Determination of Effective Operating Diesel Engine Power on Ventilation

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ABSTRACT

An analysis was carried out to determine actual continual operating engine horsepower of all the diesel equipment used underground. The effective engine horsepower was calculated by collecting equipment operating hours on a daily basis and estimating diesel engine idle, partial and full load times. Engine fuel consumption while idling and operating also was determined. The primary data was gathered using engine hour meters, DDEC readings for Detroit diesel engines, consultation with mechanics and operators, engine fuel consumption ratings and monthly mine diesel fuel use records. It can be shown that this effective operating horsepower is a small fraction of the nameplate engine power and its effect on ventilation can be estimated. At Barrick Goldstrike Mines Inc. there are three major interconnected mining areas. The Rodeo area has its own fleet of diesel equipment while Meikle and Griffin share a common fleet. Rodeo has a nameplate horsepower of about 9,100 hp while Meikle and Griffin operate about 12,100 hp. Results of this study revealed that the average total horsepower of all the diesel equipment at any point in time for Meikle/Griffin was 782 hp and for Rodeo was 554 hp. Engine hours per month were 10,735 and 8,765 hrs respectively for Meikle/Griffin and Rodeo. An attempt also was made to determine the thermal energy contribution to the ventilation air due to diesel equipment based on the actual used horsepower and a diesel engine efficiency of 40%. The Diesel engines were found to contribute 3.7 % and 2.6 % respectively for both Meikle/Griffin and Rodeo. This corresponds to 875 kW and 689 kW, respectively. The total heat transfer to the air stream was determined using air mass flow and the difference in enthalpy from the intake to exhaust. The total heat transfer for Meikle is 23,884 KJ/s and for Rodeo is 27,053 KJ/s. The heat contribution from diesel equipment to the airflow is very low compared with the heat generated by the rock at Barrick Goldstrike Mines Inc. Overall airflow in Meikle/Griffin is 860,000 cfm (423 kg/s) making it 1,100 cfm/operating hp and in Rodeo it is 900 000 cfm (443 kg/s) corresponding to 1,624 cfm/ operating hp. The emission rates of the diesel engines for the mine also should be computed based on the effective or net operating horsepower of the equipment and not on a blanket or nameplate number of overall engines underground.

2.0 INTRODUCTION

Diesel powered equipment is very popular in today's mechanized mining. Some mines depend heavily on diesel equipment for all aspects of the development and production cycle. However, with the use of diesel equipment in underground mining, pollutants and engine heat are generated. An unsafe atmosphere can be created without proper ventilation. Adequate ventilation is the only means of removing the pollutants from the mine environment.

The question often asked is that of required airflow quantity for a given engine, or for a mine using a fleet of diesel engines. Worldwide, several guidelines have been used in the past. Most of these guidelines suggest that for each unit of engine brake horsepower, approximately 100 to 150 cfm should be provided.

This is a good rule of thumb, provided the engine is well maintained per manufacturer's recommendations, and is suited for the work environment.

Currently, there is much environmental and health interest in underground diesel equipment. It is now realized that excessive exposure to diesel particulate matter (DPM) will result in detrimental health effects. Certain kinds of DPM are carcinogenic or cause respiratory problems if allowed to accumulate in the deeper lungs. In the USA, the Mine and Safety Health Administration (MSHA) now regulates the use of diesel equipment underground and a threshold limit has been set for DPM exposure. The philosophy is that less of a bad thing is better and if it can be avoided completely it is best. Unfortunately, there is no acceptable technology to replace the diesel engine underground. Fuel cells are promising, but they still are far from being economic. Hydrogen-powered engine are feasible, but handling hydrogen in an underground environment is unsafe because of its explosive nature. Moreover, diesel fuel has a superior power density compared to liquid or gaseous hydrogen.

The underground complex at Barrick Goldstrike Mines Inc., which entails the Meikle, Griffin and Rodeo areas, uses a large fleet of diesel equipment. Meikle/Griffin workings have a fleet with a nameplate rating of about 12,100 bhp, and Rodeo has 9,100 bhp. The total amount of airflow supplied to Meikle/Griffin is about 860,000 cfm and that of Rodeo is about 900,000 cfm. All these zones are interconnected and the current amount of air moved underground is about 1,760,000 cfm. Throughout the workings, the total daily advance is approximately 160 feet/day. The gold ore produced can be up to 4,500 tpd and it will increase in 2003.

The mined rock generates a considerable amount of heat. The average virgin rock temperature is about 140 ^{o}F. In some cases, drill holes have exceeded this temperature, reaching over 200 ^{o}F. In the Griffin zone and some parts of Meikle and Rodeo, hot vapors containing carbon dioxide and sulfur dioxide are produced.

It was decided to undertake a study to assess the effects of diesel equipment on ventilation. The study aimed at determining the heat diesel engines contribute to the mine ventilation air, based on the actual operating diesel engine horsepower, as used or tracked anytime on the operators' log sheets.

The following first had to be determined in order to achieve this:

- Total idle and operating engine hours for each piece of equipment on daily or monthly bases
- Total horsepower at any point in time for each mine
- Rate of fuel consumption for the diesel engines

In order to obtain the most accurate information for all the above, relevant information was examined on a monthly basis for six months, and then averaged. This was done because the downtime for all diesel engines was most consistent on a monthly basis as opposed to a weekly basis. The average monthly data then could be reduced to operating time on a per second basis.

3.0 PROCEDURE FOR ANALYSIS OF DIESEL EQUIPMENT

3.1 Total idle and operating engine hours for each piece of equipment on a monthly basis

To determine total engine hours for each piece of machinery, weekly engine meter readings were used. Mechanics metered each piece of equipment weekly in both Meikle/Griffin and Rodeo and recorded this data in a database. In order to determine monthly engine hours, the difference in readings across the month were used. The problems with this system can be listed as follows (i) a mechanic could take the reading from the wrong meter, (ii) a mechanic may not have accounted for a meter roll-over, and (iii) a mechanic may not always check every machine each week. The way to compensate for these errors was to plot the data and use a trend line to eliminate erroneous data points and correct for a meter rolling over. This system gave very accurate monthly totals for each piece of machinery.

In order to determine the ratio of idle to operating engine time, a DDEC was used on all Detroit Diesel engines. Mechanics and operators gave estimates for the remaining engines. These ratios were applied to each category of equipment, as this measure is dependent on the piece of equipment not the engine. For all Detroit Diesel engines, total engine hours, idle hours and operating hours were obtained. The readings gave a ratio of 50:50 (idle : operating). Since these Detroit Diesel engines are predominantly in haul trucks and loaders, the categories of haul trucks and loaders were assigned an idle factor of 0.5 and an operating factor of 0.5.

3.2 Total Horsepower at any point in time for each mine

There were two methods used to determine this.

Method 1: Energy calculation of diesel fuel

Number 2 diesel fuel used in all underground engines has a calorific value of 35.6 MJ/L. Using the recorded values for total monthly fuel consumption and assuming a diesel engine efficiency of 40%, it is possible to calculate the amount of energy from the fuel that is used for useful work.

Example - Meikle
Calorific value of Fuel oil: 35,600,000 J/L
Total fuel consumed – monthly average: 106,120 L
Rate of fuel consumption: .04094 L/s

Energy from fuel = Calorific Value * Rate of Fuel Consumption
= (35,600,000 J/L)*(.04094 L/S)
= 1,457,512 J/s

This value is the total available energy from the fuel oil. With a 40% efficient diesel engine, the useful work (hp at any time in Meikle) = (Energy from Fuel) * (0.40)
= (1,457,512 J/s) * (0.40)
= 583,004 J/s (583 kW)
= 781 hp

Method 2:

Sum the horsepower at any point in time for each engine.

For each engine:

$$\text{hp at any point in time} = \frac{(\text{monthly idle Hrs} \times \text{idle hp}) + (\text{monthly op Hrs} \times \text{op hp})}{720\ (\text{Hrs in a month})} \tag{1}$$

To determine the idle horsepower and operating horsepower, monthly idle and operating hours were assumed to be accurate, and the above equation was equated to the result from Method 1. To determine values for the idle hp and operating hp that would fit the equation; mechanics, operators, manufacturers and engine dealers were consulted. It was determined that at idle the hp of an engine is 10% of its rated brake horsepower (bhp) and while operating the average hp was 42% of its rated bhp.

Rate of fuel consumption

There were two methods to solve for this.

Method 1:
Refer to the monthly fuel consumption records.

Method 2:
Sum the monthly fuel consumption of each engine and divide that by the number of seconds in a month to give the rate of fuel consumption in gallons/s.

For each engine:

$$\text{monthly fuel consumption} = (\text{monthly idle Hrs} \times \text{idle rate of fuel consumption}) + (\text{monthly op Hrs} \times \text{op rate of fuel consumption}) \tag{2}$$

To determine the idle and operating rates of fuel consumption; monthly idle and operating hours were assumed to be accurate, and the above equation was equated to the result from Method 1. To determine values for the rate of fuel consumption at idle and while operating, the rate of fuel consumption at full load was retrieved from the engine manufacturers. Only one manufacturer had specifications for the rate of fuel consumption at idle, however most agreed that it would be equivalent to 10% of the rate of fuel consumption at full load. To determine the rate of fuel consumption while operating, the DDEC was used on the Detroit Diesel engines. The DDEC listed the hours of operation and the fuel consumed during operation. From this information, it could be determined that for all Detroit Diesel engines, the rate of fuel consumption while operating is 45% of the rate of fuel consumption at full load. This percentage was applied to all other engines. To confirm the accuracy of 10% and 45%, the above equation was calculated with these values for each engine underground and the result was compared to the result from Method 1. The calculations closed to within one percent.

4.0 RESULTS

	Averge per Month - 2002		**Meikle**	**Rodeo**	**Total**
Study	Total Engine Hours (Engine Meter)	Hrs	10,375	8,765	19,140
	Total Horsepower Hours per month	hpHrs	563,135	398,997	962,133
	Hours per month	Hrs	720	720	720
	Average Horsepower at any given time	hp	782	554	1,336
	Ventilation (actual)	cfm	860,000	900,000	1,760,000
	Ventilation/hp	cfm/hp	1,100	1,624	1,317
	Total Fuel (study)	gallons	27,822	22,417	50,239
	Total Fuel (actual)	gallons	28,000	22,000	50,000
	% Difference	%	1%	2%	0%
Study	Power in mine at any point in time	J/s	583471	413406	996876
	Heat rejected to air	J/s	875206	689009	1661461
Actual	Total fuel	L	106120	83380	189500
	Rate of fuel consumption	L/s	0.04094	0.03217	0.07311
	Energy Content of Fuel - Calorific Value	J/L	35600000	35600000	35600000
	Energy from fuel	J/s	1457512	1145188	2602701
	Useful work from fuel	hp	782	614	1396
	Heat rejected to air	J/s	874,507	687,113	1,561,620
	%Difference		0.8%	2.2%	6%

Table 1 Summary of all results.

Total Engine Hours were determined by the corrected engine meter readings.

Total Horsepower hours were determined by summing the total monthly horsepower hours for each engine.

$$\text{Total monthly hpHrs for each engine} = (\text{monthly idle hrs} \times \text{idle hp}) + (\text{monthly op hrs} \times \text{op hp}) \tag{3}$$

Idle horsepower was 10% of the rated brake horsepower of each engine and the operating horsepower was 42% of the rated brake horsepower of each engine. Monthly idle hours and monthly operating hours were determined by multiplying the monthly engine hours by the respective factor of the piece of equipment. Those hourly factors, determined as described in Section 3.1, are shown in Table 2.

Equipment	Running Factor	Idle Factor
LHD	0.5	0.5
Haul Truck	0.5	0.5
Drills	0.9	0.1
Bolters	0.9	0.1
Shotcrete	0.75	0.25
Scissors	0.6	0.4
Crane Boom	0.6	0.4
Emulsion	0.6	0.4
Maintenance	0.5	0.5
Cassette	1	0
Tractors	0.6	0.4
Forklifts	0.6	0.4
Miscellaneous	1	0

Table 2 Factors of the different categories of equipment.

Total monthly fuel consumption is determined using equation (4)

$$\text{Total monthly fuel consumption for each engine} = (\text{monthly idle Hrs} \times \text{idle fuel consumption}) + (\text{monthly op Hrs} \times \text{op fuel consumption})$$
(4)

Idle fuel consumption was equivalent to 10% of the fuel consumption at full load as determined by the manufacturer, and the operating fuel consumption was equivalent to 45% of the fuel consumption at full load as determined by the manufacturer. Table 3 lists the full load fuel consumption of each engine used underground and the equivalent fuel consumption at idle and while operating.

	Horsepower	Fuel Consumption 45% Load g/hr	Idle	100% Load
Cat - 3046	80	2.0	0.6	4.4
Cat - 3054	88	2.1	0.6	4.6
Cat - 3304	135	2.8	0.8	6.3
Cat - 3306	140	2.9	0.9	6.5
Cat - 3408	490	11.6	2.0	25.8
Cummins - 3.3	110	2.0	2.0	4.4
Cummins - 5.9	152	3.9	4.0	8.6
Detroit - 471	180	4.1	0.4	9.0
Detroit - Series 50	250	5.7	0.5	12.6
Detroit - Series 60	285	6.8	0.8	15.1
Deutz - 1012	94-145	2.6	0.3	5.8
Deutz - 1013	145	3.6	0.4	7.9
Deutz - 912	52-86	3.0	0.3	6.7
John Deere - 3029	60	0.9	0.5	2.0
John Deere - 4045	80	1.0	0.6	2.3
Kubota - 1902	40	1.0	0.5	2.2
Kubota - 2203	49	1.8	0.9	4.1
Kubota - 2803	50	1.5	0.7	3.3
Kubota - 3300	68	1.8	0.6	4.1
Mazda	50	1.4	0.6	3.2
Mitsubishi - S4S	38	1.8	0.7	4.0
VM Motori - 704	82	2.9	1.1	6.4
VM Motori - 706	130	3.4	1.4	7.5

Table 3 Engine power output and corresponding fuel consumption

Heat rejected to the mine ventilation air is calculated using a diesel engine efficiency of 40%.

$$\text{Diesel engine efficiency} = \frac{\text{Useful work (hp)}}{\text{Useful work (hp)} + \text{Rejected heat}} = .4 \quad (5)$$

Rearranging this gives,

$$\text{Heat rejected} = \text{Useful work} \times 1.5. \quad (6)$$

The rate of fuel consumption is calculated by dividing the total fuel monthly average by the number of seconds in a month. The heat content of fuel used is the calorific value of Number 2 diesel fuel. The energy from fuel is calculated by multiplying the rate of fuel consumption by calorific value. This represents the sum of useful work and rejected heat of the engine. Heat rejected to air is calculated by multiplying the energy from fuel by .6, because 60% of the energy from fuel is rejected as heat, assuming an engine efficiency of 40%.

	Temp. Wet/Dry	Vol. Flow Rate	Vol. Flow Rate	Mass Flow Rate	Enthalpy	Heat Flow
	Fahrenheit	cfm	m^3/s	kg/s	kJ/Kg	kJ/s
Miekle						
Intake -shaft	42/42	1,040,000	491	472	40	19,090
Intake						
From Meikle	42/42	620,000	293	281	40	11,381
From Rodeo	45/45	240,000	113	109	44	4,836
Exhaust	72/90	860,000	406	390	103	40,100
Rate of heat addition in mine (kJ/s)						23,884
Rodeo						
Intake - shaft	45/45	720,000	340	327	44	14,508
Intake						
From Rodeo	45/45	480,000	227	218	44	9,672
From Meikle	42/42	420,000	198	190	40	7,709
Exhaust	75/90	900,000	425	408	109	44,434
Rate of heat addition in mine (kJ/s)						27,053
			kJ/s	% of total heat addition	kJ/s	% of total heat addition
Meikle - Heat input from diesel engines			875	3.66%	875	3.66%
Rodeo - Heat input from diesel engines			689	2.55%	687	2.54%

Table 4 Results from all heat calculations.

Rate of Heat addition in the mine is determined by:

$$\dot{Q} = \dot{m}(E_2 - E_1) \tag{7}$$

$$\dot{Q} = -((\dot{m}\times E)_{Meikle} + (\dot{m}\times E)_{Rodeo}) + (\dot{m}\times E)_{Exhaust} \tag{8}$$

Heat input from diesel engines was solved for in the above results as the heat rejected by diesel engines. Percentage (%) total heat addition is calculated by dividing the heat rejected by the diesel engines by the total heat gain in the mine ventilation air.

5.0 DISCUSSION

In evaluating the effects of diesel equipment used underground an actual usage analysis is necessary as opposed to using blanket nameplate engine output brake horsepower. Not all equipment is utilized to the same extent throughout the shift in a 24-hour cycle and therefore determining an effective horsepower used is an accurate way of assessing diesel engines.

By careful tracking of each equipment engine over the shift and maintenance cycle, more accurate data can be obtained on all equipment used underground to determine an overall horsepower output for the mine. In this study, it is interesting to note that although the total equipment nameplate horsepower is 21,200 hp, only about 1,336 hp is the actual operating power at any one time. This is only about 6.3% of effective usage. Most of the time an engine is either idling or is operating at part load. Perhaps a very tiny fraction of the time full load is achieved. The equipment may be waiting to fill its part of the cycle. For example, scissor lifts, shotcrete machines, or bolters may be used only for a small fraction of the time in a 24-hour cycle because these activities are not continuous. Large equipment such as loaders or heavy haul trucks may also be used only for a short time at full load in a production cycle.

For this study an assumption is made that most good diesel engines will operate at an efficiency of about say 40%. Only this percentage of the used diesel fuel is used for useful work and the other 60% is rejected as heat in the mine ventilation air. This assumes of course, that other substances found in the diesel fuel such as sulfur can be neglected. Using this assessment, the net amount of heat rejected to the mine air is calculated from the effective operating cycle of the equipment and hence the actual used horsepower. This effective engine horsepower, which amounts to 782 hp for Meikle/Griffin and 554 hp for Rodeo, and was obtained from engine operating data, has been compared to the overall power from monthly fuel consumption data (Table 1). The two horsepowers are very close. Using fuel information gives a very good estimate of power generated by the diesel engines and all other secondary parameters.

Calculation of the overall heat gain of the main ventilation air is very simple because the enthalpy of the air at the intake and exhaust is known and the difference is the net amount of heat picked up by the air as it travels throughout the mine. The heat gain in Meikle/Griffin area is 23.88 MW and that for Rodeo alone is 27.05 MW making a total of 50.93 MW for a combined airflow of 866 kg/s. Respectively in Meikle/Griffin and Rodeo the percentage engine heat contribution to the overall mine ventilation air is 3.7% and 2.6%.

The net amount of airflow for the operating engine horsepower is about 1,100 cfm/bhp for Meikle/Griffin and 1,624 cfm/bhp for Rodeo. This seems to be very high, but if the same computation is carried out in blind headings where the airflow rate is limited to, say 40,000 cfm, the cfm/bhp comes out lower. This data shows clearly that in Meikle/Griffin and Rodeo the overall heat load is due to the virgin rock which measures about 140 ^{o}F. In certain cases, drilled holes can exceed temperatures of 200 ^{o}F. In some parts of the mine especially in Griffin and Rodeo very hot saturated water vapors are a common site. Oxidation of the sulfide rock is also a major contributor of heat.

Despite the fact that the mine air is refrigerated for all intakes with typical temperatures of around 40 ^{o}F, some parts of the mine experience very hot temperatures with wet and dry bulb temperatures of 90 ^{o}F and 110 ^{o}F, respectively.

Diesel Particulate Matter (DPM)

The same analysis for diesel engines can be used to assess the DPM problem. Assuming that the DPM found in the ventilation air originates from underground equipment, the DPM measured in the overall exhaust mine air correlates to the net horsepower of the operating equipment. If DPM samples are collected over a 24-hour period and at the same time all diesel operating activity also is logged accurately, a pattern will eventually emerge for a particular mine say, over a six month period, which can be used to reduce pollution rates for a mine. If DPM is a problem, an assessment can be made whether poor maintenance is to blame or the ventilation rate need to be increased. Typically, in Rodeo and Meikle area, DPM samples range between 200 and 600 μm^3 for elemental carbon. Sometimes, these figures are exceeded depending on the area and the activity at the time of the measurements. The current MSHA regulation is 400 μm^3 and will be 160 μm^3 in 2006 .

It is quite possible that the overall DPM concentration measured in the mine exhaust air could be much less than the regulations, and yet in some areas where activities are intense the DPM concentrations are high. In that case it becomes necessary to compare all collected area samples with the DPM loading in the exhaust air and correlate that information with the operation of diesel equipment in those areas. Diesel equipment operator personal exposure samples also should be compared to the overall picture and remedial steps taken to reduce exposures.

One study that would be useful is to use a soot collection device with data logging on exhaust while an engine is operating. A diesel particulate trap can be designed that can be attached to the exhaust of the engine before the shift begins and removed at the day and the soot collected can then be correlated to the engine operating cycle and time. If this is carried out for each and every typical engine used in that mine, very accurate information can be obtained linking the effective operating horsepower or cycle, mine ventilation, DPM and all other pollution parameters including heat. Essentially all data eventually ties in the mine development and production activities. On average at the Barrick Goldstrike Mines Underground Division, about 50,000 gallons per month of diesel fuel are consumed and this amounts to 1,645 gallons per day or 68.5 gallons per minute or better still 1.14 gallons per second. It should be possible to construct some kind of relationship linking the fuel consumed, horsepower, DPM and ventilation air for the mine, assuming of course that all engines are well maintained per manufacturer’s guidelines.

6.0 CONCLUSION

This study has presented a very interesting method of analyzing diesel equipment used in underground mining. The total net operating horsepower of all diesel equipment used underground has been calculated using the actual engine logs and estimating percentage idle time and part load. It is found that the actual operating horsepower is much less that the nameplate horsepower of all diesel equipment added together. In this case it amounts to 6.3%, for the whole underground complex. The fuel consumption of the mine can also be used accurately to determine this useful power by assuming that all diesel engines in good conditions operate at 40% cycle efficiency and the rest (60%) of the fuel heat content is rejected to the mine ventilation air. The amount of heat added to the mine ventilation air from diesel equipment is very small, only 3% of the heat generated by the rock. The overall enthalpy heat gain for the underground complex is about 51 MW. A similar analysis can also be carried out linking the fuel consumed, mine ventilation air, the net effective operating horsepower and diesel particulate matter. Time averaged DPM concentrations could be linked to engine operating logs and very useful information may be obtained for reducing pollution due to diesel equipment. Overall mine ventilation exhaust DPM concentration could be compared to area and personal operator exposure concentrations and ventilation strategies may be formulated to improve the underground environment.

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