ANALYZING THE HEALTH AND COST BENEFITS OF UTILIZING ELECTRIC ENGINES VERSUS DIESEL ENGINES FOR EQUIPMENT FLEETS IN HOT UNDERGROUND MINES

Jon Fox[1], August Greth[1], Karoly (Charles) Kocsis[1], Cheryl Allen2*
[1]University of Nevada, Reno, United States
[2]Vale SA, Canada
**Corresponding author: kkocsis@unr.edu*

It is the duty of the mine operator to ensure the mine environment is healthy and safe for the mine workers. For deep and hot underground mines, this requires maintaining adequate working temperatures by means of mitigating the heat load generated by strata, auto-compression, mining equipment, explosives, ground water, and human metabolism. The heat load is best reduced by minimizing the amount of heat transferred to the mine air from these sources and through the use of efficient ventilation with effective cooling systems. The heat emitted by mining equipment and vehicles contribute a significant proportion to the combined heat load of an underground mine. This is especially a problem for diesel equipment due to the fact that besides heat, a large amount of water vapor is produced, which increases the humidity in the production workings. Diesel engines have proven advantageous in recent history due to their high power output and reliability. However, as mines continue to become more mechanized and deeper the climatic problems introduced by elevated heat generation will continue to rise. With that, the issue of heat generated by diesel equipment must be addressed.

The economic alternative for diesel engine equipment fleets in underground mines is the electric engine. Technological advances in battery technology, increased mechanical output and improved reliability have made the electric engine significantly more competitive in comparison to diesel engines. Because electric engines do not utilize internal combustion, the heat produced by them is significantly less than of the diesel engines. Battery powered mining equipment likewise eliminate diesel particulate matter (DPM) produced by diesel engines. Utilizing battery electric equipment in underground mines provides many advantages, such as: (a) reduced heat load, (b) healthier and safer environment for the mine workers, and (c) reduced mine operating costs due to lower ventilation requirements. This paper will highlight the health and cost benefits of using battery/electric fleets versus diesel fleets in deep and hot underground mines. The study analyzes simulations produced from thermodynamic ventilation models. Early simulations show significant cost reductions in terms of net present value (NPV) when comparing the air volume requirements for battery/electric equipment versus diesel powered equipment for the same production rate.

INTRODUCTION

The competitiveness of the world mineral market demands that mine operators continue to increase production and decrease costs as commodity prices fluctuate in often unplanned directions. This has forced underground mines to operate at deeper depths and to become more mechanized to remain competitive. Because of these changes, ventilation challenges have continued to increase as the mines combat an enlarged influx of contaminants such as heat and diesel particulate matter (DPM).

Some of the most common sources of heat generation in underground mines includes pipelines, rock movement, oxidation, human metabolism, underground water influx, strata heat, auto-compression, and machinery. Underground mine heat generation varies from mine to mine depending on a variety of variables including rock thermal properties, geothermal activity, mine power sources, mine depth, mechanization, and more. Excessive heat loads will lead to high temperatures in the underground mine environment. Mine workers may suffer heat related injuries or potentially death if an appropriate temperature threshold isn't maintained [1].

Machinery and equipment that employ diesel engines will produce not only heat but also DPM and noxious fumes as exhaust. This is the result of the internal combustion engine used to turn diesel fuel into mechanical force. As the engine isn't 100% efficient, the combustion of the diesel fuel results in energy being released into the underground mine environment in the form of heat. Diesel engines have an approximate thermal efficiency of 30% which results in a significant amount of heat being exhausted [2]. Likewise, not all of the diesel fuel is completely combusted. A complete combustion would only produce carbon dioxide and water vapor. However, the incomplete combustion of the diesel fuel also produces nitrogen, carbon monoxide, oxides of nitrogen, sulphur dioxide and DPM. DPM is made up of unused fuel, soot and aldehydes that are suspended in the air. This is a problem in the underground mine environment as continuous exposure to DPM is harmful to human health [3]. The combination of both the heat and DPM produced by diesel engines creates a double-edged hazard for mine workers.

Traditionally, the concentration of DPM and the heat load has been reduced by increasing airflow. Though this is a simple solution, it comes at a price as increased airflow correlates to increased electricity usage. This is continuing to become more and more of a problem as mining depths and mechanization increases. Mine operators should investigate solutions for these problems as it is the mine operator's responsibility for maintaining a safe work environment for the mine workers. So rather than diluting the contaminants, the alternatives are to reduce or eliminate the production of contaminants at the source. In this case, the diesel engine should be replaced by another viable technology.

Battery powered equipment is one such technology that can reduce or eliminate the problems associated with diesel mining equipment. Electric motors are more efficient than diesel engines as the heat generation is proportional to the power consumed by the machine. DPM emissions are also eliminated since diesel is not a fuel source [2]. Manufacturers are currently embracing the advancements in battery support by developing heavy-duty loaders with extended tramming capabilities and larger haul trucks. This current market interest has led to reduced charging times and extended battery life for electric engines capable of being using in mining equipment. This gives electric engines the edge they need to be competitive with diesel engines [4]. This study intends to analyze safety and cost benefits of using battery powered engines versus diesel engines in order to show the true advantage.

For the purposes of this research, a case study of Vale's Totten Mine in the Sudbury Basin of Ontario, Canada is analyzed. The ventilation for this deep, underground metal mine was modeled under three different fleet scenarios: all diesel, a combination of electric and diesel, and all battery. As each scenario is presented with complex design criteria, factors including air volume, air velocity, ventilation plan, contaminants, economics, and hazards are considered. The ventilation models for each scenario are used to quantify the required air quantities and the heat load. This data along with the required infrastructure, fan energy usage, and fan operating cost are used to determine the net present value of future fan operating costs to measure the impact an all battery fleet has over diesel [4].

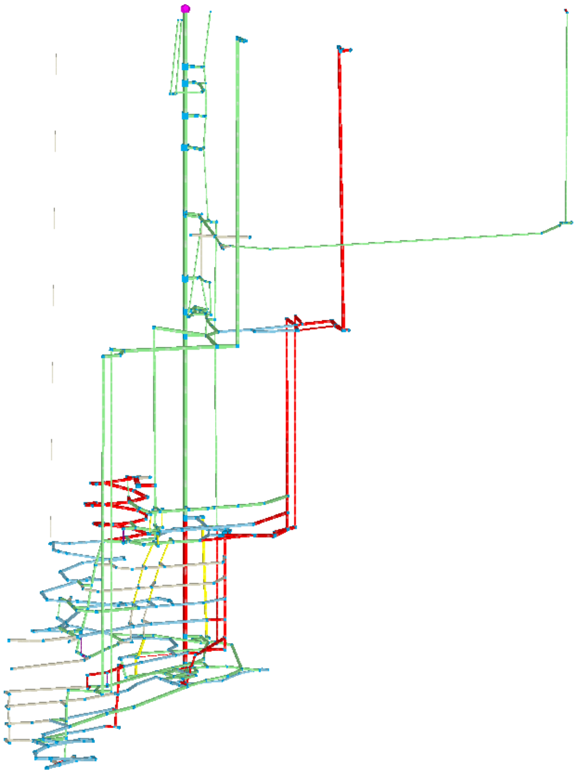

Figure 1: Schematic of the Mine Ventilation System for Vale's Totten Mine [5]

CONSIDERATIONS

Before modeling the scenario, all parameters and design criteria need to be considered. Each scenario will be almost identical as only the engine type and required airflow parameters will be different. Parameters such as the mine layout, mining method, production schedule, haulage distances, depth, intake/exhaust temperatures, and more will remain unchanged.

A temperature threshold must be maintained in order to protect mine workers. Reject temperatures from return air from different levels need to be below the acceptable standard as it will be mixed with air in the return airways. Each scenario will experience a different heat load due to the difference in equipment. Because of this, the areas modeled will show different air flow quantities and velocities as more or less of each is needed in order to maintain the temperature threshold [4].

Air volume requirements are determined based off of the heat load, concentration of contaminants and regulation. As the Totten Mine is located in Ontario, Canada, regulation requires airflow of 100 cfm/bhp for diesel dilution. The amount of appropriate equipment and infrastructure needs be determined and assigned operating locations and percent utilization. Equipment fleet changes and leakage are also accounted for [4].

Once the air flow quantities are determined the air velocity is then considered. This is important for reducing dust concentration as too low of a velocity reduces the ventilation's ability to remove -5 micron particles while too high of a velocity reduces the ventilation's ability to remove +10 micron particles. An optimum velocity would be 200 ft/min (1.0 m/s) with a minimum velocity of 100 ft/min (0.5 m/s) [4].

MODELING

Three different scenarios are evaluated using the ventilation design for the Totten mine and the appropriate considerations in order to model the heat generation and the airflow requirements. The first scenario will be an all diesel equipment fleet. The second scenario will be a mixed fleet. The LHDs and haul trucks will utilize battery engines while other support vehicles will utilize diesel engines. The third scenario will be an all battery fleet.

The heat load for each scenario is calculated based on the heat exhaust from the mobile engines, the wall rock, fans, and other electric heat sources which are not mobile. The airflow quantities required for each scenario are based on what is necessary to dilute DPM and to maintain threshold temperatures. The models for scenarios with diesel engines need to account for increased airflow to mitigate DPM as required. The all diesel fleet scenario for will require 200,000 cfm on the main level and 90,000 cfm in each mining access. The mixed fleet scenario will require 150,000 cfm on the main level and 55,000 cfm in each access. The all battery fleet scenario will require 116,000 cfm on the main level and 35,000 cfm in each access [4].

The main drift airflow values and the engine heat load will be used to calculate the total heat load, find the required air velocities, size the primary fans, determine the raise diameters, and to estimate the operating costs of the primary fans. The raise diameter is changed in order to maintain the same pressure drop for each level. The mining access areas airflow values will be used to find the required air velocities, size the auxiliary fans, determine the duct diameters, and to estimate the operating costs of the auxiliary fans. There are three different active levels using auxiliary fans. For this model, the auxiliary fan requirement is the same on each level. Knowing this, the auxiliary fan power costs for each can be added with the primary fan power costs to determine the total costs per year [4].

RESULTS

The models for the all diesel fleet, mixed fleet, and all battery fleet showed a total heat load of 2962 kW, 2301 kW, and 1380 kW respectively. The total heat load of the all battery fleet was 53.4% less than that of the all diesel fleet. Most of the reduced heat load is because of the reduced heat exhaust from the electric equipment and from the reduced fan usage due to decreased air quantities requirements [4].

The air velocities which were calculated in the models were broken down by main drift and stope access. The all diesel scenario produced air velocities of 735 ft/min for the main drift and 330 ft/min for the stope access. The mixed scenario produced air velocities of 662 ft/min for the main drift and 202 ft/min for the stope access. The all battery scenario produced air velocities of 426 ft/min for the main drift and 128 ft/min for the stope access. It should be noted that the all battery scenario's stope access air velocity is a little close to the minimum velocity of 100 ft/min (0.5 m/s) but should not be problematic [4].

Different air quantity and velocity requirements between the different scenarios results in different raise bore diameters for ventilation. This was compared per level and by area. The required raise bore diameters per level for all diesel fleet, mixed fleet, and all battery fleet were 11 feet, 10.5 feet, and 8.7 feet respectively. The required main raise bore diameters per area for all diesel fleet, mixed fleet, and all battery fleet were 19 feet, 17.5 feet, and 16.5 feet respectively. This shows a reduction in the diameter between the diesel and battery scenarios by 21% per level and 13% per area. Though the numbers are low, this is noteworthy as the cost of raise boring is significant when considering the length and number of raises needed [4].

The auxiliary systems for the different scenarios also have different sized ducting to account for the air quantities and velocities. The all diesel fleet has a 54" diameter duct for the 90,000 cfm airflow. The mixed fleet has a 48" diameter duct for 55,000 cfm airflow. The all electric fleet has a 42" diameter duct for the 35,000 cfm airflow. The pressure drops for each will be calculated in the models. This represents a reduction in the ducting diameter of 22.2%. Like the raise bores, at face value this may not seem significant but the costs of purchasing and installing ducting over time will add up [4].

The fan power of the six auxiliary fans was determined using the air flow quantities and the generated pressure drops for each scenario. The resulting pressure drops in the auxiliary ducting for the all diesel fleet, mixed fleet, and all battery fleet was found to be 9.0" w.g., 5.5" w.g., and 3.4" w.g. respectively. Given an airflow quantity of 90,000 cfm and 9" w.g., the auxiliary fans for the all diesel fleet were sized at 180 HP. For the all diesel fleet this would generate a yearly power cost of $529,000 for the auxiliary fans. Given an airflow quantity of 50,000 cfm and 5.5" w.g., the auxiliary fans for the all diesel fleet were sized at 180 HP. For the mixed fleet this would generate a yearly power cost of $235,000 for the auxiliary fans. Given an airflow quantity of 35,000 cfm and 3.4" w.g., the auxiliary fans for the all diesel fleet were sized at 180 HP. For the all battery fleet this would generate a yearly power cost of $118,000 for the auxiliary fans. The fan power of the six auxiliary fans for the all battery fleet was 78% less than that of the all diesel fleet [4].

The fan power for the primary fans was determined using the air flow quantities through the main raises with equal pressure drops for each scenario. For the all diesel fleet with a main raise diameter of 19 feet and an airflow quantity of 830,000 cfm, the primary fans were sized at 2616 HP. Over a year, the primary fans would have an operating cost of $1,282,200 for an all diesel fleet. For the all diesel fleet with a main raise diameter of 17.5 feet and an airflow quantity of 690,000 cfm, the primary fans were sized at 2283 HP. Over a year, the primary fans would have an operating cost of $1,118,900 for a mixed fleet. For the all diesel fleet with a main raise diameter of 16.5 feet and an airflow quantity of 570,000 cfm, the primary fans were sized at 1719 HP. Over a year, the primary fans would have an operating cost of $842,500 for an all battery fleet. The fan power of the primary fans for the all battery fleet was 34% less than that of the all diesel fleet [4].

Table 1: Heat Generation, Fan Power, and Operating Costs for Each Fleet Alternative

Operating Cost Scenario	**Heat Generation**	**Total Fan Power**	**Operating Costs**
	(kW)	**(kW)**	**(CAD/yr)**
All Diesel Fleet	2962	4307	$2,869,200
Mixed Fleet	2301	2738	$1,823,900
All Battery Fleet	1380	1794	$1,196,500

Examining the fan power costs per year for the three levels with auxiliary fans and the primary fans yields the total fan power costs per year. Results showed costs of $2,869,200, $1,823,900 and $1,196,500 for the all diesel fleet, mixed fleet, and all battery fleet. This is a total power savings of $1,672,700 per year, a reduction of 58.3%, between the all diesel fleet and electric fleet [4].

The generated associated costs per year (S_o) can be used to calculate the net present value (P_o) of future fan operating costs [3]. For this scenario, the net present value of the future operating costs over fifteen years is compared at different interest rates for an all diesel fleet vs. a mixed fleet vs. an all battery fleet, using the following equation:

$$P_o = \frac{S_o}{i}\left[1 - \frac{1}{(1+i)^n}\right]$$

Where: P_o = Net Present Value
S_o = Associated Yearly Operating Costs
i = Interest Rate
n = Number of Years

Equation for the Net Present Value of Future Operating Costs [3]

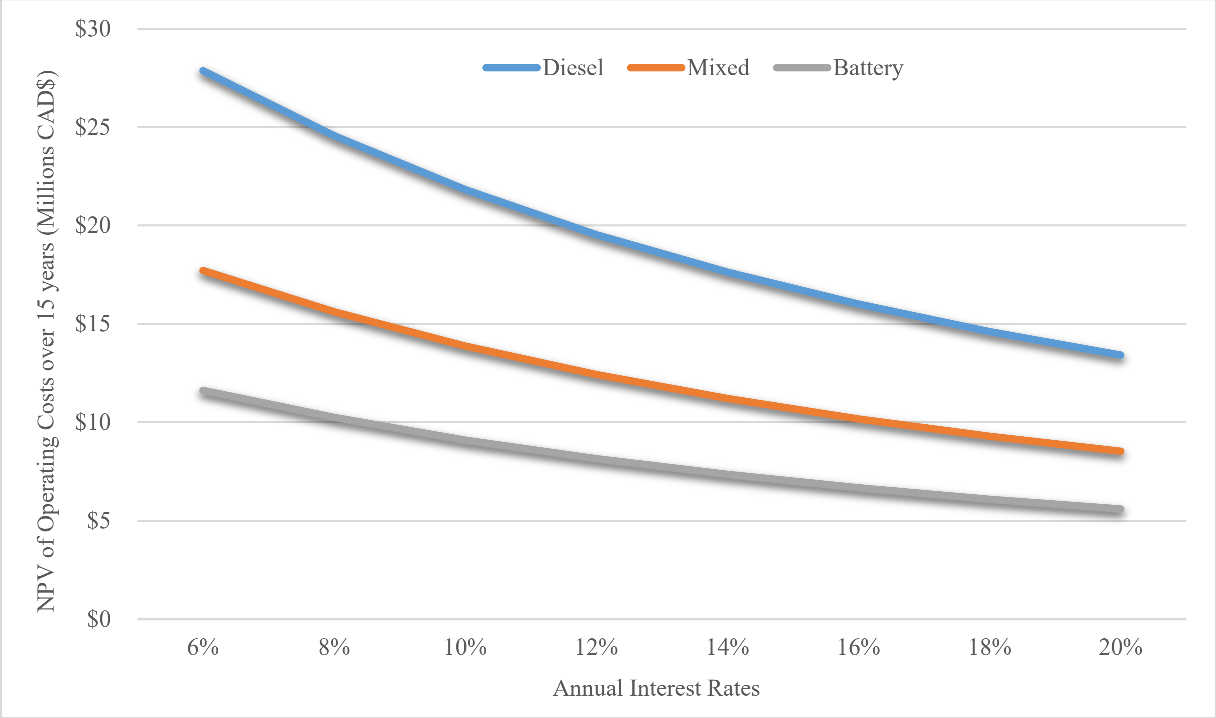

Figure 2: Comparison of the Net Present Values of the Operating Costs over 15 years for each fleet scenario

The numbers in Figure 2 speak for themselves as they show how an all battery fleet is a cost-reducing alternative to a mixed fleet and an all diesel fleets. The difference would be even greater if capital expenditures for each scenario were considered. This is because the increased diameter raises and larger fan sizes required by the mixed fleet and diesel fleet would be a higher cost than that of an all battery fleet. However, what the numbers don’t show is the benefit to mine workers. The reduced heat load and removal of DPM provides a safer environment for the presence of mine workers. These health and cost benefits show that mine operators should adopt battery powered fleets over diesel powered fleets.

DISCUSSION

Mining costs and safety are some of the biggest driving factors for decisions made in mine planning. This is because of increasing mining depths and higher mechanization needed in order to produce continually scarcer materials in quantities necessary to be profitable. These extreme mine conditions found in deep, hot, underground mines also mean that safety is a big focus. For this reason, mining is strategically planned, and new alternatives are always considered in order to saving money or increase safety.

Equipment selection is particularly affected by mining costs and safety not only for the sake of production but also for ventilation concerns and costs. Diesel engines have been extensively used in recent decades due to their reliability and well needed power capabilities. At the same time, diesel engines generate a significant amount of DPM and heat which requires increased airflow quantities. With the trend towards increased mechanization in underground mines this is increasingly becoming a problem that needs to be solved. An alternative such as a battery powered engine fleet can be the solution. Utilizing an all battery fleet would eliminate DPM and reduce the heat load. Not only would this create a safer mine environment, but operating costs would also be reduced.

Market forces have made battery technology more competitive across all industries including mining. The mining industry will adopt battery powered engine use for equipment fleets as its use continues to prove its benefits over diesel engines. Change takes time, but ultimately mine operators will seek battery powered engines out as the need for costs savings and improved safety increases.

REFERENCES

[1] K. E. Carpenter, P. Roghanchi, & C.K. Kocsis, “Investigating the importance of climatic monitoring and modeling in deep and hot US underground mines,” Proceedings of 15th North American Mine Ventilation Symposium, Virginia Tech, Virginia, pp. 1-4, 2015.

[2] Underground Mining Battery Electric Vehicles Working Group. “GMSG Recommended Practices for Battery Electric Vehicles in Underground Mining,” Global Mining Standards and Guidelines Group, Quebec, Montreal, Canada, 2016.

[3] M. J. McPherson, Subsurface Ventilation Engineering, Mine Ventilation Services, Inc., Fresno, 2009.

[4] C. Allen, “*Ventilation Design Case Studies*,” MDEC Workshop, Toronto, Ontario, Canada, 2016.

[5] C. Allen & E. Acuna-Duhart, “Ventilation Control System Update,” North American Mine Ventilation Symposium, Denver, Colorado, 2017.