as it is often proprietary

information. However, leaders from Bluhm Burton Engineering (BBE) estimated what it could be. BBE is a worldwide consulting firm which specializes in both ventilation and artificial cooling systems. Based on their wide range of recent surface BAC projects, they estimated that the capital costs would be between \$600/HP to \$900/HP (\$800/KW to \$1200/KW). This highly ranges due to the economy of scale, cooling system mechanics, and more (van den Berg et al., 2013). For the partner mine studied in this project, this would come out to \$3.14-\$4.71 million dollars. Nevertheless, this is merely an estimate and doesn't truly quantify what the cost would be today in a country which sees little artificial cooling in underground mines.

Though estimating the cost of shafts and artificial cooling have their pitfalls, estimating the cost of the equipment fleets do as well. Diesel equipment fleets are not a problem as equipment manufacturers are plentiful for a wide range of mining needs. Battery powered equipment on the other hand lack such a variety of options as they are still an emerging technology. Battery powered LHDs have seen a greater growth as a smaller motor can be used to power it in comparison to diesel engine LHDs (Salama et al., 2015). Battery powered haul trucks on the other hand are extremely limited. There are only two haul trucks available on the market, the RDH Muckmaster EB 20 and the Artisan Z40. This is due to the nature of materials handling in mining, which requires heavy loads to be hauled up steep grades. Because of this, battery powered equipment is still limited despite their benefits when compared to diesel equipment fleets.

Every scenario is by no means a perfect alternative to the baseline scenario for the partner mine in this study. The same goes for other underground mines which will vary based on factors which include the heat load, geographic location, employed mining

method, the material handling system, mine layout, state/federal regulation, economic constraints and more (Walt, Pye, Pieterse, & Dionne, 1996). Other artificial cooling methods can also be investigated as surface BAC can be complimented with underground BACs and spot coolers. No matter the means of heat reduction, the goal still stands to reduce the heat load to protect the mine worker.

All though this work reviews the effectiveness of various heat reduction strategies and methods for the partner mine, there is still more work that can be done. For the partner mine alone, further scenarios can be investigated. This includes utilizing spot cooling systems in areas of the mine which experience higher heat loads such as the production workings. Other considerations include using different intake temperatures to determine the resulting temperatures underground at different times of the day or year depending on the seasons. Another option for future work, which would be beneficial for this area of research would be to assess the efficiency of these cooling methods and strategies at other mines which operate at greater depth, employ larger scale mining methods, and different material handling systems. Doing so would give a greater representation of how mine cooling systems and mine ventilation strategies can be applied in deep and hot U.S. mines.

Conclusions

Underground mine heat reduction strategies are an immensely important consideration going into the future as mines become deeper and more productive. Mine operators need to ensure that mine workers aren't exposed to unsafe temperature and humidity conditions in order to reduce the risk for heat related illness, injury or death.

Doing so means utilizing heat mitigation methods and strategies. This includes supplying increased air volumes, applying artificial cooling, or reducing the sources of heat generation such as with more efficient and zero emission battery powered mining equipment. These strategies may be individually applied or used in conjunction. Though some strategies provide more cooling than others, they come at a cost due to the electricity used and infrastructure installations. Other factors such as materials handling, mine life, and employed mining method should also be considered. The required cooling, costs, and factors should all be major considerations by the mine operator when investigating means to reduce the heat load underground. It may be costly, but in the end it serves the most important goal on a mine site - protecting the mine worker.

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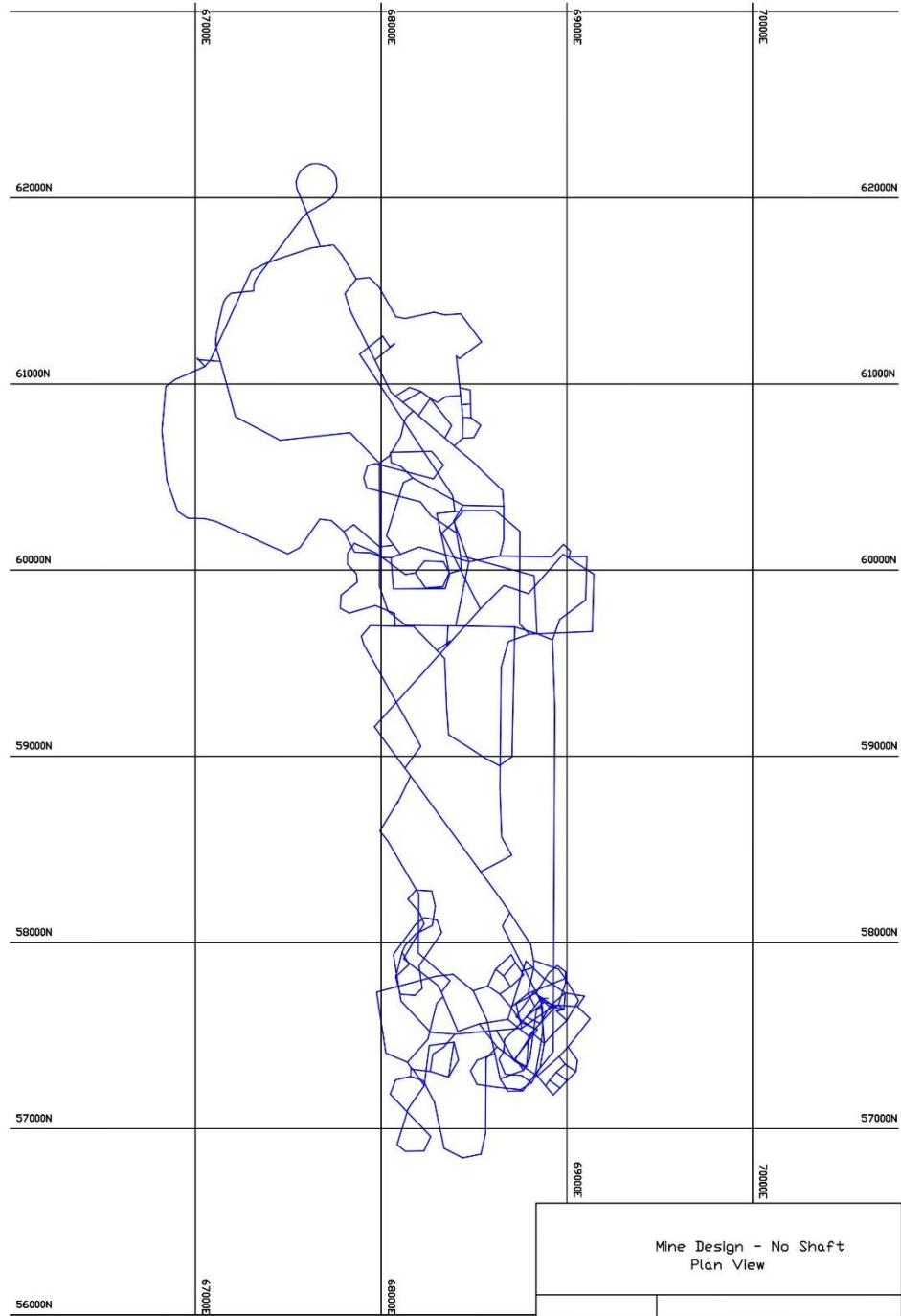
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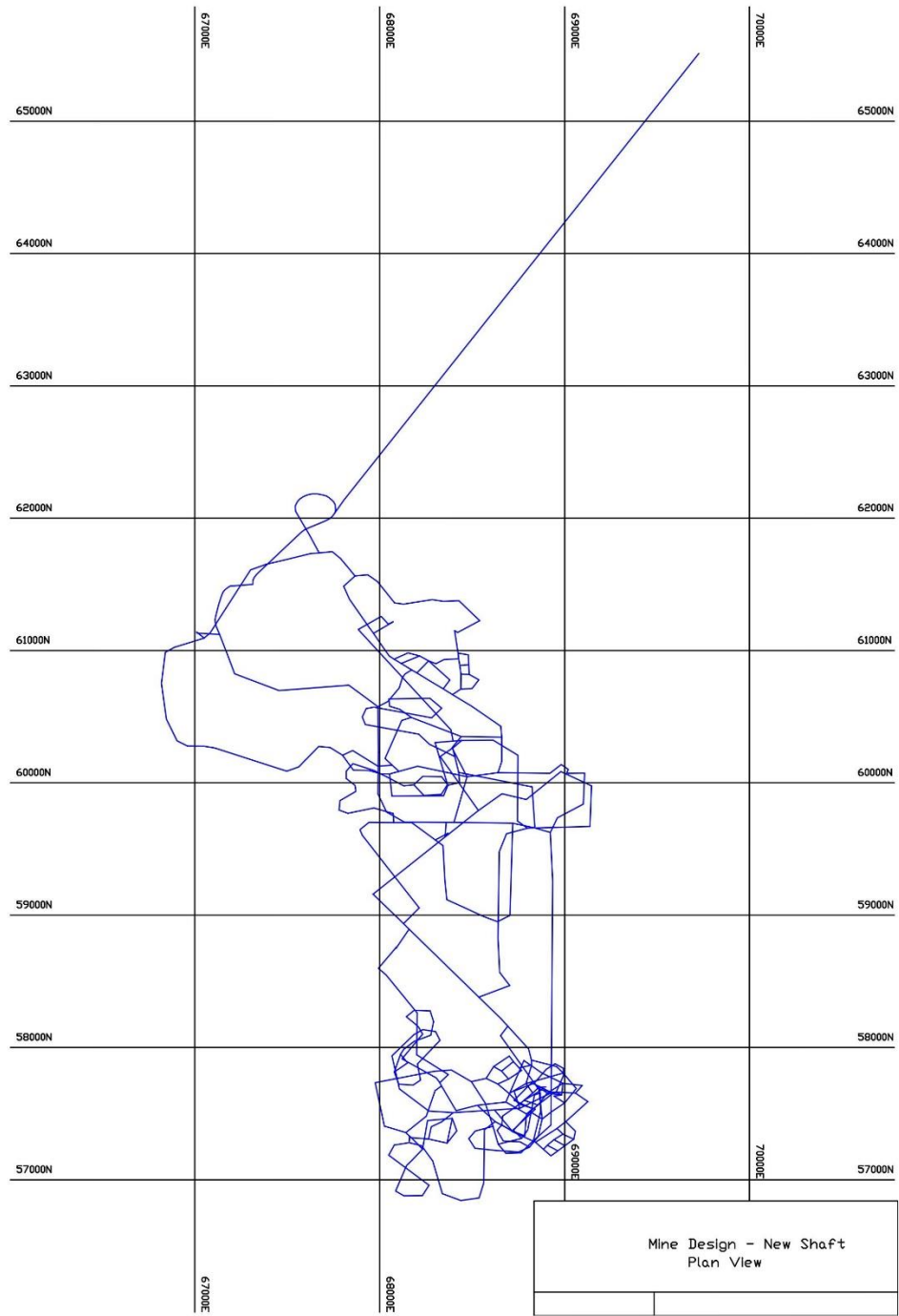
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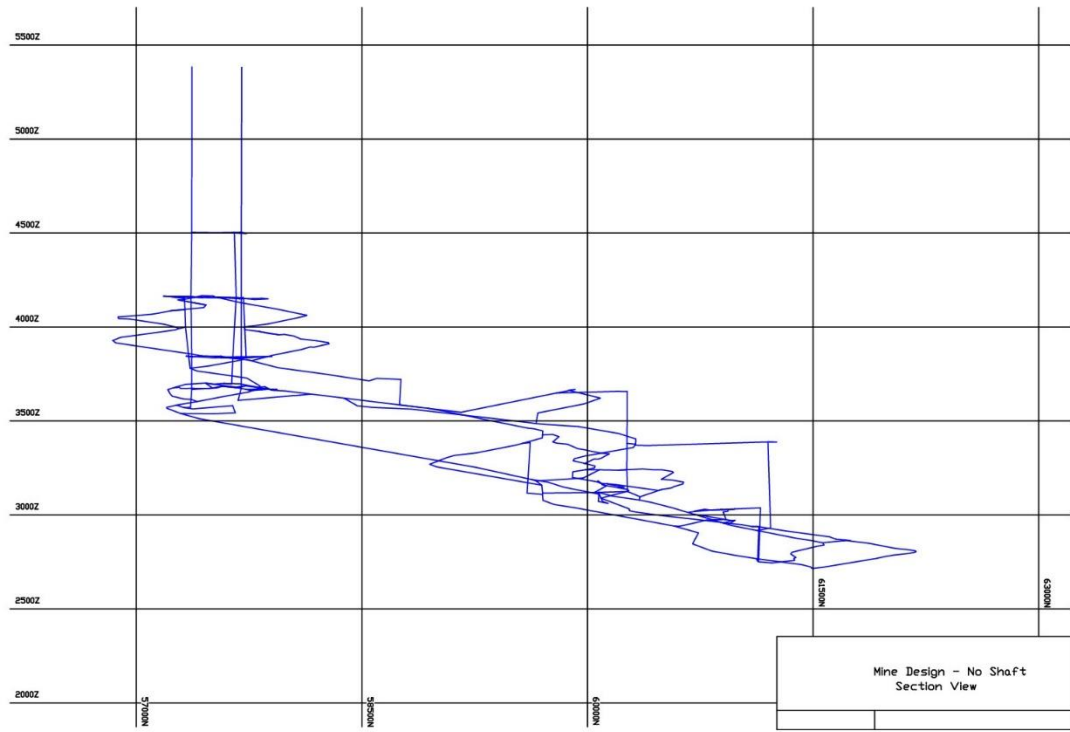
Appendix



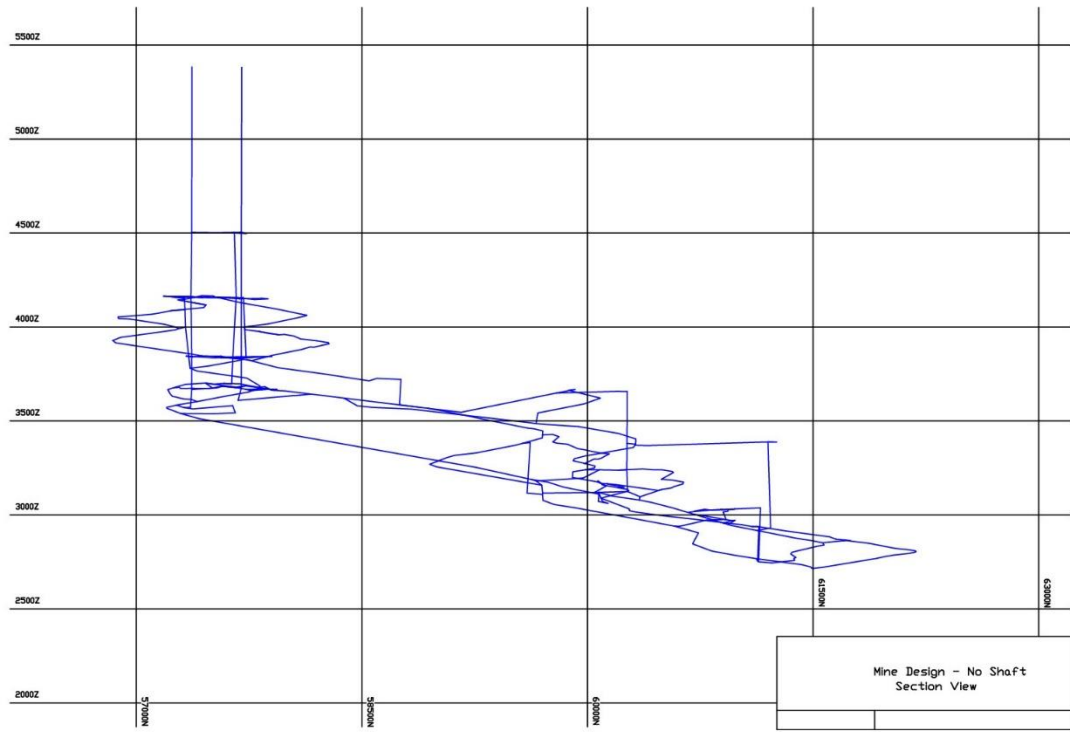
Plan view of mine design without new shaft



Plan view of mine design with new shaft



Section view of mine design with new shaft

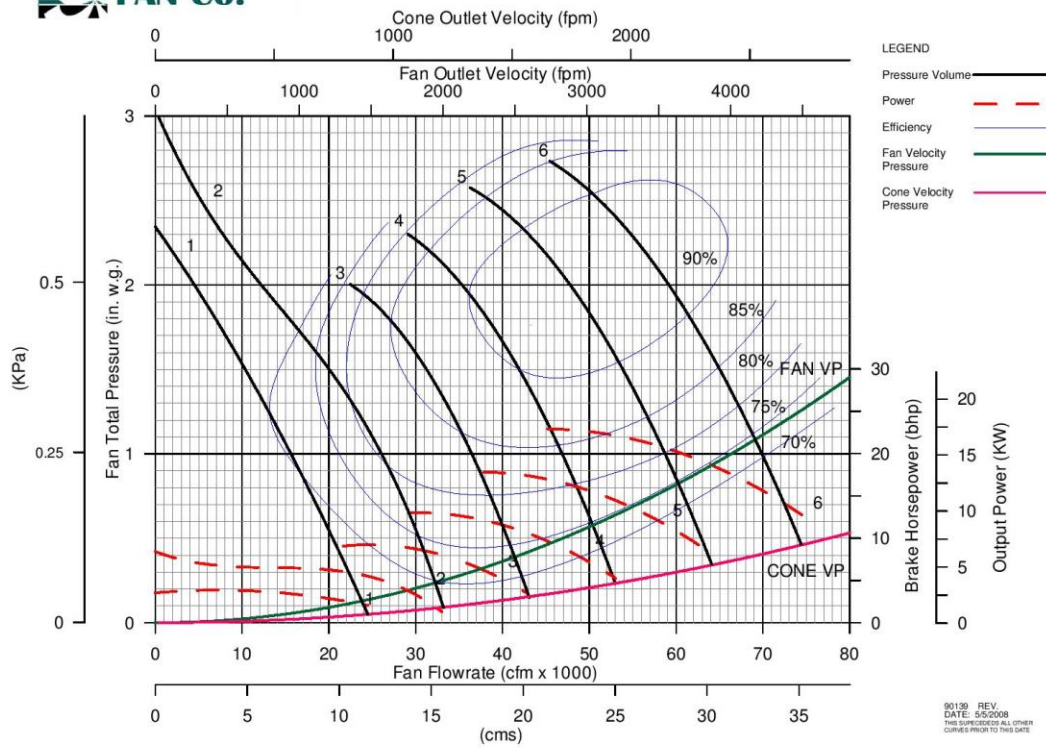


Section view of mine design without new shaft



Series 140-060-900-A-1

Fan Diameter 55.125 inches
Air Density 0.075 lbs./cu. ft.



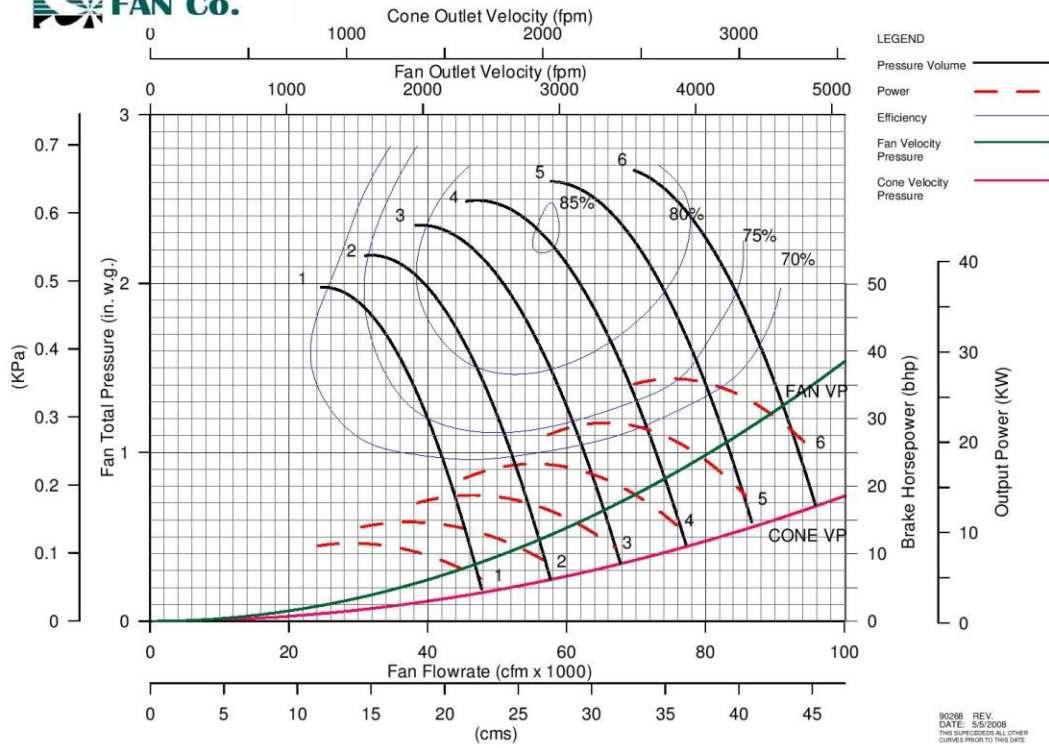
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Series 152-066-900-A-2

Fan Diameter 60 inches
Air Density 0.075 lbs./cu. ft.



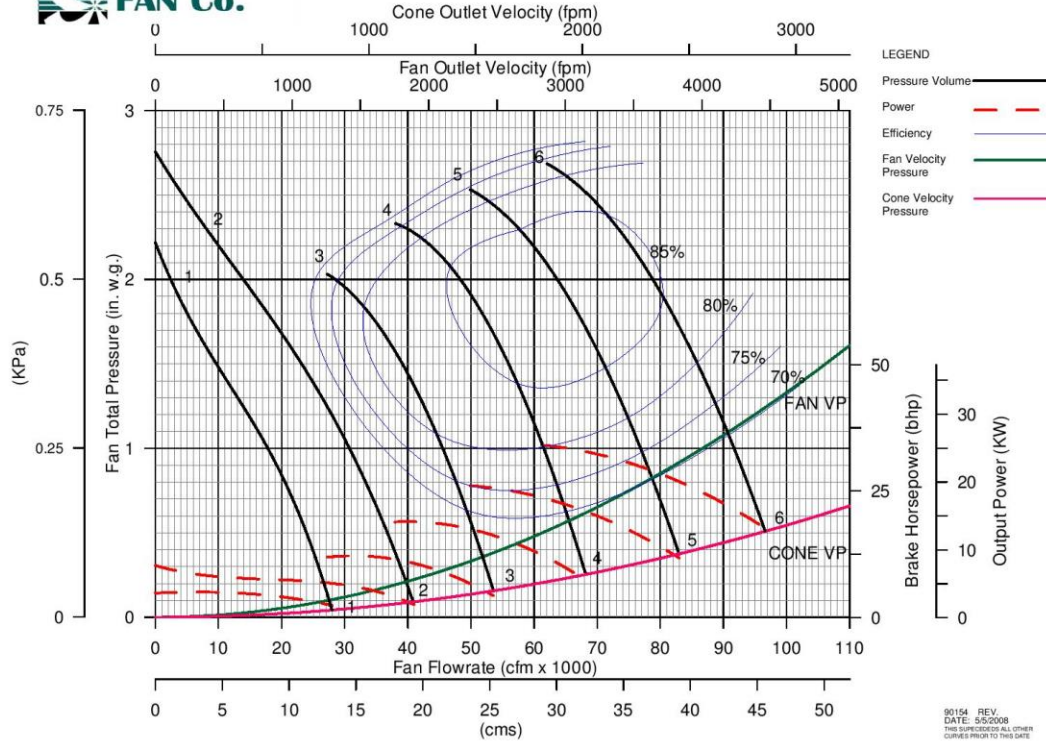
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Series 160-060-900-A-1

Fan Diameter 63 inches
Air Density 0.075 lbs./cu. ft.

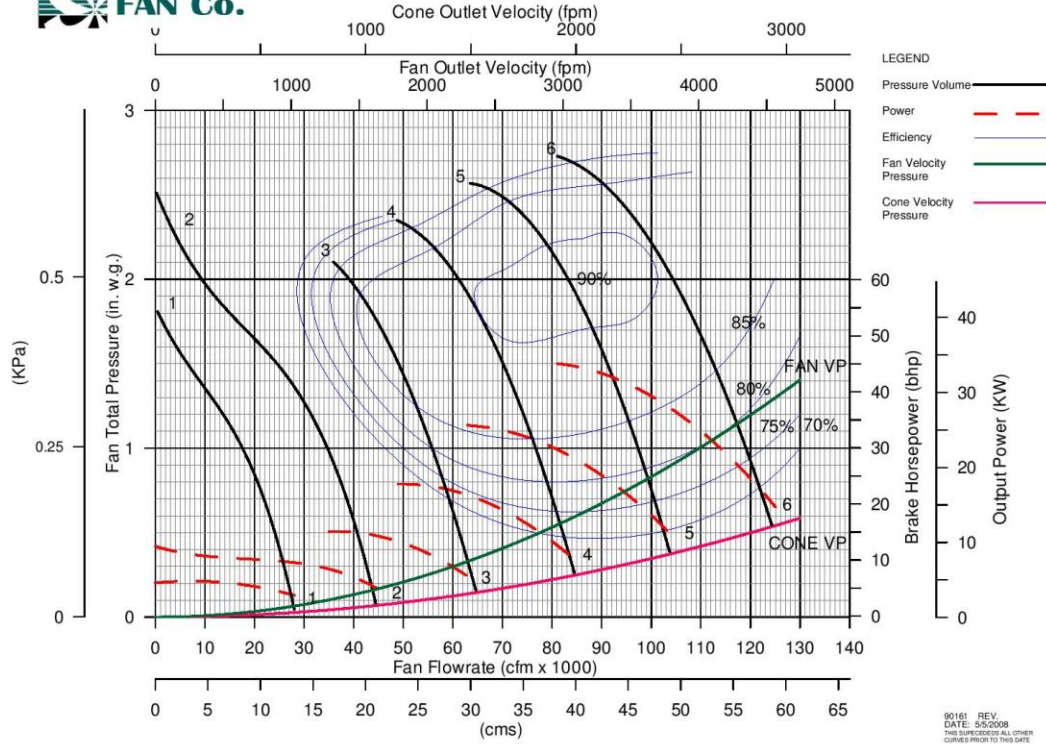


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Series 180-060-900-A-1

Fan Diameter 70.875 inches
Air Density 0.075 lbs./cu. ft.

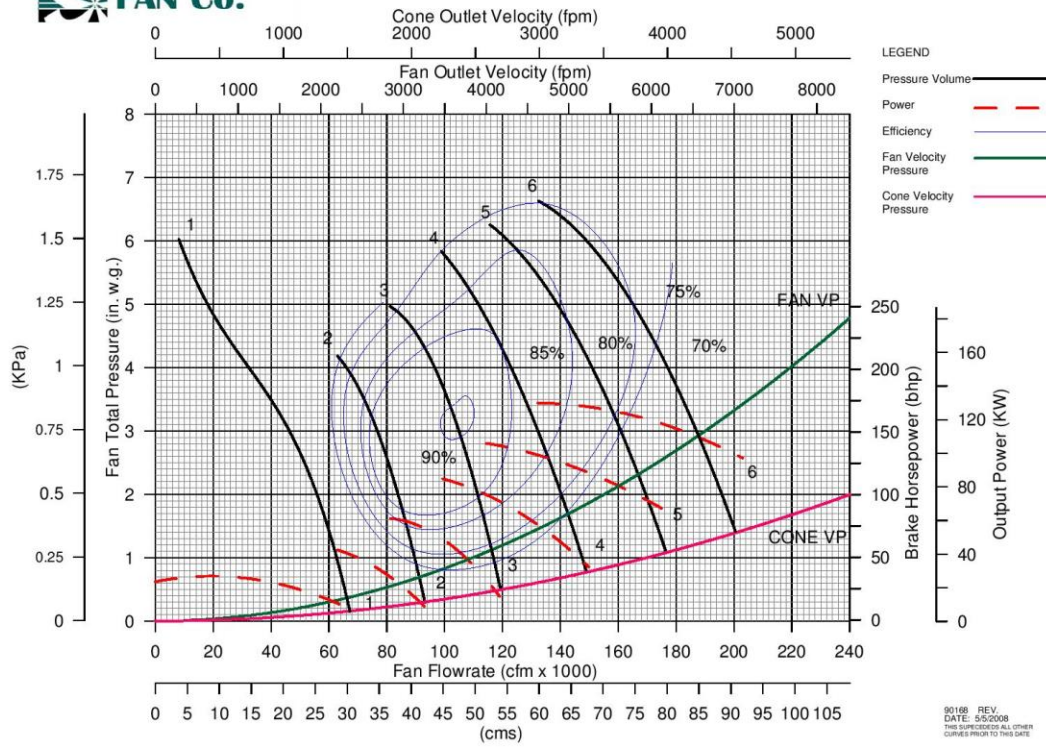


Spendrup 71 inch fan, Series 160-060-900-A-1



Series 180-080-1200-A-1

Fan Diameter 70.875 inches
Air Density 0.075 lbs./cu. ft.



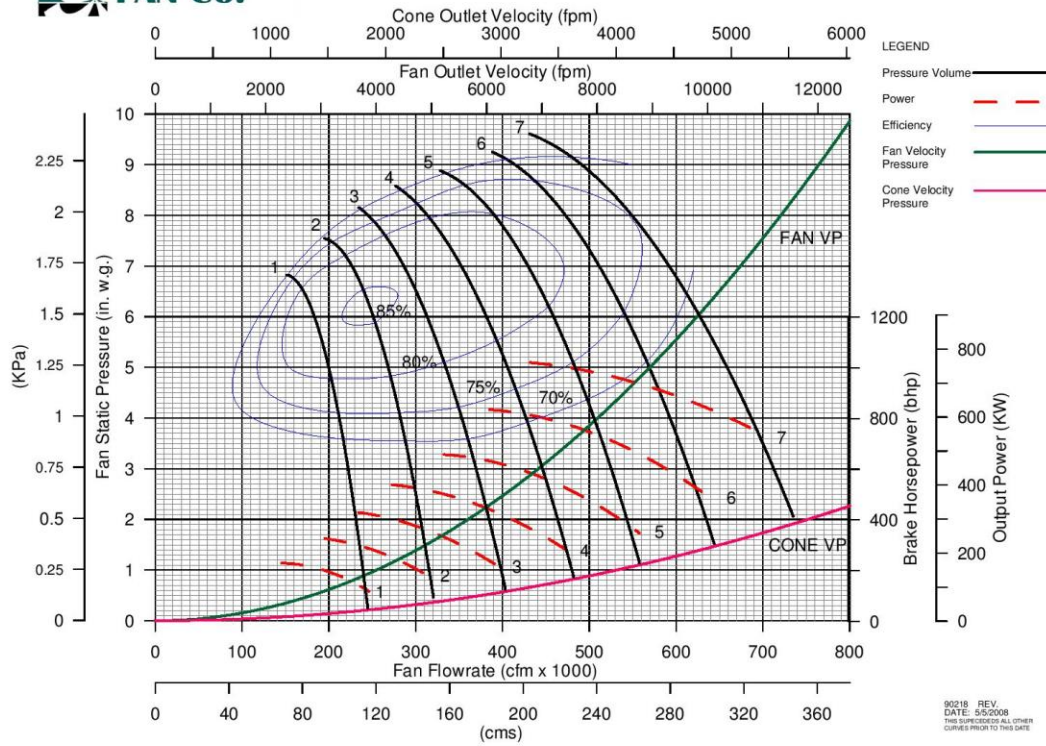
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Spendrup 71 inch fan, series 180-080-1200-A-1



Series 274-127-900-A-1

Fan Diameter 108 inches
Air Density 0.075 lbs./cu. ft.



Spendrup 108 inch fan, series 274-127-900-A-1

Fan	Airflow		Boost Total Pressure		No. of Fans	Configuration	Fan model	Fan Curve	Input Power	
	kcfm	m ³ /s	in wg	kPa					hp	kW
Fan 01	533.5	250.7	4.2	1.046	2	Parallel	Spendrup 108 in 274-127-900-A-1	1.7	490.4	365.7
Fan 02	108	50.8	0.8	0.199	2	Parallel	Spendrup 60 in 152-066-900-A-2	2.2	22.1	16.5
Fan 03	80.7	37.9	0.3	0.075	2	Parallel	Spendrup 63 in 160-060-900-A-1	2.1	6.3	4.7
Fan 04	101.5	47.7	0.4	0.100	2	Parallel	Spendrup 60 in 152-066-900-A-2	1.4	12.2	9.1
Fan 05	130.8	61.5	1.6	0.399	1	Single	Spendrup 71 in 180-080-1200-A-1	3.5	43.5	32.4
Fan 06	88.9	41.8	0.3	0.075	2	Parallel	Spendrup 63 in 160-060-900-A-1	2.4	6.3	4.7
Fan 07	87.5	41.1	0.9	0.224	2	Parallel	Spendrup 50 in 140-060-900-A-1	3.6	16.2	12.1
Fan 08	101.7	47.8	0.2	0.050	2	Parallel	Spendrup 71 in 180-060-900-A-1	2.3	6.8	5.1
Fan 09	18.6	8.7	2.8	0.697	1	Single	Spendrup 35.5 in 090-035-1800-A-1	2.3	10.4	7.8
Fan 10	22.6	10.6	3.6	0.897	1	Single	Spendrup 35.5 in 090-035-1800-A-1	4.7	16	11.9
Total:					17			Total:	630.2	469.9

Baseline scenario and artificial cooling scenario fans (Scenario #1 and #4)

Fan	Airflow		Boost Total Pressure		No. of Fans	Configuration	Fan model	Fan Curve	Input Power	
	kcfm	m ³ /s	in wg	kPa					hp	kW
Fan 01	558.7	262.6	3.3	0.822	2	Parallel	Spendrup 108 in 274-127-900-A-1	1.7	439.6	327.8
Fan 02	107.4	50.5	0.9	0.224	2	Parallel	Spendrup 60 in 152-066-900-A-2	2.2	22.7	16.9
Fan 03	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
Fan 04	102.7	48.3	0.4	0.100	2	Parallel	Spendrup 60 in 152-066-900-A-2	1.4	10.8	8.1
Fan 05	133.2	62.6	1.3	0.324	1	Single	Spendrup 71 in 180-080-1200-A-1	3.5	38.3	28.6
Fan 06	88.1	41.4	0.3	0.075	2	Parallel	Spendrup 63 in 160-060-900-A-1	2.4	7	5.2
Fan 07	88.1	41.4	0.9	0.224	2	Parallel	Spendrup 50 in 140-060-900-A-1	3.6	15.8	11.8
Fan 08	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
Fan 09	20.1	9.4	2.5	0.623	1	Single	Spendrup 35.5 in 090-035-1800-A-1	2.3	10	7.5
Fan 10	24.4	11.5	3.3	0.822	1	Single	Spendrup 35.5 in 090-035-1800-A-1	4.7	15.9	11.9
Total:					13			Total:	560.1	417.7

New shaft with no additional airflow scenario fans (Scenario #2)

Fan	Airflow		Boost Total Pressure		No. of Fans	Configuration	Fan model	Fan Curve	Input Power	
	kcfm	m ³ /s	in wg	kPa					hp	kW
Fan 01	807.3	379.4	6.2	1.544	2	Parallel	Spendrup 108 in 274-127-900-A-1	2.3	978.1	729.4
Fan 02	101.6	47.8	1.2	0.299	2	Parallel	Spendrup 60 in 152-066-900-A-2	2.2	27.2	20.3
Fan 03	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
Fan 04	103.9	48.8	0.3	0.075	2	Parallel	Spendrup 60 in 152-066-900-A-2	1.4	8.9	6.6
Fan 05	134.9	63.4	1.1	0.274	1	Single	Spendrup 71 in 180-080-1200-A-1	3.5	32.9	24.5
Fan 06	87.4	41.1	0.3	0.075	2	Parallel	Spendrup 63 in 160-060-900-A-1	2.4	7.5	5.6
Fan 07	89.8	42.2	1.3	0.324	2	Parallel	Spendrup 50 in 140-060-900-A-1	4.1	22.2	16.6
Fan 08	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
Fan 09	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
Fan 10	22.1	10.4	3.7	0.922	1	Single	Spendrup 35.5 in 090-035-1800-A-1	4.7	16.2	12.1
Total:					12			Total:	1093.0	815.1

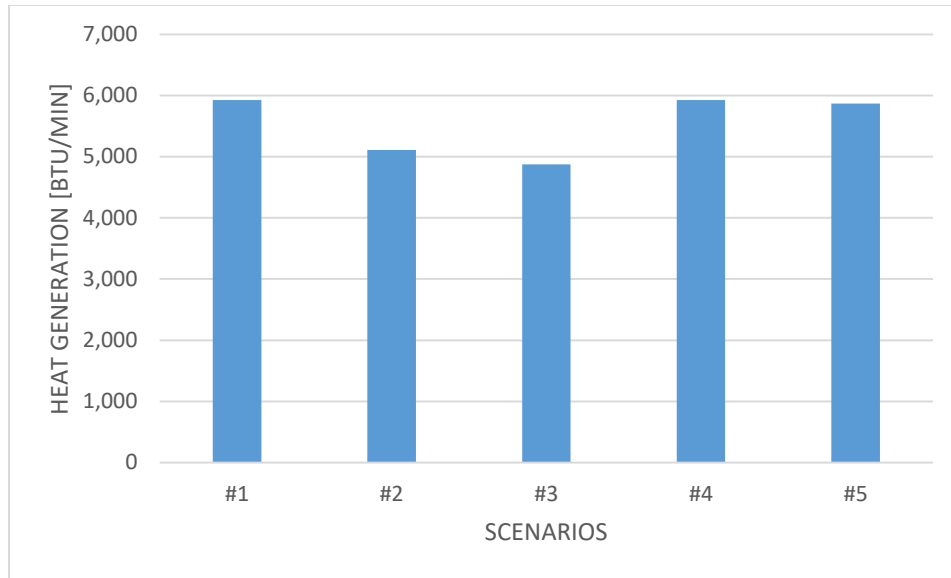
New shaft with additional airflow scenario fans (Scenario #3)

Fan	Airflow		Boost Total Pressure		No. of Fans	Configuration	Fan model	Fan Curve	Input Power	
	kcfm	m ³ /s	in wg	kPa					hp	kW
Fan 01	533.5	250.7	4.2	1.046	2	Single	Spendrup 108 in 274-127-900-A-1	2.4	490.4	365.7
Fan 02	108	50.8	0.8	0.199	2	Parallel	Spendrup 60 in 152-066-900-A-2	2.2	22.1	16.5
Fan 03	80.7	37.9	0.3	0.075	2	Parallel	Spendrup 63 in 160-060-900-A-1	2.1	6.3	4.7
Fan 04	101.5	47.7	0.4	0.100	2	Parallel	Spendrup 60 in 152-066-900-A-2	1.4	12.2	9.1
Fan 05	130.8	61.5	1.6	0.399	1	Single	Spendrup 71 in 180-080-1200-A-1	3.5	43.5	32.4
Fan 06	88.9	41.8	0.3	0.075	2	Parallel	Spendrup 63 in 160-060-900-A-1	2.4	6.3	4.7
Fan 07	87.5	41.1	0.9	0.224	2	Parallel	Spendrup 50 in 140-060-900-A-1	3.6	16.2	12.1
Fan 08	101.7	47.8	0.2	0.050	2	Parallel	Spendrup 71 in 180-060-900-A-1	2.3	6.8	5.1
Fan 09	18.6	8.7	2.8	0.697	1	Single	Spendrup 35.5 in 090-035-1800-A-1	1.1	10.4	7.8
Fan 10	22.6	10.6	3.6	0.897	1	Single	Spendrup 35.5 in 090-035-1800-A-1	3.1	16	11.9
Total:					17			Total:	630.2	469.9

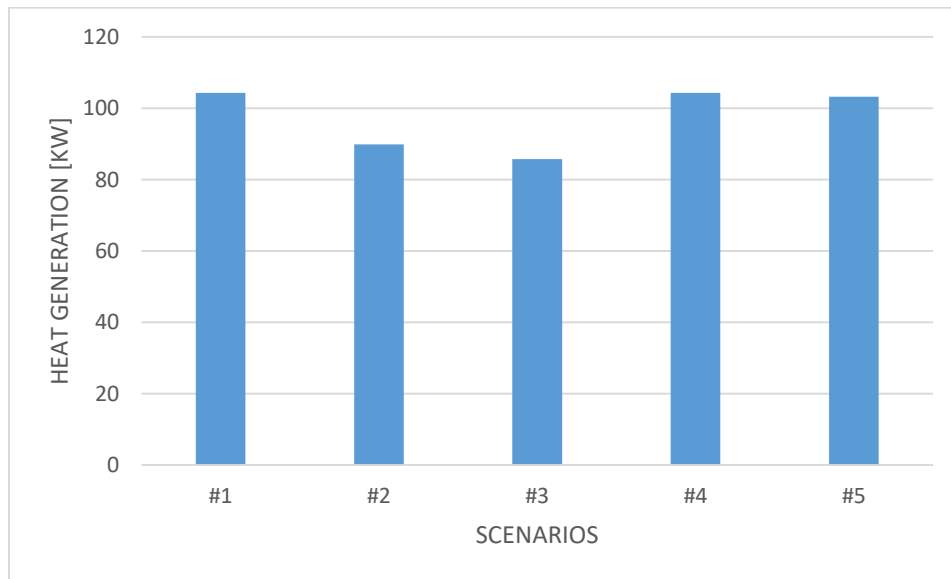
Battery powered equipment fleet scenario (Scenario #5)

Rock Thermal Conductivity	1.16	Btu/h/ftF	2.01	W/m [°] K
Rock Specific Heat	0.036	Btu/lbF	4.186	kJ/kgK
Thermal Diffusivity	0.2	ft ² /h	0.0186	m ² /h
Rock Density	169	lb/ft ³	2707	kg/m ³
Geothermal Gradient	1.4	°F/1000 ft	2.6	°C/km

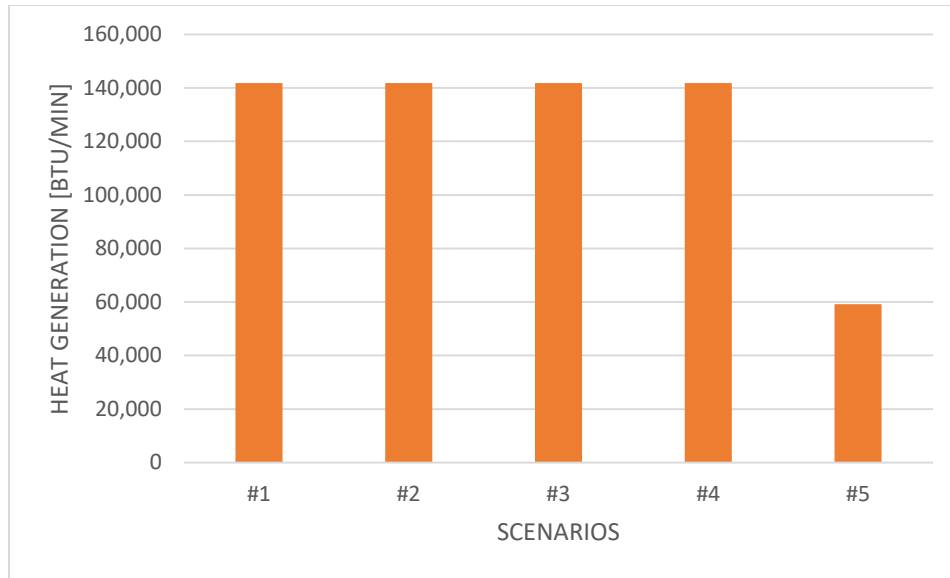
Rock properties



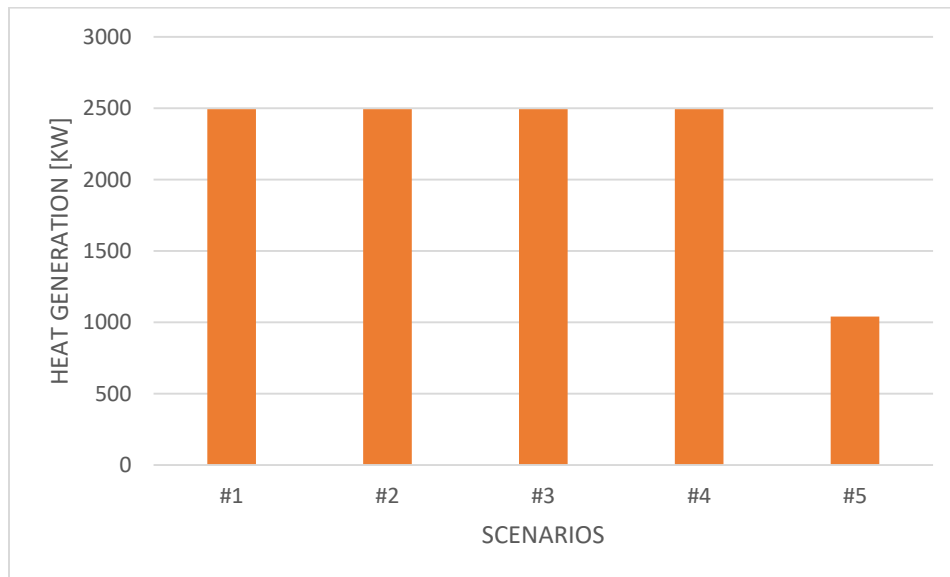
Fan Heat Generation Source Visual Comparison [Btu/min]



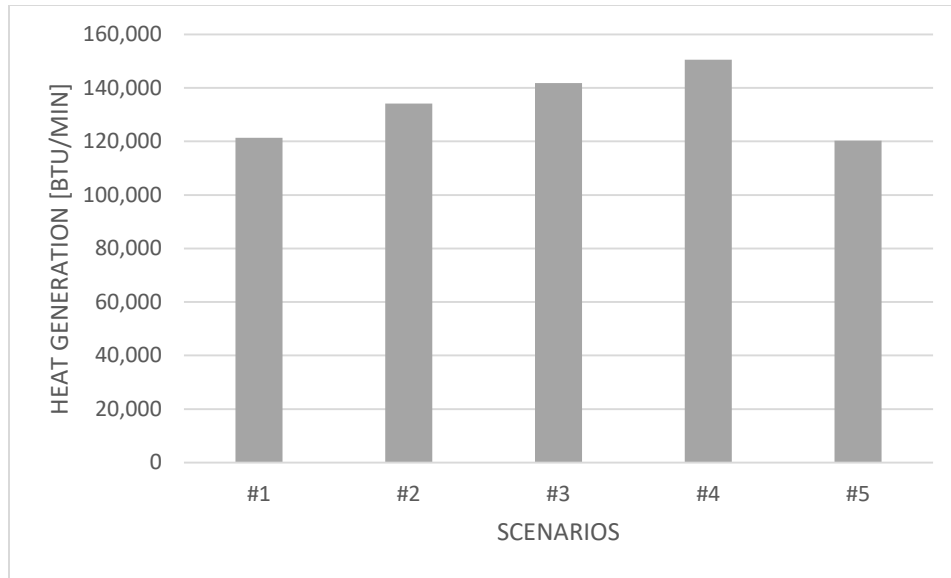
Fan Heat Generation Source Visual Comparison [KW]



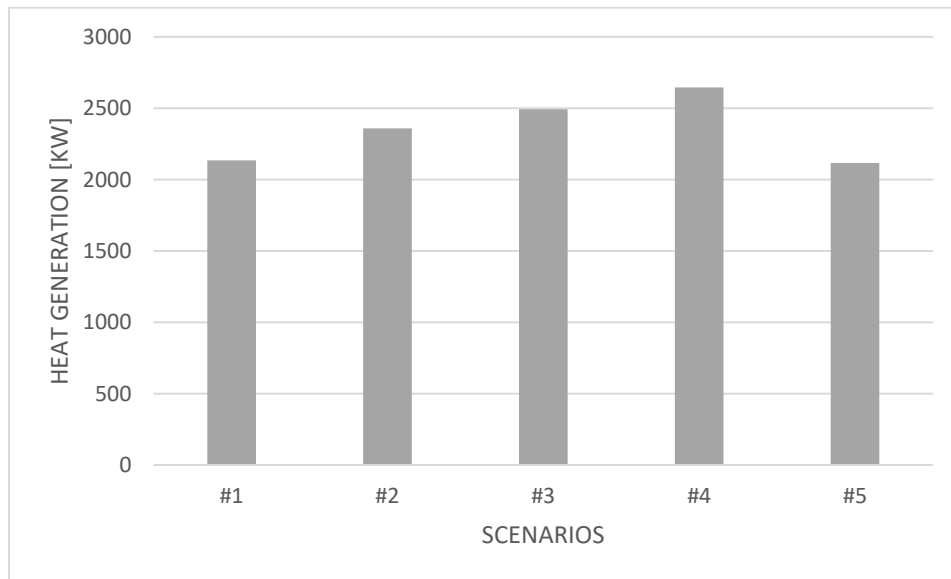
Equipment Heat Generation Source Visual Comparison [Btu/min]



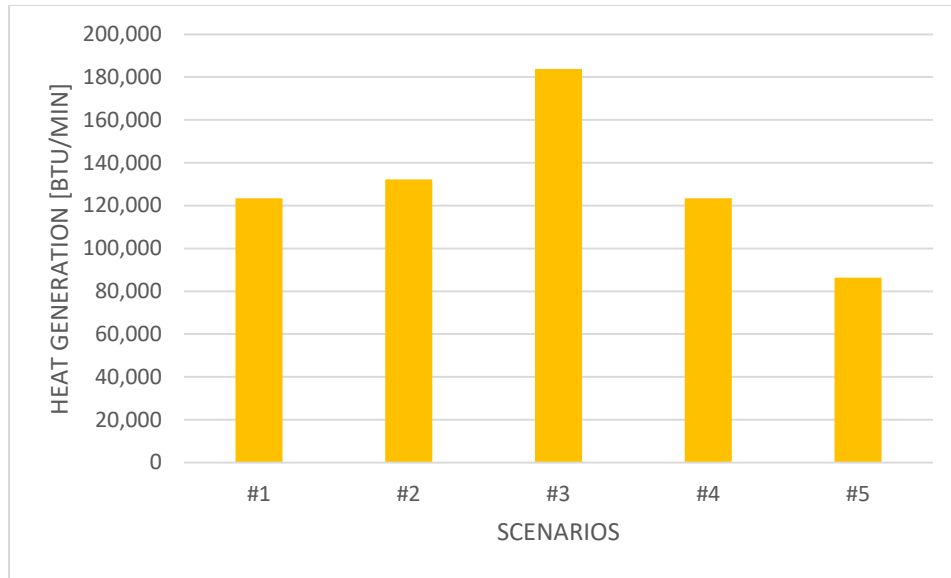
Equipment Heat Generation Source Visual Comparison [KW]



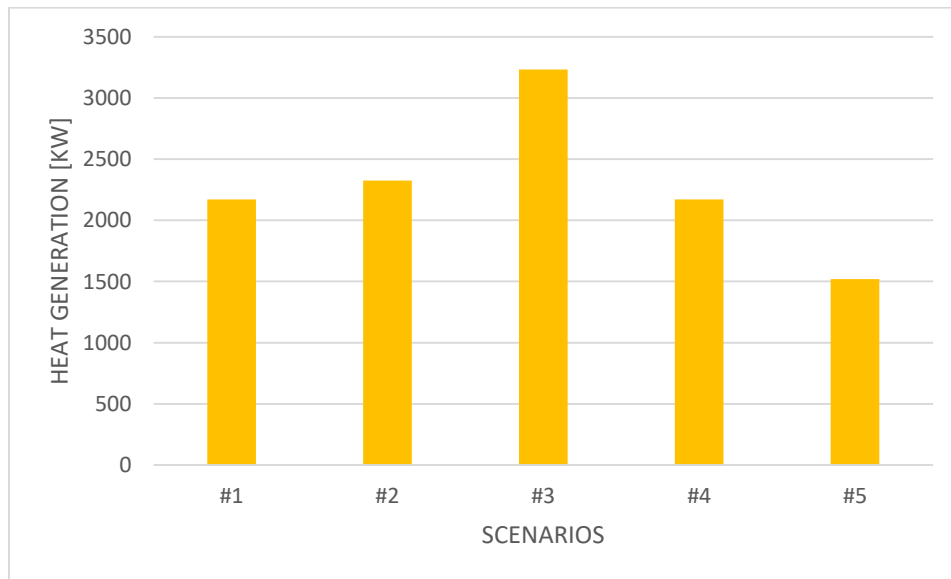
Strata Heat Generation Source Visual Comparison [Btu/min]



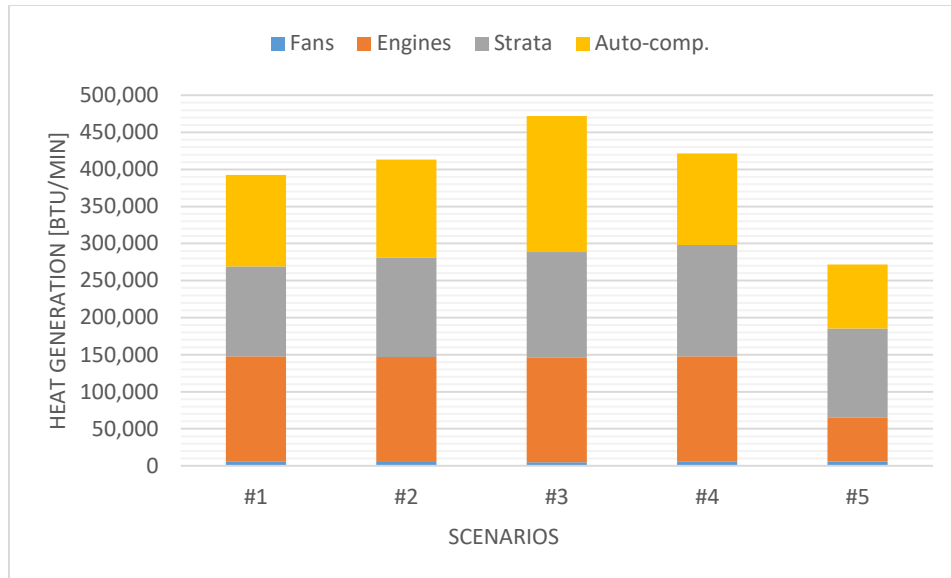
Strata Heat Generation Source Visual Comparison [KW]



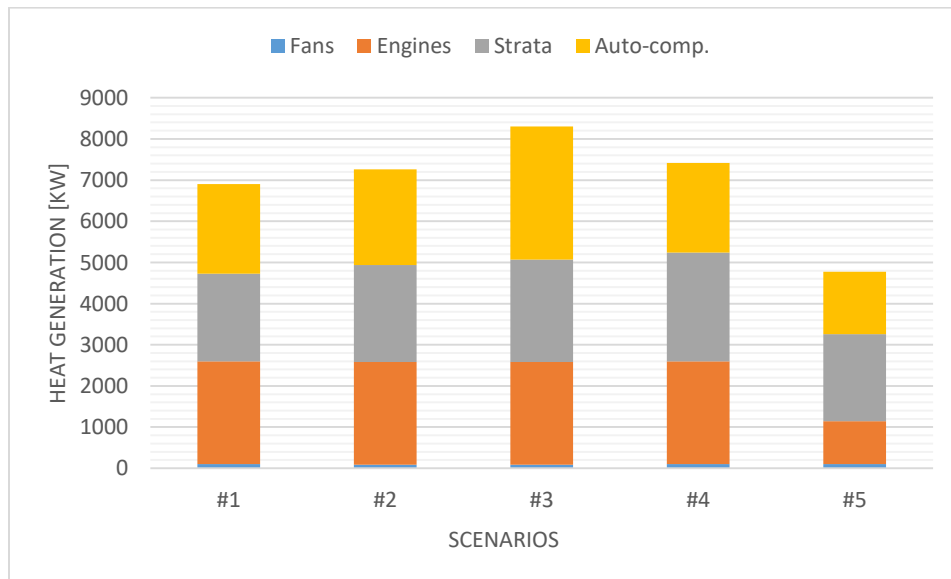
Auto-compression Heat Generation Source Visual Comparison [Btu/min]



Auto-compression Heat Generation Source Visual Comparison [KW]



Total Heat Generation Source Visual Comparison [Btu/min]



Total Heat Generation Source Visual Comparison [KW]