

## ESTABLISHING TOTAL AIRFLOW REQUIREMENTS FOR UNDERGROUND METAL/NON-METAL MINES BASED ON THE DIESEL EQUIPMENT FLEET

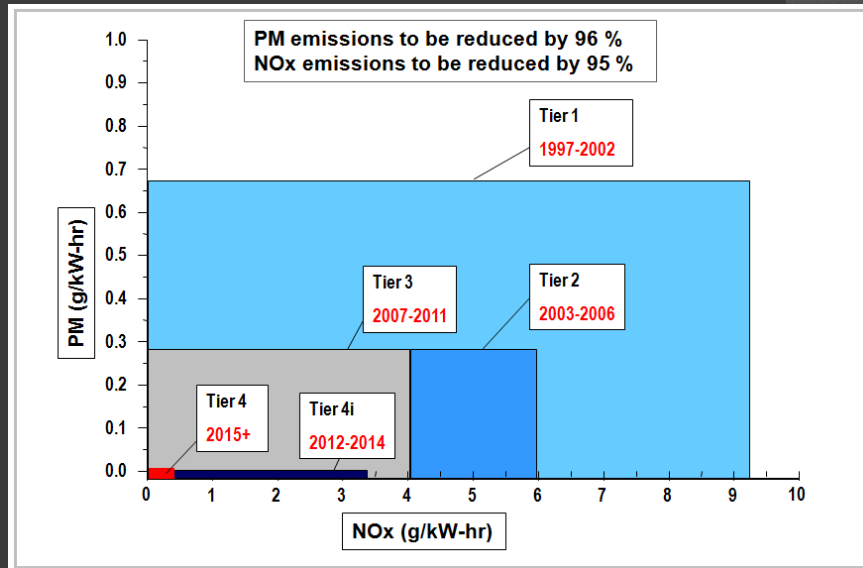
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### Overview

- Traditionally, total airflow requirements for underground mines were based upon the power of the underground diesel fleet.
- In an effort to improve overall air quality, the U.S. EPA mandated compliance with the so called “Clean Air Rules of 2004”, that were designed to decrease emissions from nonroad diesel engines by more than 90%, being implemented in a phased approach, with the most stringent requirements (Tier IV) becoming effective in 2014.

## Overview

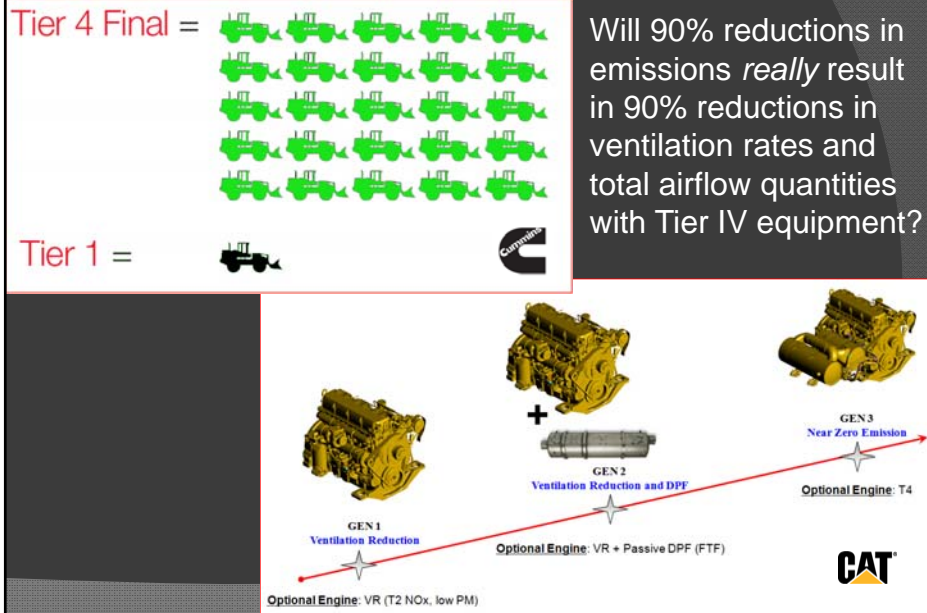


Emissions Reductions Required to Achieve Tier IV Compliance (Deutz).

## Overview

- In June 2012, IARC reclassified diesel engine exhaust as a human carcinogen (Group 1) based on sufficient evidence. Previously, diesel engine exhaust was classified only as *probably carcinogenic to humans* (Group 2A).
- The EPA Tier IV/Euro Phase IV regulations have resulted in widespread confusion and uncertainty regarding the amount of airflow required to safely operate diesel equipment in underground mines.
- This thesis was envisioned to address this need within the industry for a specific, repeatable protocol for calculating total airflow quantities required for the ventilation of underground diesel equipment.

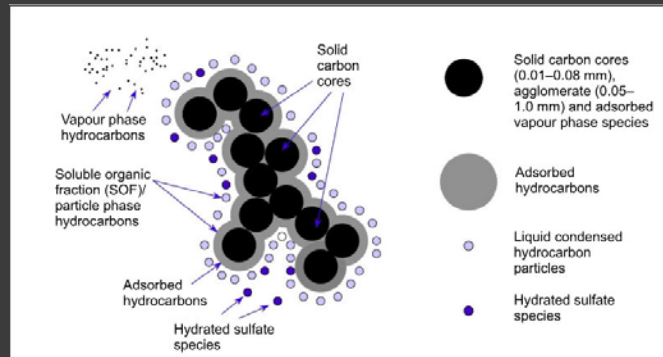
## Overview



## Diesel Contaminant Products

- toxic gases (CO, CO<sub>2</sub>, NO<sub>x</sub>)
  - particulates (DPM)
  - heat
  - mineral dust
- Each component has unique qualities that pose particular threats to humans and require individual mitigation strategies.

# Particulate Emissions

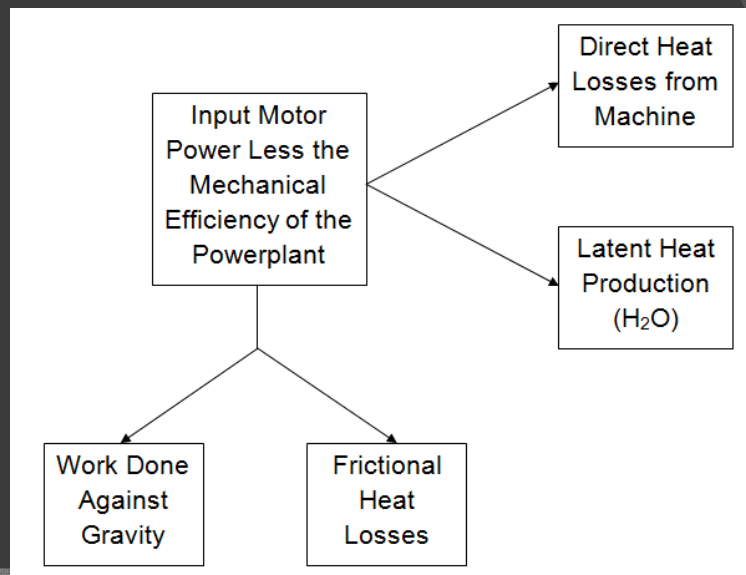


Graphical Representation of Aerosol DPM (Twigg and Phillips, 2009).

- Particles < 1 micron in diameter.
- Frequently adsorb other harmful chemicals (e.g., aromatic hydrocarbons, aldehydes, etc).
- Health effects are still being identified and quantified.

## Heat

Diesel-powered equipment can be expected to produce roughly three times as much heat (kW) as mechanical work (kW).



Heat Production of Diesel Engines by Type/Mode.

## Mineral Dust

- ◉ Classification
  - component particle size (respirable and non-respirable)
  - mineral composition (e.g. silica, asbestos, coal, etc.).
  
- Toxic Dust
- Carcinogenic Dust
- Fibrogenic Dust
- Explosive Dust
- Nuisance Dust
  
- ◉ The negative health effects of various forms of dust can vary significantly from minor discomfort to acute and life-threatening symptoms.

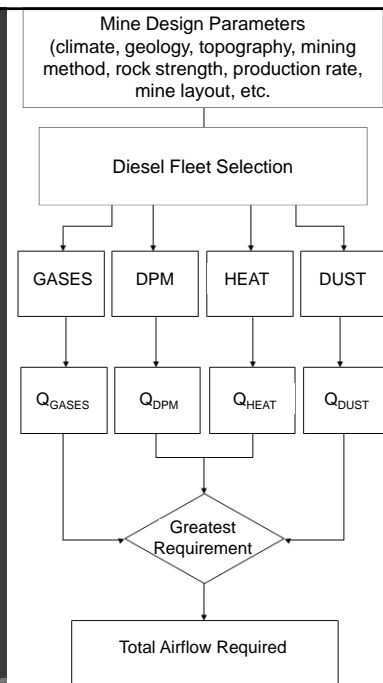
## Existing Method(s)

- ◉ Multiplier of the equipment power and with reductions made for the utilization and/or availability of individual pieces of equipment.
- ◉ Disadvantages
  - non-scientific / experience based
  - inefficient
  - unpredictable
  
- ◉ Nameplate or Approval rates for individual engines.
- ◉ Disadvantages
  - engine-specific information may not be available
  - does not account for heat and dust

## Proposed New Method

- Any proposed new method must account for all four contaminant types generated by underground diesel equipment (i.e., Gases, Particulates, Heat and Dust).
- Any proposed new method must be based on existing scientific knowledge and principles.
- Any proposed new method must be practicable and “reasonable”.

## Proposed New Method



Relationship between Design Parameters and Ventilation Rates.



## Gaseous POC and DPM

Historic Ventilation Rates for Approved MSHA Engines (Haney, 2012).

EPA Tier	Number of Engines Tested	Gaseous Vent Rate, m <sup>3</sup> /s/kW (cfm/hp)	PI, m <sup>3</sup> /s/kW (cfm/hp)	5 × PI, m <sup>3</sup> /s/kW (cfm/hp)
Non EPA Compliant Less than 73 kW (99 hp)	21	0.050 ± 0.057 (79 ± 90)	0.119 ± 0.088 (188 ± 139)	0.595 ± 0.438 (942 ± 693)
Non EPA Compliant Gr. or Eq. to 73 kW (99 hp)	41	0.038 ± 0.0076 (60 ± 12)	0.059 ± 0.024 (94 ± 38)	0.297 ± 0.119 (468 ± 188)
Tier 1/2 Less than 73 kW (99 hp)	73	0.030 ± 0.0095 (60 ± 15)*	0.041 ± 0.015 (65 ± 24)	0.206 ± 0.076 (324 ± 120)
Tier 1/2 Gr. or Eq. to 73 kW (99 hp)	141	0.035 ± 0.0076 (55 ± 12)*	0.012 ± 0.0095 (31 ± 15)	0.098 ± 0.047 (156 ± 74)
Tier 3 Less than 73 kW (99 hp)	27	0.032 ± 0.0044 (50 ± 7)**	0.028 ± 0.015 (44 ± 23)	0.139 ± 0.071 (219 ± 113)
Tier 3 Gr. or Eq. to 73 kW (99 hp)	47	0.025 ± 0.0032 (39 ± 5)**	0.025 ± 0.0089 (39 ± 14)	0.123 ± 0.046 (194 ± 72)
Tier 4	2	0.025 ± 0.0032 (39 ± 5)**	0.002 (3.2)***	0.010 (16.0)***

\*Based on NO

\*\*Based on CO<sub>2</sub>

\*\*\*Based on a PI of 0.01 gm/hp-hr.

## Gaseous POC and DPM

- Approved ventilation rates should be available in the future for all Tier IV engines, and nameplate values from NRCan and MSHA can be used for existing equipment fleets and older engines provided that the airflow required based on the contaminants of heat and dust are also calculated.
- For more general calculations, a value of 0.025 m<sup>3</sup>/s per kW (0.022 – 0.028) may be used for determining the airflow required for diluting gaseous contaminants and 0.010 m<sup>3</sup>/s per kW (0.009 – 0.011) for DPM.

## Heat

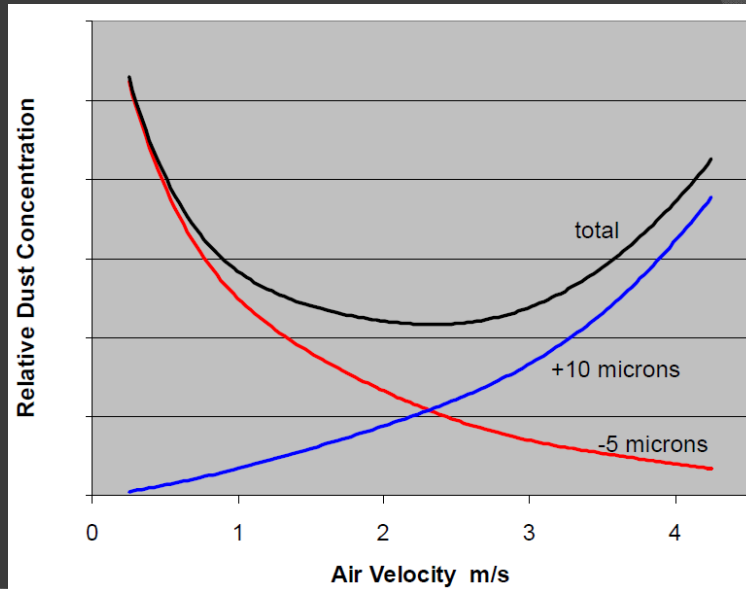
- ◉ Calculating the heat production from a diesel-powered machine can be practically accomplished through the following process(es):
- ◉ First, the **Total Heat** is determined based on the fuel consumption rate...
- ◉ Next, the **Latent Heat** is calculated...
- ◉ The **Sensible Heat** generated is simply the difference between the Total Heat and the Latent Heat...
- ◉ The associated **temperature** rise in the ambient air across the machine is a function of the mass flow rate of air (set to a certain point to ensure that conditions do not reach the design criteria for stop-work temperature)...
- ◉ The **mass flow rate** of air should be converted to a **volume flow rate** for comparison to the other ventilation rates.

## Mineral Dust

- ◉ Dust created by new diesel-powered equipment does not vary significantly from that generated by older equipment; the examination of how much airflow is required to remove the hazard has become more important based on the reduction(s) of the airflow required based on other contaminant products (i.e. gases, DPM).
- ◉ Ventilation remains the most commonly used means of removing mineral dust from the underground environment.
- ◉ Respirable (sub-micron) dust settles from the airstream at an almost negligible rate, and should be controlled via dilution in a manner similar to other gaseous contaminants. In the case of larger particles it is primarily the airflow velocity that dictates the distance and time the dust particles will be entrained in the air stream.

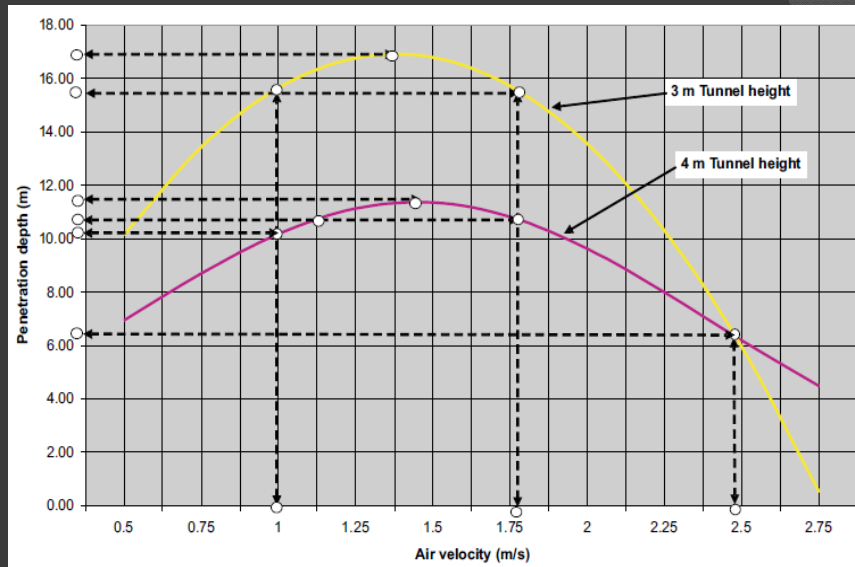


## Mineral Dust



Dust Concentrations at Various Air Velocities (McPherson, 2009).

## Mineral Dust



Air Penetration Depth vs. Airflow Velocity (Rawlins and Phillips, 2005).

## Comparison of Methods

- The total airflow required for an LHD was determined utilizing the existing methods of Direct Engine Testing and Empirical Derivation, as well as individually for the contaminants of Gaseous POC, DPM, Heat and Dust.
- The LHD selected for this comparison is the commercially available Sandvik LH517 powered by a Volvo TAD1361VE 285 kW Tier IVi engine.
- This LHD has a capacity of 17,200 kg or 7 cubic meters and is approved for use underground by NRCan under CSA M424.2-90 (non-gassy mines).
- Minimum drift dimensions of approximately 5 m wide by 6.5 m high are required for this Loader to achieve full mobility.

## Comparison of Methods

Comparison of Methods for Calculating Required LHD Airflow.

Method of Determining Airflow	Total Airflow (m <sup>3</sup> /s)	Ventilation Rate (m <sup>3</sup> /s per kW)	% of Greatest (%)
Direct Engine Testing*	5.9	0.021	18%
Empirical Derivation	18.0	0.063	55%
Proposed Method Gaseous POC	8.0	0.028	25%
Proposed Method DPM	3.1	0.011	10%
Proposed Method Heat	21.4	0.075	66%
Proposed Method Dust	32.5	N/A	100%

\*NRCan, 2011.

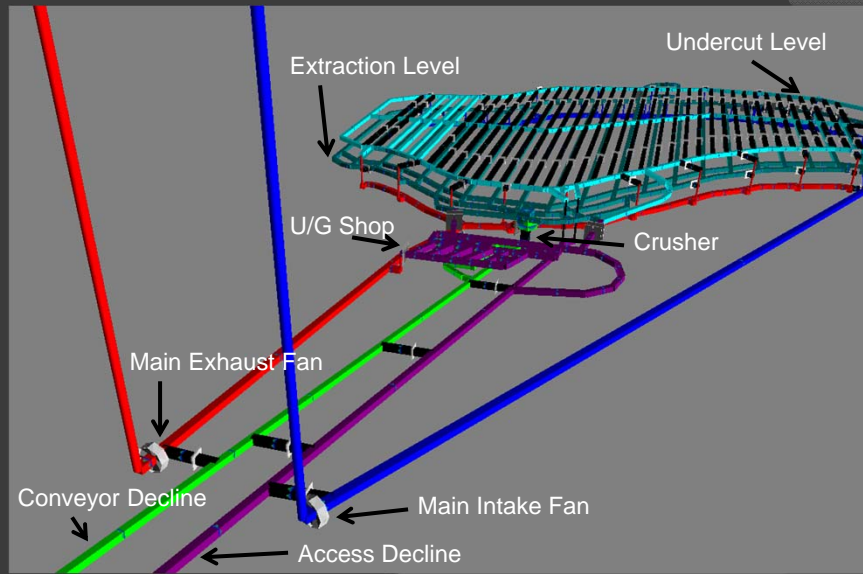
## Comparison of Methods

- ◉ Despite the significant reductions made in the gaseous POC and DPM emissions of the Tier IVi engine, the overall airflow required has not significantly changed, and may even be increased in cases where the critical design parameters of heat and dust were not previously considered.
- ◉ Clearly, a 90% reduction in required airflow that many anticipated based upon a similar decrease in the amount of gaseous and particulate contaminants at the tailpipe is not justified.

## Case Study

- ◉ A case study was performed to comprehensively evaluate the differences between the proposed new model for determining total airflow requirement for the diesel fleet.
- ◉ The mine chosen for this study was a North American metal mine that utilizes the block-caving technique for mineral extraction.
- ◉ Airflow requirements were first calculated using established techniques (statutory compliance dictates ventilation rates of 0.063 m<sup>3</sup>/s per kW of engine power).
- ◉ The total airflow was then determined based on the method(s) outlined in this thesis for the purpose of comparison.

## Case Study



Isometric View of the Main Mining Area.

## Case Study

- The implementation of the new method for making total airflow determinations had several profound impacts.

	Original Method Statutory Compliance	Proposed Method Greatest Demand	Difference (%)
Total Airflow (m <sup>3</sup> /s)	425	544	28%
Ventilation Shaft Diameter (m)	5	6	20%
Capital Cost (USD)	18,400,000	24,800,000	35%
Operating Cost (USD)	2,800,000	3,100,000	11%

## Case Study

- Other impacts included the slight increase in the size of the auxiliary duct diameter from 1.4-m to 1.5-m (resulting in decreased equipment clearance and a likely increase in both leakage (operating) and maintenance costs associated with the auxiliary ventilation systems).
- Although there was an increase in the amount of air required for the LHDs in the production panels this did not result in significantly higher airflows on the Extraction Level owing to the fact that these areas were previously limited by airflow velocity criteria (which at 1 m/s on the 5 m by 4.5 m drifts already required additional airflow over what was required for the equipment based solely on engine power).

## Case Study

- Additionally, it should be noted that since the equipment chosen for this case study was already Tier IVi, and that since a relatively high ventilation multiplier ( $0.063 \text{ m}^3/\text{s}$  per kW) was used to determine the original flows, the resulting change between scenarios is not nearly as dramatic as it could have been (e.g. if nameplate ventilation rates for Tier III equipment had been compared).
- This was done very much on purpose, however; and highlights a real, like for like comparison between the methods of calculation in a realistic scenario, and not simply recognition of the changes that stem from the reduction in engine emissions themselves.

## Conclusions

- ◉ Given the significant reductions in the emissions of modern diesel equipment, it seems highly unlikely that total flow calculations for future mines and mine expansions will be calculated based solely on tailpipe emissions.
- ◉ What is more likely is that other parameters will take precedence, and that in the future, airflow calculations will become slightly more complex and based on a combination of factors that will be unique to each mine.
- ◉ By revisiting the methodology for making total airflow determinations for diesel equipment in mines, it will be possible to improve the efficiency of mine ventilation systems and create a healthier environment underground.

## Conclusions

- ◉ The heat generated by Tier IV engines (particularly on the larger side of the spectrum) mandate a ventilation rate that is not significantly lower than what is commonly used today (generally developed empirically over years of study and measurement).
- ◉ Based on the heat production of diesel engines, the sensitivity analysis showed ventilation rates that varied from approximately 0.06 m<sup>3</sup>/s per kW to 0.094 m<sup>3</sup>/s per kW over the range of input parameters likely to be encountered in most mining scenarios with a rate of 0.075 m<sup>3</sup>/s per kW for “average” conditions.



## Conclusions

- These newly calculated rates reinforce long-used factors that have been developed prior to the drastic reductions in emissions resulting from the EPA Tier IV/EU Stage IV engine regulations, and further the belief held by some, that it is in fact diesel heat that is the limiting factor in determining required airflow rates for underground diesel equipment.
- Regardless of past scenarios (certainly, DPM and some noxious gases were cause for concern in pre-Tier engines), it is likely that heat is now the determining factor in calculating airflow requirements for Tier IV / Stage IV diesel engines except in cases of cold-climate mines and/or where other dust control methods (i.e., water) are not effectively utilized (or not possible).

## Conclusions

- As with any proposed change, it will be necessary to justify the added time and expense associated with both the calculations and the implementation of ventilation systems that use the protocol suggested in this thesis for determining the airflow needed for diesel equipment fleets.
- Through this thesis, a solid, scientific basis is formed and a case is made for why heat and dust from diesel equipment should be considered and included in making calculations of this nature.
- If it makes underground mines safer for their workers, is any greater justification needed, or even possible?

Questions?

