Diesel Emissions in Hard Rock Mines – Challenges and Solutions

OCCR Sudbury Symposium July 10/11. 2017

DRAFT VERSION

Jozef Stachulak, Ph.D, P.Eng; Mirarco
Context

• Diesel Emissions
• Why it Matters?
• Solutions at Glance
• DEEP Research and Learning's
• Breakthrough DPF Technology
• Next Steps: Implementation of Solutions and Further Work
DIESEL EMISSIONS
Formation of Diesel Emissions

• Combustion time in ICE is only milliseconds. Mixture of air and fuel can never be perfect.
• Combustion is > 99% complete! Efficiency very high.
• But this remaining 1% is a concern.
Diesel Engine Emissions (Kasper, 2010?)

Soot Particles
Ash Particles
Liquid Droplets

Gases:
CO, HC, NOx
PAH, Nitro-PAH

and many trace substances
Soot Particle

- black
- small
- anywhere
- inevitable
- carcinogenic
- Difficult to control
- Mass of one particle is $0.000\,000\,000\,001\,\text{mg} = 1\,\text{fg}$
- up to 10 Mio particles in one $\text{cm}^3$
- diameter = 0.1 micron

(source: Mayer, 2016)
Diesel Particulate Matter/Soot

• Most of the mass is composed of carbonaceous agglomerates
• Particles are coated by PAH and decorated by metal oxides
• There are **25,400 microns in one inch**, or 10,000 in one cm.
Size Comparison of Various Classes of PM

- **UFPs**: Hydrocarbon compounds, metal oxides, sulfates, etc <0.1 μm (microns) in diameter

- **PM2.5**: Combustion particles, organic compounds, metals, etc <2.5 μm (microns) in diameter

- **PM10**: Dust, pollen, mold, etc <10 μm (microns) in diameter

*Adapted from U.S. EPA*
The weakest size range of the Lungs is the strongest emission range of the Engines and the weakest size range of Filters.

The Lung is an open door for engine emitted particles.
Typical Diesel Particulate Size Distribution

Nuclei Mode - Usually forms from volatile precursors as exhaust dilutes and cools. In some cases this mode may consist of very small particles below the range of conventional instruments, Dp < 10 nm.

Coarse Mode - Usually consists of reentrained accumulation mode particles, crankcase fumes.

Accumulation Mode - Usually consists of carbonaceous agglomerates and adsorbed material.

Fine Particles
Dp < 2.5 mm

Ultrafine Particles
Dp < 100 nm

Nanoparticles
Dp < 50 nm

PM10
Dp < 10 mm

Normalized Concentration, dC/C_total/dlnDp

Diameter (nm)

Number
Surface
Mass
Deposition (Alveolar + Tracheo-Bronchial, ICRP 1994)
### Relevance of Particle Size

<table>
<thead>
<tr>
<th>Airborne mass concentration (μg/m³)</th>
<th>Particle diameter (μm)</th>
<th>Particles/ml of air</th>
<th>Particle surface area (μm²/ml air)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2</td>
<td>1.2</td>
<td>24</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
<td>153</td>
<td>120</td>
</tr>
<tr>
<td>10</td>
<td>0.02</td>
<td>2400000</td>
<td>3016</td>
</tr>
</tbody>
</table>

Table modified from data of G Oberdorster. The relevance of this lies in the fact that any monitor collecting all of these particles in these three different conditions would always give the same airborne mass concentration of 10 μg/m³. However, the physical characteristics of the cloud are very different for particle number and surface area and both of these are properties that might have important impact on the lung.

*Occup. Environ Med (2001)*
Solutions

Modern Engine
ENGINE MAINTENANCE
Clean-burning engine, good fuel to air ratio.

INCREASED VENTILATION
Increasing airflow, will lead to greater diesel exhaust dilution, but:

doubling flow requires eight times the power

DIESEL PARTICULATE FILTERS (DPF)
Reduction/Elimination of diesel soot from exhaust.
Engine Combustion Development was so far not able to eliminate Particle Emissions (Mayer 2007)

PM has been reduced but PN was not changed, particles are smaller \( \rightarrow \) more toxicity

Modern engines emit 10 % of the total particulate mass emitted by engines built two decades ago. Although these low emission engine technologies hold considerable promise for reducing the total mass of “soot”, the laboratories studies (Switzerland) demonstrated no reduction in the number of small nuclei-mode particles 20-500nm. (Mayer 2007)
An important factor in maintaining a clean-burning engine is the regular maintenance of the intake air cleaners. A blocked air filter increases the fuel to air ratio, resulting in an increase in tailpipe diesel particulate concentration. Similarly, dust-laden air causes engine wear and leads to an increase in diesel particulate matter (Waytulonis, 1992).

Source: Southwest Research Institute, USA
Improvements in ventilation have permitted the productivity of mines to be enhanced. Neither the first powered machines, nor the latest heavy duty scoop tram or haulage truck equipment could have been employed without an adequate supply of air. **Good ventilation is indispensable but would not be feasible to eliminate all of the diesel particulate matter emissions by itself.**
DEEP RESEARCH AND LEARNING'S
DEEP Program

DEEP focused on the importance of good ventilation practices, well planned maintenance, filter technology, use of high quality fuels and lubricants and measurement methods.

Vale conducted long term – 4 years over $2.5M evaluation of 9-nine state-of-the art DPF system retrofitted to heavy and light duty underground mining vehicles.

Develop Canadian expertise on the DPF technology and DPM measurement methodology.
• Both heavy duty and light duty underground vehicles can be fitted with DPF systems
• The systems can obtain a filtration efficiency of 98%
• Several challenges were:
  • Ability to eliminate the operator involvement from the operation of the filter
    » Plugging in for regeneration
  • Generation of NO\textsubscript{2} in filters with platinum catalyst

<table>
<thead>
<tr>
<th>NO\textsubscript{2} Concentrations [ppm]</th>
<th>Percentage Increase [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream of DPF</td>
<td>81.3</td>
</tr>
<tr>
<td>Downstream of DPF</td>
<td>32.9</td>
</tr>
<tr>
<td>Percent Increase</td>
<td>130.8</td>
</tr>
</tbody>
</table>

TCS (2001) 40.0 53.0 55.0 50.0
HI (2001)  34.0 51.0
TCS (2002) 40.0 53.0 55.0 50.0
HI (2002)  34.0 51.0

What is needed is a DPF system that works in a fashion similar to an catalytic converter that does not require operators intervention under normal operating conditions.

In the wake of DEEP studies, Vale undertook additional efforts in identifying products suitable for underground mining operations.

J. Stachulak, Bruce Conard,, M. Gangal; 2009, Experience and Evaluation of Innovative Diesel Particulate Filter System at Vale-Inco, presented at the International Mine ventilation Congress, New Delhi India
BREAKTHROUGH DPF TECHNOLOGY
Light duty vehicles were tested underground at Creighton Mine

HJS DPF system (SMF®-AR) installed on 33 kw Kubota and 60 kw locomotive

Results

The system:

- Removed more than 98% of DPM
- Regeneration is automatic and does not effect an operating cycle
- Tolerant of variations in engine operating conditions.
- Does not require downtime during operation (the spare unit was used at cleaning time)

The implementation of the SMF-AR systems is currently underway at two Vale’s mines in Sudbury region, having acquired over 10,000 hours of operation over multiple vehicles.

Mining version JM DPF system was selected for evaluation at Vale’s Creighton, Totten and CC Mines.

- Bench testing was carried out at CANMET’s Bells Corner Lab.
- JM DPF system was installed on a Caterpillar R1700 - LHD 263 kW HP Tier 3 engine.
The system was evaluated at steady-state and transient conditions.

- Low HC-injection rates (max. 190 ml/hour)
Diesel Emission Reduction Research (DERR) Project/s

- Consortium of:
  - Glencore Nickel
  - Glencore Copper
  - Vale Ontario
  - Vale Manitoba
  - KGHM
  - CAMIRO Mining Division

- 3 Projects under the DERR consortium were DPF trials for Light Duty and Heavy Duty, as well as a DOC study regarding NO₂ emission.
Breakthrough Post DEEP Projects – Production/Heavy Duty Vehicles

- Mining JM/CRT was tested at Totten in a surface application
  - Load rock from ground stock pile (~200,000 tons, 1200 hrs of operation), haul rock to dump site located 100 to 1000 feet away and dump into caved area
  - Modifications were made before next underground trial at Copper Cliff Mine
Totten Surface Trial

Operators Booth

Caved Zone

Remote LHD with DPF System

Rock stock pile area

Loading, Hauling, Dumping & pushing into cave area
Diesel Emissions Reduction Research Project
Results at Totten Mine

- Over-all the system operated very well with little maintenance issues and associated down time
- DPF regeneration did not require operator’s involvement
- After 630 hours of operation vibration loosened the components of the DPF system and corrections were made immediately to get the scoop running.
- DPF system accumulated 1200 hours
Diesel Emission Reduction Research (DERR) Project
Copper Cliff Underground Trial

• Mining-CRT was installed on a Caterpillar Elphinstone R1700 LHD with C11 263 kW HP Tier 3 engine in April of 2014

• Emission tests were completed weekly through the project to determine gaseous and soot emissions.
Diesel Emission Reduction Research (DERR) Project Results

- The system was able to:
  - Effectively reduce DPM concentrations and particle number count (+98%)
  - Operational acceptance
  - No increase in NO₂ emissions
- The equipment prep for the filter system included removal of one of the fuel tanks to make room for the double canister
- The system operated without intervention from the operator
- Low maintenance requirements. The project maintenance consisted of ECOM readings and data downloads.
- Minor challenges consisted of:
  - fuel injection corrections,
  - exhaust re-direction,
  - sensor wiring changes
- The project is complete and the LHD is currently operating with the filter in normal conditions and part of the diesel fleet.

Breakthrough/Results – 98% Elimination of Diesel Soot

- **The light duty applications** selected proved to be a practical solution.
  - Vale has 30 light duty DPF units operating on tractors,
  - locomotives and light duty trucks

- **The heavy duty application:**
  - Unit successfully eliminated 98%, accumulated 2000 hrs. The unit was removed and a spare unit re-installed within one shift
  - The LHD is currently in the normal production fleet

NEXT STEPS
Recommendation – Pathforward

- Applied research is urgently required to consolidate the diesel curtailment breakthrough
- Research partners: Canadian, International
Acknowledgements

- NIOSH, USA – Drs. A. Bugarski and G. Schnakenberg
- University of Minnesota, USA – Dr. W. Watts
- Dr M. Gangal, D. Young, B. Rubeli, E. Leung, and V. Feres, NRCan/CANMET
- LKAB and Boliden Mines, Sweden – L. Mukka and T. Eriksson
- Kali und Salz Mines, Germany – Dr H. Soenksen
- Univ. of Appl..Sces. Biel Bienne – Prof Dr Jan Czerwinski
- VERT, Switzerland – Dr. Andreas Mayer
- JM, UK/Germany – P. Werth and Dr R.O’Sullivan
- HJS/Germany – V. Hensel
- Cheryl Allen, Principal Engineer - Vale
- Vale’s Totten Mine Team
- Vale’s Creighton Mine Team