Field Evaluation of Diesel Particulate Filters: Size Selective Measurements of Aerosols in Mine Air and Engine Exhaust

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1

Introduction

- Ultimate goal is to reduce exposure of underground miners to diesel particulate matter (DPM) and noxious gases.
- Curtailment of DPM emissions at the source using diesel particulate filters (DPF) appears to be most viable solution to the problem.
- DPFs need to be optimized and proven for underground applications.

2

Introduction

- **Evaluation of diesel particulate trap technology at Noranda-Brunswick Mining Division (BM&S)**
  - The objective of this project is the long term field evaluation of four different types of diesel particulate filters (DPF) installed on the production vehicles (two trucks and two load-haul-dump, LHD vehicles).
  - Project is sponsored by international consortium Diesel Emissions Evaluation Program (DEEP).

3

Methodology

- Periodic measurements of DPM and gaseous emissions have been used to monitor **filtration efficiency** of the filters throughout trial period. The project also has for goal to investigate **durability** and **suitability** of the filters for underground applications.

PHASES

- Field measurements of tailpipe emissions.
- Measurement of effects of DPF on ambient concentrations of DPM (isolated zone study).
- Laboratory measurements of tailpipe emissions.

4

Methodology/Instrumentation

- **Nanomet**
  - Real time PAH monitor (elemental carbon);
  - Diffusion charger (total particulate matter);
  - Dilution system.
- **EC/OC analysis**
  - Sampling strategy;
  - Analysis using NIOSH Analytical Method 5040.
- **Size selective sampling**
  - Size distribution of aerosols:
    - By number, surface area or mass.
  - Additional information pertinent to health aspects;
  - Source attribution.

5

Size Selective Measurements

- **Objectives**
  - One objective was to assess the effects of selected aftertreatment technologies on size distribution of aerosols in mine air and diluted exhaust.
  - The other objective was to use results of those measurements to assess efficiency of tested diesel particulate filters in curtailing diesel particulate matter (DPM) emissions by number and volume.

6

Size Distribution of Aerosols in Mine Air

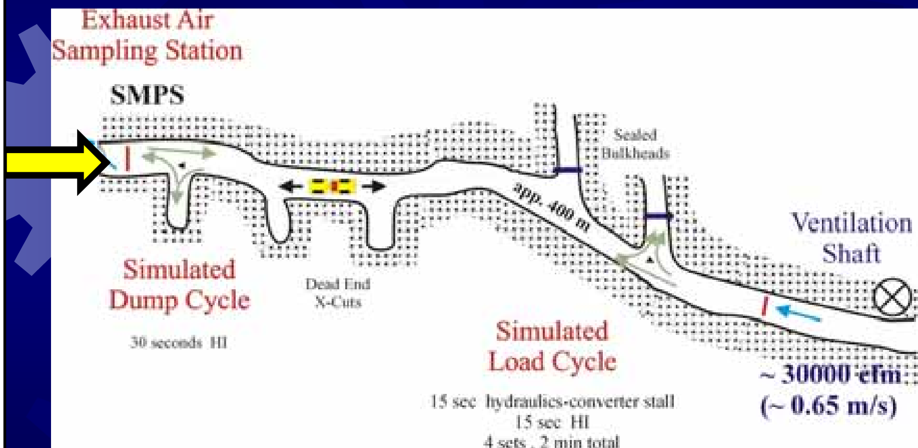
7

Isolated Zone

- The testing took place in the 400-meter long isolated zone at level 525 of BM&S.
- Cross-sectional area of opening at the sampling station was 21 m^2 (230 ft^2)
- There was no production in the zone and neighboring levels.
- Zone was isolated from the other parts of the mine by sealed bulkheads and ventilated with fresh air.

8

Figure 1. Isolated Zone



9

Ventilation

- Ventilation air was introduced directly from the surface through ventilation shaft located 100 meters upstream of the zone.
- Ventilation rate was maintained at about 14 m^3/s (30000 cfm) for duration of the testing.
- Temperature at surface was about –20 ^oC.
- Ventilation air was heated at the surface using cycling propane burners.
- Air temperatures at inlet to the zone was ranging between 5 and 8 ^oC. The temperature at sampling point (at downwind end of the zone) was 5 to 15 ^oC.

10

Test Vehicles

- Six production vehicles were tested (Table 1):
  - Three trucks:
    - Two retrofitted with DPF,
    - One equipped wit DOCC and muffler
  - Three LHDs:
    - Two retrofitted with DPF,
    - One equipped wit DOCC and muffler.
- Each of the six test vehicle was individually operated in 400-meter long test zone.
- All the test vehicles were operated by single experienced miner over the same, custom designed, duty cycle.
- The vehicles were introduced into the zone after background measurements were concluded.

11

Table 1. Test Vehicles

Vehicle	Engine Rating	Aftertreatment Technology	Fuel	Hours of operation with after-treatment Installed
Truck 1	375 Hp el. contr.	DOCC and muffler	Diesel	500
Truck 2	375 Hp el. contr.	Silicon carbide monolith DPF	Diesel + Additive	1848
Truck 3	375 Hp el. contr.	Knitted fiber DPF	Diesel + Additive	878
LHD 1	325 Hp el. contr.	DOCC and muffler	Diesel	300
LHD 2	325 Hp el. contr.	Catalyzed ceramic monolith DPF	Diesel	2129
LHD 3	325 Hp el. contr.	Silicon carbide monolith DPF elec. regenerated	Diesel	1823

12

Duty Cycle

- The duty cycle consisted of:
  - 2-minute load cycle of 4 repetitions of two a 30-second full throttle work cycle: 15 seconds torque converter stall with hydraulics engaged; 15 seconds no load (high idle). performed at the load point at upwind end of the zone.
  - Normal vehicle driving from the load point to the downwind dump point followed by three point turnaround.
  - 30-second dump cycle at high idle at the dump point.
  - Normal vehicle driving back to the load point with a three point turnaround.
- Trucks and load-haul dump vehicles were loaded with ore prior to the testing and operated loaded throughout the tests.

13

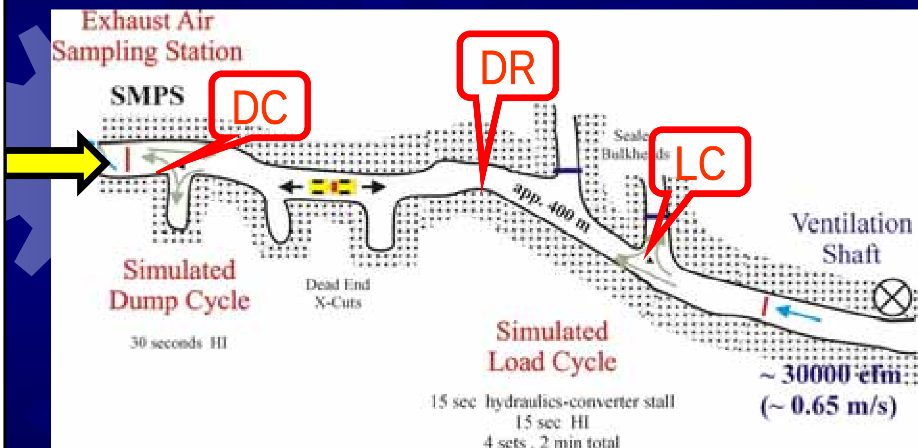
Instrumentation

- Scanning Mobility Particle Sizer (SMPS, TSI Inc.) was used to measure size distributions of aerosols in mine air. Particle concentrations in the air were in the instrument range therefore additional dilution was not required.
- SMPS Model 3936 (EC Model 3081, CPC Model 3025) parameters were kept unchanged throughout sampling
  - Instrument was operated in steady-state mode (60 + 15 second scan).
  - Particles with electrical mobility diameters in range from 10 to 392 nm were measured.
- Sampling sequence*:
  - vehicle performing load cycle at load point;
  - vehicle driving toward dump point/sampling station;
  - vehicle performing dump cycle at dump point.

* Delay times were estimated on the basis of measured air velocity

14

Figure 2. Sampling Methodology



15

Size Distribution of Aerosols in Mine Air Methodology

- Sampling was conducted over four-hour period (30-34 data sets were collected for each of the vehicles and for each of the stages in the duty cycle).
- In order to allow comparison of the results obtained for different vehicles, the concentrations were corrected for vehicle-to-vehicle fluctuations in ventilation rate.
- Performance of the aftertreatment devices is judged on a basis of averaged integral count concentrations for instrument range (10 – 392 nm) and averaged integral volume concentrations calculated using assumption about spherical shape of the particles.

16

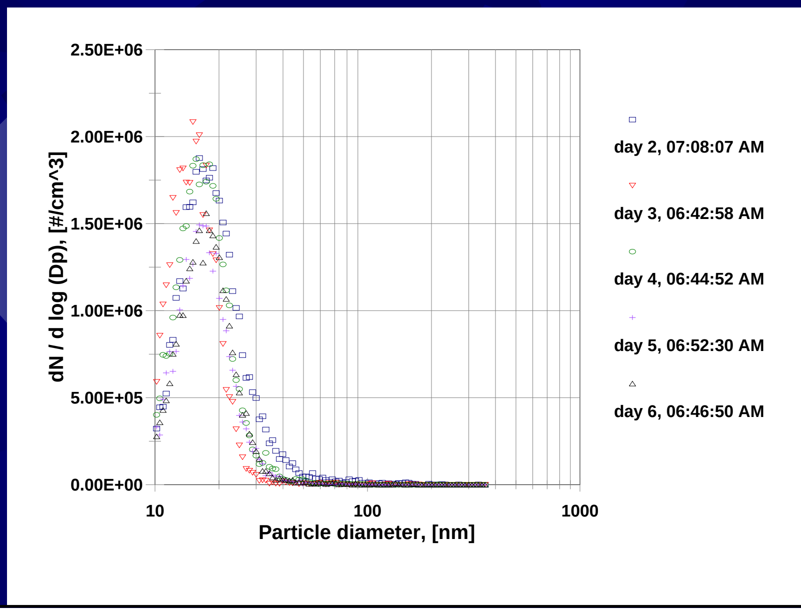
Figure 3. Scanning Mobility Particle Sizer at Sampling Station

17

Results of Size Distribution Measurements in Mine Air

18

Figure 4. **Size Distribution of Aerosols in Mine Air Prior to Introduction of the Vehicles in the Zone**



19

Size Distribution of Aerosols in Mine Air Prior to Introduction of the Vehicles in the Zone

- Relatively high concentrations of nanoparticles (d_{50} ~ 15 nm) in the air prior to introduction of diesel powered vehicles into the zone.
- The most probable source are cyclic propane burners used for heating ventilation air at the intake structure.
- The sampling station was located about 1000 meter downstream of the intake structure and burners.
- Potentially provide nucleation core for diesel exhaust constituents.
- Chemical composition was not determined.

20

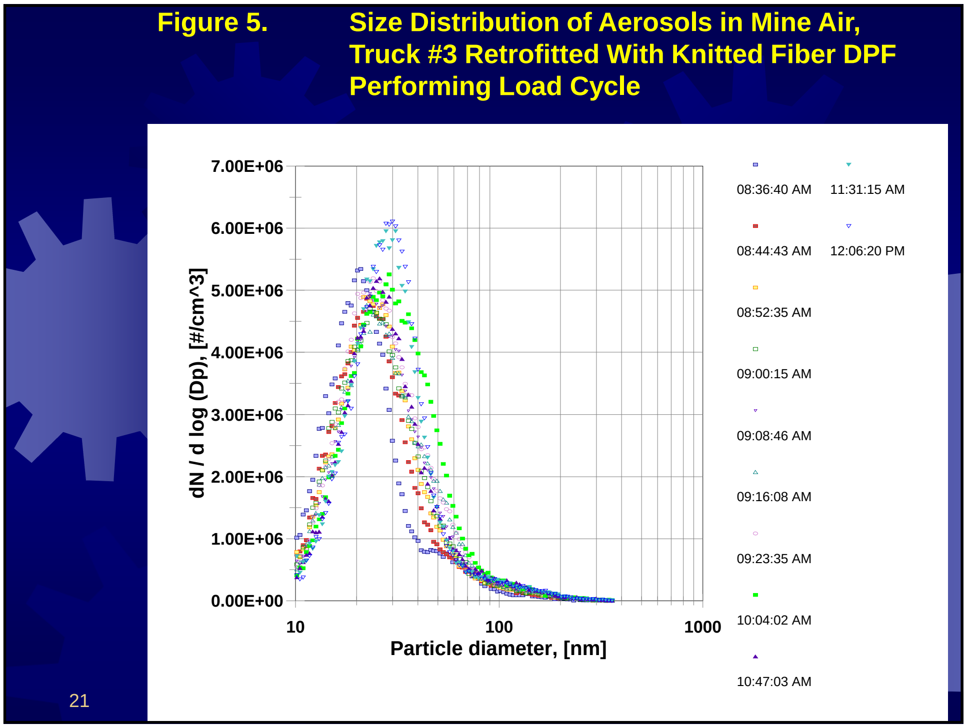


Figure 5.
Size Distribution of Aerosols in Mine Air, Truck #3 Retrofitted With Knitted Fiber DPF Performing Load Cycle
7.00E+06
6.00E+06
5.00E+06
4.00E+06
3.00E+06
2.00E+06
1.00E+06
0.00E+00
dN / d log (Dp), [#/cm^3]
10
100
1000
Particle diameter, [nm]
08:36:40 AM
08:44:43 AM
08:52:35 AM
09:00:15 AM
09:08:46 AM
09:16:08 AM
09:23:35 AM
10:04:02 AM
10:47:03 AM
11:31:15 AM
12:06:20 PM
21

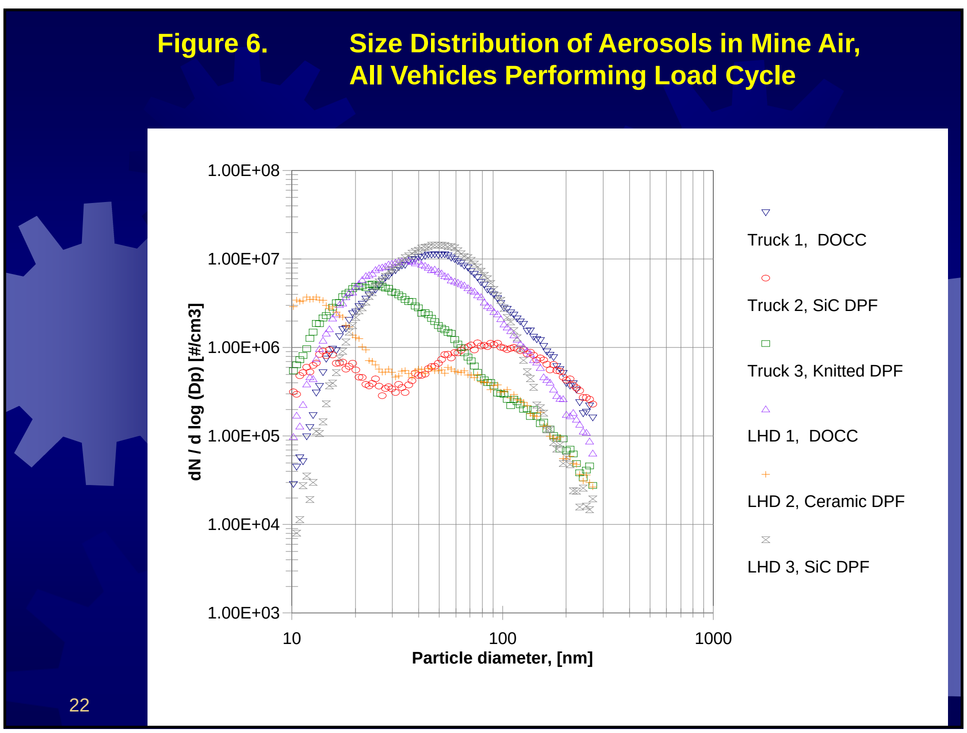


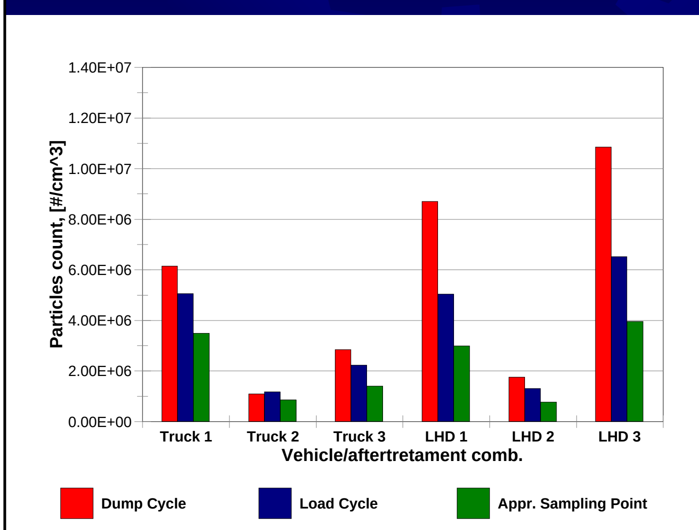
Figure 6.
Size Distribution of Aerosols in Mine Air, All Vehicles Performing Load Cycle
1.00E+08
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
dN / d log (Dp) [#/cm3]
10
100
1000
Particle diameter, [nm]
Truck 1, DOCC
Truck 2, SiC DPF
Truck 3, Knitted DPF
LHD 1, DOCC
LHD 2, Ceramic DPF
LHD 3, SiC DPF
22

Size Distribution of Aerosols in Mine Air

- Size distributions of aerosols in the mine air downstream of the all tested vehicles were not changing significantly over four-hour test periods.
- The distributions for the vehicles retrofitted with filters were found to be bimodal, with **relatively high concentrations of nanoparticles** (D_{50} < 50 nm).
- The distributions for the vehicles equipped with DOCC were found to be characterized with relatively **high concentrations of ultra fine particles** (D_{50} < 100 nm).

23

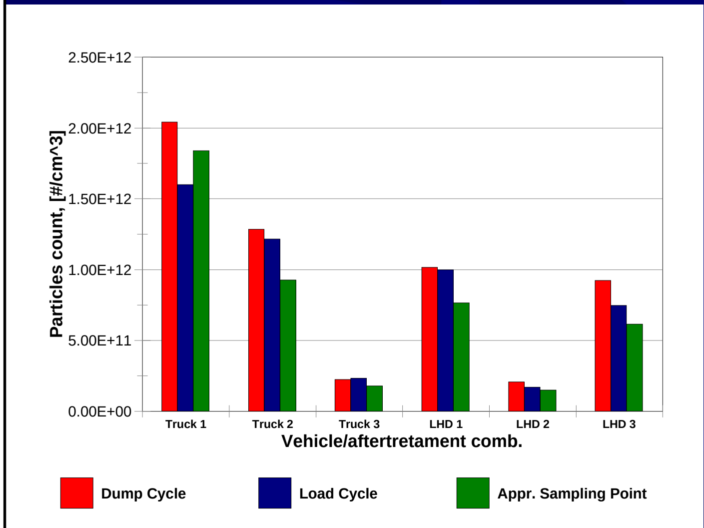
Figure 7. Effects of Diesel Particulate Filters on Total Particle Count Concentrations in Mine Air



Vehicle	Mean	STD
Dump cycle		
Truck 1	6.15E+06	1.59E+06
Truck 2	1.09E+06	1.72E+05
Truck 3	2.84E+06	6.70E+05
LHD 1	8.70E+06	1.21E+06
LHD 2	1.76E+06	4.96E+05
LHD 3	1.09E+07	1.54E+06
Load Cycle		
Truck 1	5.05E+06	9.23E+05
Truck 2	1.17E+06	1.01E+06
Truck 3	2.23E+06	4.20E+05
LHD 1	5.03E+06	9.37E+05
LHD 2	1.31E+06	2.93E+05
LHD 3	6.52E+06	1.95E+06
Appr. Sampling Point		
Truck 1	3.49E+06	8.59E+05
Truck 2	8.63E+05	5.50E+05
Truck 3	1.40E+06	1.36E+05
LHD 1	2.99E+06	1.72E+05
LHD 2	7.68E+05	8.83E+04
LHD 3	3.96E+06	1.66E+05

24

Figure 8. **Effects of Diesel Particulate Filters on Total Concentrations of Particles by Volume in Mine Air**



Vehicle	Mean	STD
Dump cycle		
Truck 1	2.04E+12	1.59E+06
Truck 2	1.09E+06	1.72E+05
Truck 3	2.24E+11	4.75E+10
LHD 1	1.02E+12	1.90E+11
LHD 2	2.07E+11	2.88E+10
LHD 3	9.25E+11	3.43E+10
Load Cycle		
Truck 1	1.60E+12	1.60E+11
Truck 2	1.22E+12	1.66E+11
Truck 3	2.34E+11	2.52E+10
LHD 1	1.00E+12	1.06E+11
LHD 2	1.70E+11	2.37E+10
LHD 3	7.48E+11	1.91E+11
Appr. Sampling Point		
Truck 1	1.84E+12	1.76E+11
Truck 2	9.28E+11	2.97E+11
Truck 3	1.80E+11	1.97E+10
LHD 1	7.66E+11	1.48E+11
LHD 2	1.50E+11	2.08E+10
LHD 3	6.15E+11	5.40E+10

25

Effects of Diesel Particulate Filters on Total Concentrations of Particles

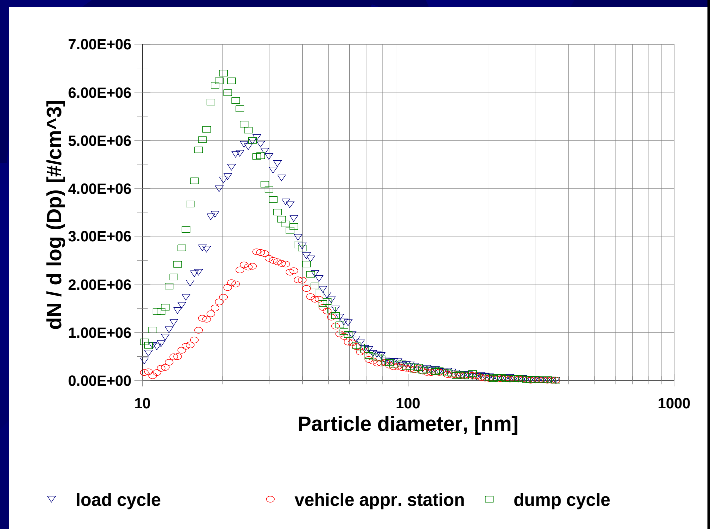
- All the filters, except the filter installed on **LHD #3**, offered excellent reductions in particle number concentrations in the mine air.
- Estimated reductions in particle volume/mass were bellow expectations for the filters installed on **Truck #2** and **LHD #3**.
- The exhaust systems on all the vehicles equipped with DPF showed evidence of **leaks in the exhaust system** between engine and filter. This diminished the effectiveness of the filters to reduce work place concentrations.
- Maintaining **integrity of the exhaust system** is crucial for meeting new DPM work place exposure standards.

26

Figure 9. **Truck #3 Equipped With Knitted Fiber DPF, Particle Aging, Number**

Integral Number of Particles [#/cm³]:

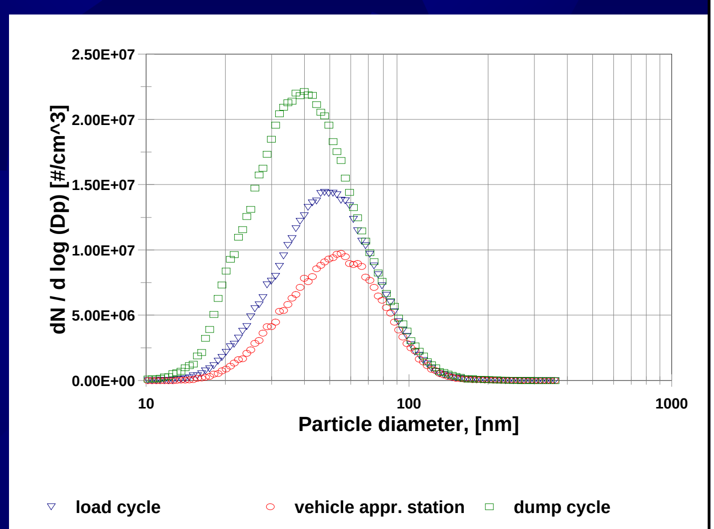
LC = 2.38e+6
VAS = 1.32e+6
DC = 2.78e+6



27

Figure 10. **LHD #3 Equipped With SiC Monolith DPF, Particle Aging, Number**

Integral number of Particles [#/cm³]:
LC = 6.64e+6
Vas = 4.39e+6
Dc = 1.10e+7



28

Particle Aging

- Size distributions of particles were significantly affected with position of the vehicles relative to sampling station and engine operating conditions.
- It appears that due to coagulation, adsorption and other physical processes, the number of the nanoparticles rapidly decayed with time, therefore, distance of the vehicle/engine from the sampling station.
- Larger particles appears not to be significantly affected by those processes.
- Determining exposure of the miners to DPM is delicate dusk.

29

Size Distribution of Aerosols in Tailpipe

30

Objective and Method

- Objective was to measure size distributions and concentrations of DPM **upstream and downstream of the tested filters** and use those results to estimate their efficiency in curtailing DPM emissions.
- Testing took place in the underground shop at Noranda BM&S mine in June 2001.

31

Table 2. Test Vehicles

Vehicle	Engine Rating	Aftertreatment Technology	Fuel	Hours of operation with after-treatment Installed
Truck 2	375 Hp el. contr.	Silicon carbide monolith DPF	Diesel + Additive	160
Truck 3	375 Hp el. contr.	Knitted fiber DPF	Diesel + Additive	1503
LHD 3	325 Hp el. contr.	Silicon carbide monolith DPF elec. regenerated	Diesel	2715

- LHD 2, retrofitted with catalyzed ceramic filter, tested in the previous phases of the study, was buried inside a draw point in May 2001 and it was not available for this testing.
- The SiC filter installed on Truck #2 was replacement filter with only 160 hours of deployment since new.

32

Vehicle/engine Operating Conditions

- The first challenge was to obtain **reproducible steady state engine operating conditions** for vehicles positioned vis-a-vis instrumentation station. Fortunately, all tree vehicles included in this study were equipped with automatic transmission.
- The vehicles/engines were operated at following test conditions:
  - **High idle**:
    transmission in neutral and engine operated at rated speed without load.
  - **Torque converter stalled at full load**:
    transmission in the highest gear and brakes applied, engine operated at rated speed at full throttle.
  - **Torque converter stalled at full load with hydraulics engaged**:
    transmission in the highest gear, brakes and hydraulics engaged, engine operated at rated speed at full throttle.

33

Sampling Train

- **Scanning Mobility Particle Sizer** (SMPS, TSI Inc.) was used to measure size distributions of aerosols in the diluted exhaust upstream and downstream of tested diesel particulate filters.
- **Adjustable dilution system** (Matter Engineering AG) was used to dilute exhaust at ratio of 1:60. The dilution ratio was maintained constant throughout the measurements.
- **SMPS** parameters were kept unchanged throughout the sampling:
  - Instrument was operated in steady-state mode (60 + 15 second scan);
  - Particles with electrical mobility diameters in range from 10 to 392 nm were measured.

34

Figure 11. **Dilution System and Scanning Mobility Particle Sizer (SMPS) at Sampling Station**

35

Figure 12. **Dilution System Probe Installed Upstream of the Knitted Fiber Filter Fitted on Truck #3**

36

Size Distribution Measurements in Tailpipe Results

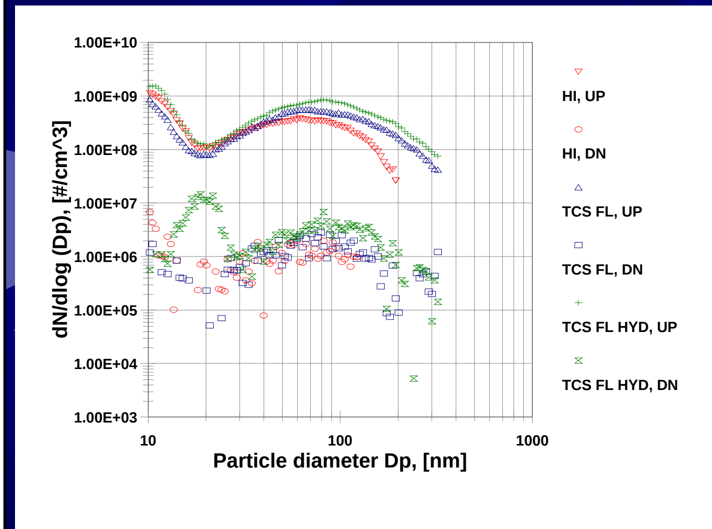
37

Results

- Only results for Truck #2 and Truck #3 are presented. The measurements obtained on the exhaust from LHD #3 were affected by transitional conditions in the dilution system and were neither considered in the analysis nor included in this presentation.
- The presented concentrations were corrected for dilution rate.
- Concentrations of the particles by volume were calculated after introducing assumption about spherical shape of the particles.

38

Figure 13. Size Distribution of Aerosols in the Tailpipe of Truck #2 Retrofitted With SiC DPF



Legend:
HI - rated speed no load
TCS FL - torque converter stall, full load
TCS FL HYD - torque converter stall, full load, hydraulics engaged
UP - upstream
DN - downstream

39

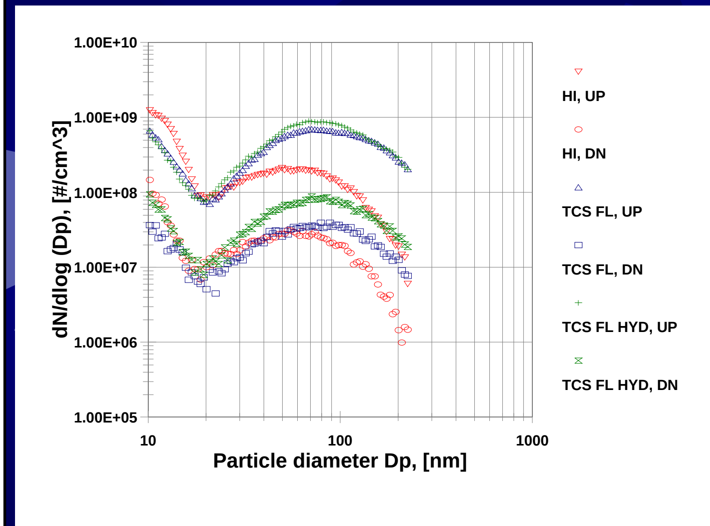
Table 3. Efficiency of Sic Monolith DPF Retrofitted to Truck #2

Number				**Volume**			
Engine Operating Conditions	Upstream, [#/cm^3]	Downstream, [#/cm^3]	Efficiency, [%]	Engine Operating Conditions	Upstream, [nm^3/cm^3]	Downstream, [nm^3/cm^3]	Efficiency, [%]
HI	3.5816E+08	6.1195E+06	**98.29**	HI	1.1576E+14	1.8971E+12	**98.36**
FL+TCS	5.0111E+08	2.4334E+06	**99.51**	FL+TCS	4.3999E+14	3.3372E+12	**99.24**
FL+TCS+HYD	7.3054E+08	4.6747E+06	**99.36**	FL+TCS+HYD	6.2815E+14	3.7479E+12	**99.40**

- Replacement silicon carbide (SiC) filter (160 hours of operation) offered excellent reductions in the number or volume of the particles with electrical mobility diameter between 10 and 392 nm.
- The filtration process did not resulted with increased concentration of nanoparticles.

40

Figure 14. Size Distribution of Aerosols in the Tailpipe of Truck #3 Retrofitted With Knitted Fiber DPF



Legend:

HI - rated speed no load

TCS FL - torque converter stall, full load

TCS FL HYD - torque converter stall, full load, hydraulics engaged

UP - upstream

DN - downstream

41

Table 4. Efficiency of Knitted Fiber DPF Retrofitted to Truck #3

Number				Volume			
Engine Operating Conditions	Upstream, [#/cm^3]	Downstream, [#/cm^3]	Efficiency, [%]	Engine Operating Conditions	Upstream, [nm^3/cm^3]	Downstream, [nm^3/cm^3]	Efficiency, [%]
HI	2.9281E+08	6.3654E+07	**78.26**	HI	5.6054E+13	7.0516E+12	**87.42**
FL+TCS	6.2682E+08	6.0866E+07	**90.29**	FL+TCS	6.3857E+14	7.1262E+13	**88.84**
FL+TCS+HYD	6.3036E+08	6.4232E+07	**89.81**	FL+TCS+HYD	6.3177E+14	5.9640E+13	**90.56**

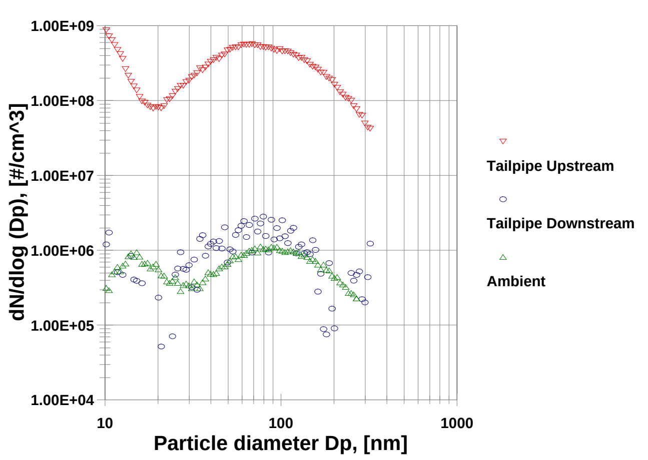
- Knitted fiber filter (~1500 hours of operation) offered somewhat lower reductions than SiC filter installed on Truck #2.
- The filtration process did not resulted with increased concentration of nanoparticles.

42

Size Distribution of Aerosols: Tailpipe Vs. Ambient

43

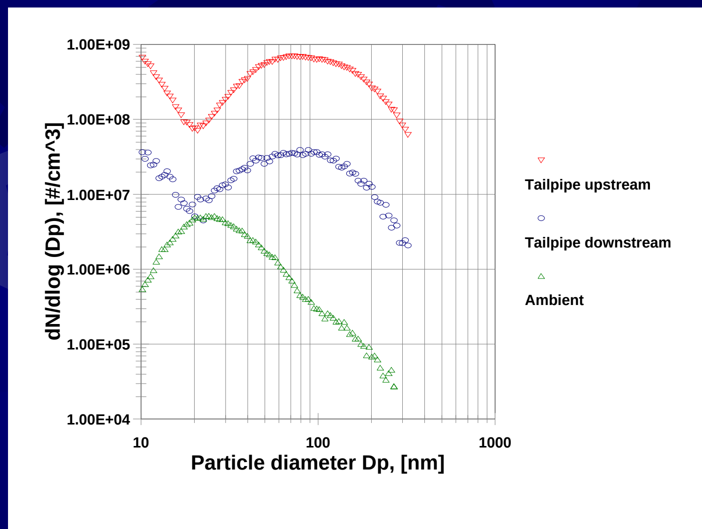
Figure 15. **Size Distribution of Aerosols: Tailpipe Vs. Ambient, Truck #2 Retrofitted With SiC DPF**



Note: Ambient measurements were done in February 2001. Tailpipe measurements were done in June 2001.

44

Figure 16. Size Distribution of Aerosols: Tailpipe Vs. Ambient, Truck #3 Retrofitted With Knitted Fiber DPF



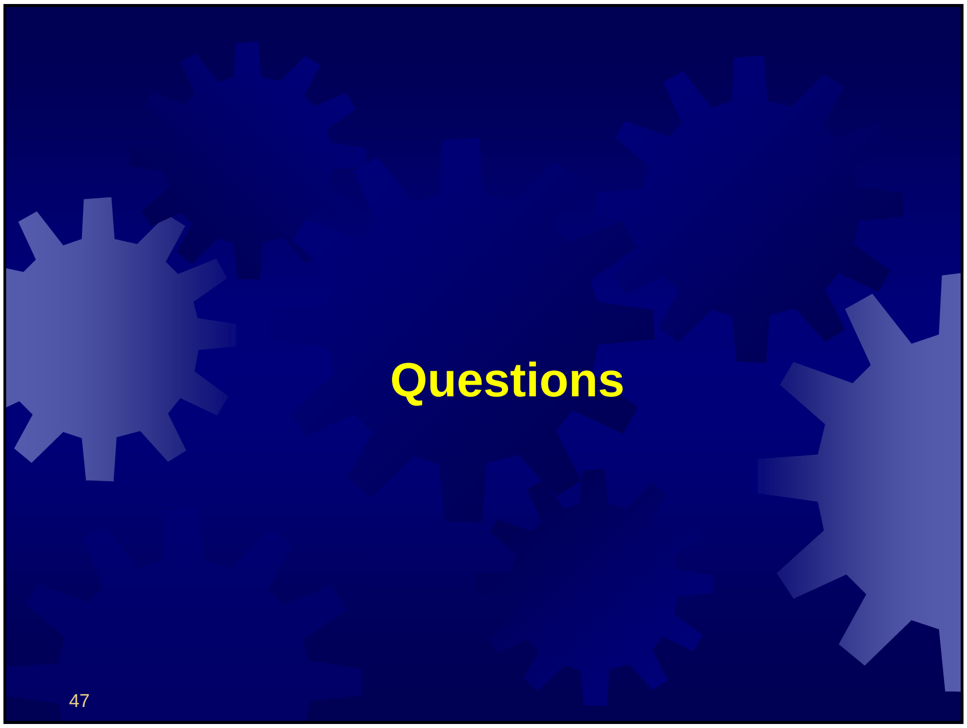
Note: Ambient measurements were done in February 2001. Tailpipe measurements were done in June 2001.

45

Size Distribution of Aerosols: Tailpipe vs. Ambient

- Since measurements of size distributions of the aerosols in the mine air and tailpipe were performed at different occasions, which happened several months apart, **direct comparison of the results can not be scientifically justified**.
- Still, size distributions measured in mine air downstream of the isolated zone where Truck #2 was operated are quite similar to those measured in the diluted exhaust downstream of the filter installed on the same vehicle.
- The equivalent size distributions measured for Truck #3 do not exhibit such similarity.

46


Questions
47