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Size distribution of diesel particulate matter in a non-metal mine

Size Distribution of Diesel Particulate Matter in Underground Metal Mine

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Introduction

Exposure of underground miners to diesel particulate matter (DPM) has recently received considerable attention from both research and legislation communities [1,2] . This is not surprising, given that underground miners, on average, are exposed to substantially higher concentrations of DPM than workers in any other occupation. An additional concern is the size distribution of diesel particles, which are found to be in nano (D_{50} < 50 nm) and ultrafine (D_{50} < 100 nm) ranges. Considerable toxicological evidence supports the idea that nano and ultrafine particles have a higher toxicity when compared to the same quantity of larger particles [3, 4, 5, 6]. Reducing miner exposure requires curtailing DPM emissions at their source. At their current stage of development, diesel particulate filters (DPF), have been found to be a promising technology [7] which needs to be optimized and proven for mine applications. The Diesel Emissions Evaluation Program (DEEP), a North American industry-labor-government research consortium, currently sponsors several projects designed to evaluate DPF for underground mining applications. The study presented in this paper was part of a DEEP project on the long-term field evaluation of diesel particulate filters at Noranda-Brunswick Mining Divisions metal underground mine. The objective of the project was to ascertain the potential of DPF to curtail DPM concentrations and evaluate their suitability for underground mining applications. The project was based on periodic measurements of tailpipe DPM and gaseous emissions and the so-called isolated zone study whose objective was to investigate the effects of aftertreatment technologies on the concentration and size distribution of aerosols in mine air. This summary and the attached presentation show the results of the isolated zone study.

Methodology

Four different DPF systems retrofitted to heavy-duty production vehicles, two trucks and two load-haul-dump (LHD) machines (see Table 1) have been subjected to a long term trial. The DPF systems on these vehicles are based on the three most widely used filter media (see Table 1). In addition, a truck and an LHD equipped with a standard exhaust system consisting of a diesel oxidation catalytic converter (DOCC) and silencer (see Table 1) were included in the study in order to assess the efficiencies of the standard exhaust system relative to the filters. The same type of modern, electronically controlled, turbo-charged, heavy-duty diesel engines powered all trucks. The LHD vehicles were powered by an engine from the same series, but with somewhat smaller displacement and rated power (see Table 1). In this particular mine, LHD machinery was mostly used for loading trucks and hauling ore on relatively short distances. Trucks were exclusively used for hauling ore on longer distances.

The testing took place in a section of the mine, which was completely isolated by bulkhead seals from other parts of the mine and ventilated using fresh air from the surface (see Figure 1). The isolated zone was located at the upper level of the mine where there was no production at the time of testing. Freshly mined ore was not available, therefore all the vehicles were loaded at the beginning of the test period and remained loaded throughout the tests. In order to distinguish the effects of each of the aftertreatment devices on DPM concentrations in the mine air, the vehicles were operated individually in the isolated zone. All the vehicles were operated for four hours, continually repeating an approximately 8-minute long duty cycle (described on Slide 4). This duty cycle was designed as a combination of average duty cycles observed for both the trucks and the LHDs. Since the ambient surface temperature averaged -20 ^{o} C during testing days, cyclic propane heaters in the intake structure were used to warm the ventilation air.

A TSI, Inc. Scanning Mobility Particle Sizer (SMPS) was used to measure the size distribution and concentration of the ambient aerosols downstream of the test section (Figure 1). The levels of aerosol in the mine air allowed researchers to use the SMPS without diluting the sample. Instrument parameters were kept constant throughout the study (see Slide 9). Size distribution samples were taken thee times per cycle: 1) during the load cycle, 2) while driving between end points, and 3) during the dump cycle. The timing was based on measured air velocities and known distances.

Results and discussion

The observed size distributions of aerosols in the mine air prior to the introduction of vehicles are shown in Figure 2. The relatively high concentrations of nanoparticles (D_{50} – 15 nm) in the air are attributed to the propane heaters, which were used extensively during the testing to heat the intake air. Surprisingly, nanoparticles were detected in these high concentrations approximately 1000 m downstream of the heaters.

Figures 3 and 4 show the size distributions for Truck # 3 and LHD # 2 obtained at different times during the test period over the load cycle. The measurements showed that after an initial transient condition which affected the first couple of data sets (not shown in the figures), the distributions of the particles in the accumulation modes were relatively consistent. The concentrations of particles in nucleation modes were fluctuating within an order of magnitude (see Figure 4).

Figures 5 through 10 show representative size distributions of particles observed for the test vehicles during different parts of the duty cycle. The distributions were significantly affected by position of the vehicles relative to the sampling point and vehicle/engine operating conditions (see Figures 5 through 10). Size distributions of particles measured when vehicles were operated over dump cycle on the most downwind end of the section, i.e. closest to the sampling point, were characterized with the highest peak concentrations and lowest count median diameters of nucleation mode. The decay of nanoparticle concentrations with time and distance was attributed to particle aging. This phenomenon needs to be better understood in order to more adequately assess exposure to DPM, particularly nanoparticle exposure.

Size distributions of aerosols measured in the mine air for different vehicles that were operated over the load cycle, driving toward dump point, and the dump cycle are summarized in Figures 11, 12 and 13, respectively. The size distributions and concentrations of aerosols were found to be strongly influenced by the type of aftertreatment technology deployed. The performance of filters (Figure 14 and 15) was evaluated on the basis of total particle number and volume concentrations per unit volume of mine air, averaged over the total number of duty cycles performed by each of the vehicles. The means and standard deviations for the samples are included in Figures 14 and 15. The total particle concentrations observed in the mine air were found to be highest with the LHD #3, using SiC filter. Those concentrations were even higher than when LHD #1, a similar vehicle using the standard exhaust system, was tested. Other filters offered significant total particle number reductions in the mine air. Analysis also revealed that estimated concentration reductions of particles by volume for filters installed on Truck #2 and LHD #3 belied expectations. Evidences of leaks in the exhaust system were found on all vehicles retrofitted with filters. It is hypothesized that particles from the leaks and other sources significantly contributed to relatively high concentrations of aerosols in the mine air.

Literature cited

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Size Distribution of Diesel Particulate Matter in Underground Metal Mine

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Introduction

- **Diesel Emission Evaluation Program (DEEP) Consortium**
  - Industry, labor, government (Canada and USA)
- **Evaluation of Diesel Particulate Trap Technology at Noranda-Brunswick Mining Division (BM&S)**
  - 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).
    - Determine filtration efficiency and
    - Determine durability (underground hard rock mine)

Objectives

- Assess efficiency of selected aftertreatment technologies for curtailing diesel particulate matter emissions from heavy-duty production vehicles/engines
- Study effects of aftertreatment technologies on size distribution of aerosols in mine air

Both objectives were accomplished by direct measurements in workplace environment

Methodology

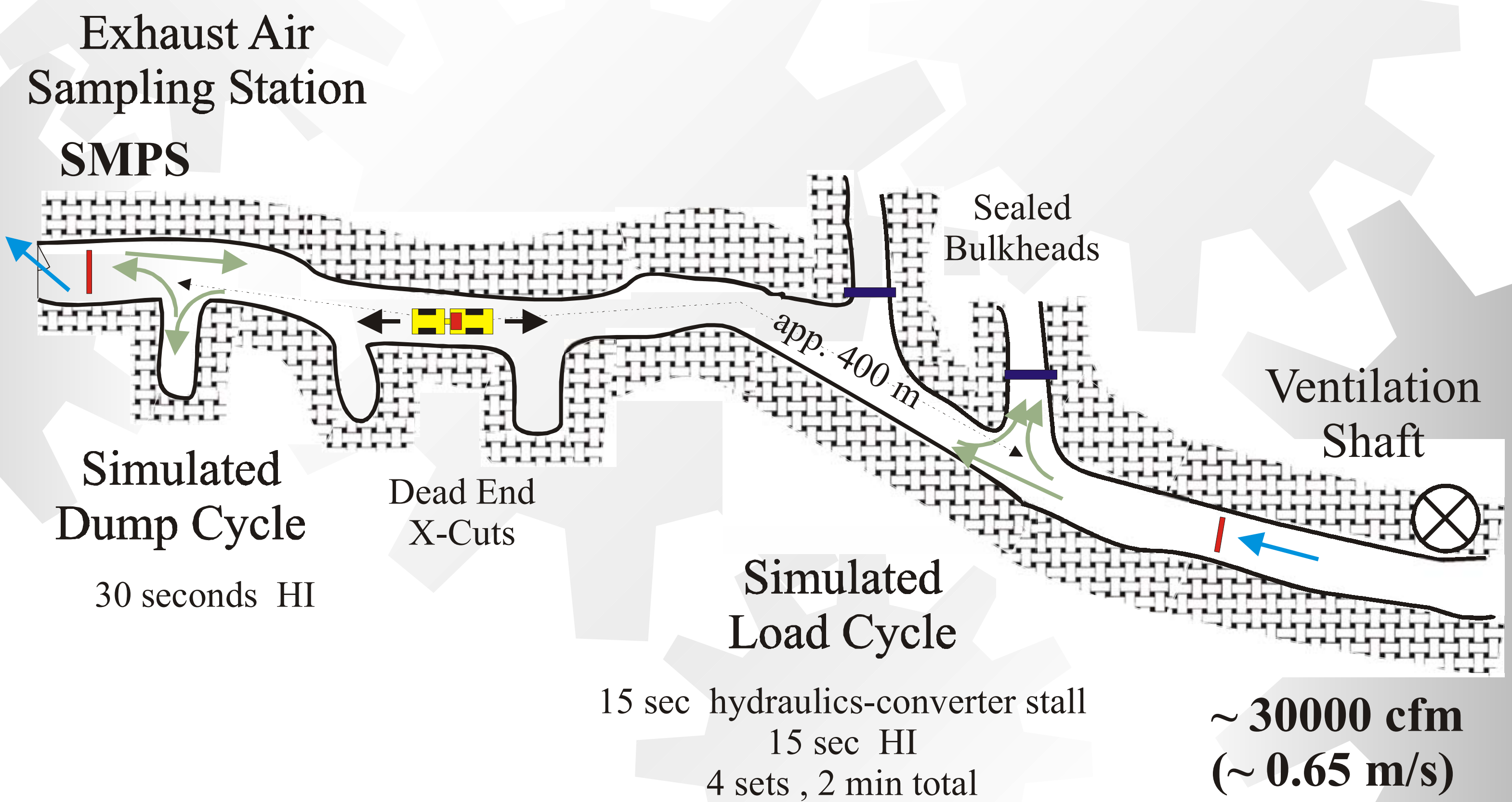
- **Isolated zone testing at level 525 BM&S :**
  - **Operate single vehicle in the 400 meter test zone per day**
  - **All vehicle operated over custom designed duty cycle**
    - **2-minute load cycle of 4 repetitions of two a 30-second full throttle work cycle: 15 seconds torque converter stall with 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**

Methodology

- Continuous execution over a four hour-period, yielding 30 to 34 repetitions.
- Ventilation air was introduced from the surface through ventilation shaft located 100 meters upstream of the zone.
- Ventilation air was heated at the surface using cycling propane burners.
- Ventilation rate was set at about 14 m^3/s (30000 cfm)
- Air temperatures: 5 - 8 ^oC at inlet to the zone

  5 – 15 ^oC at sampling point (downwind end of the zone)

Methodology
Figure 1. Isolated Zone - Test Section



Methodology
Tested Vehicles/Aftertreatment Devices

- **Four different types of diesel particulate filters (DPF) installed on the production vehicles (Table 1):**
  - **two trucks and**
  - **two load-haul-dump (LHD) vehicles**
- **Two similar vehicles equipped with exhaust treatment system mandated by New Brunswick law including diesel oxidation catalytic converter (DOCC) and muffler (Table 1):**
  - **one truck**
  - **one LHD vehicle**

Methodology
Table 1. Vehicles/Aftertreatment Devices

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.	DPF, catalyzed silicon carbide monolith	Diesel + Additive	1848
Truck 3	375 Hp el. contr.	DPF, knitted fiber cartridges	Diesel + Additive	878
LHD 1	325 Hp el. contr.	DOCC and muffler	Diesel	300
LHD 2	325 Hp el. contr.	DPF, catalyzed ceramic monolith	Diesel	2129
LHD 3	325 Hp el. contr.	DPF, catalyzed silicon carbide monolith elec. regenerated	Diesel	1823

Methodology -- Sampling

- **Ambient sampling downstream of the test section using Scanning Mobility Particle Sizer (SMPS, TSI Inc.). No dilution was required.**
- **SMPS Model 3936 (EC Model 3081, CPC Model 3025)**
  - **steady-state mode (60 + 15 second scan)**
  - **particles with electrical mobility diameters in range between 10 and 392 nm**
- **Sampling sequence***
  - **vehicle performing load cycle at load point (LC)**
  - **vehicle driving toward dump point and sampling station (DR)**
  - **vehicle performing dump cycle at dump point (DC)**
- **Continual sampling was conducted for about four hours**

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

Methodology
Filtration efficiency

- **The concentrations were compensated for day-to-day fluctuations in ventilation rates.**
- **Performance of the aftertreatment devices is judged on a basis of averaged number concentrations measured for instrument range (10 – 392 nm) and averaged volume concentrations calculated using assumptions about spherical shape of the particles.**

Figure 2. Size distribution of aerosols in air prior to introduction of the vehicles in the test zone Propane burners (T_{sur} = - 20 ^{o}C, T_{zone} = 5 ^{o}C)

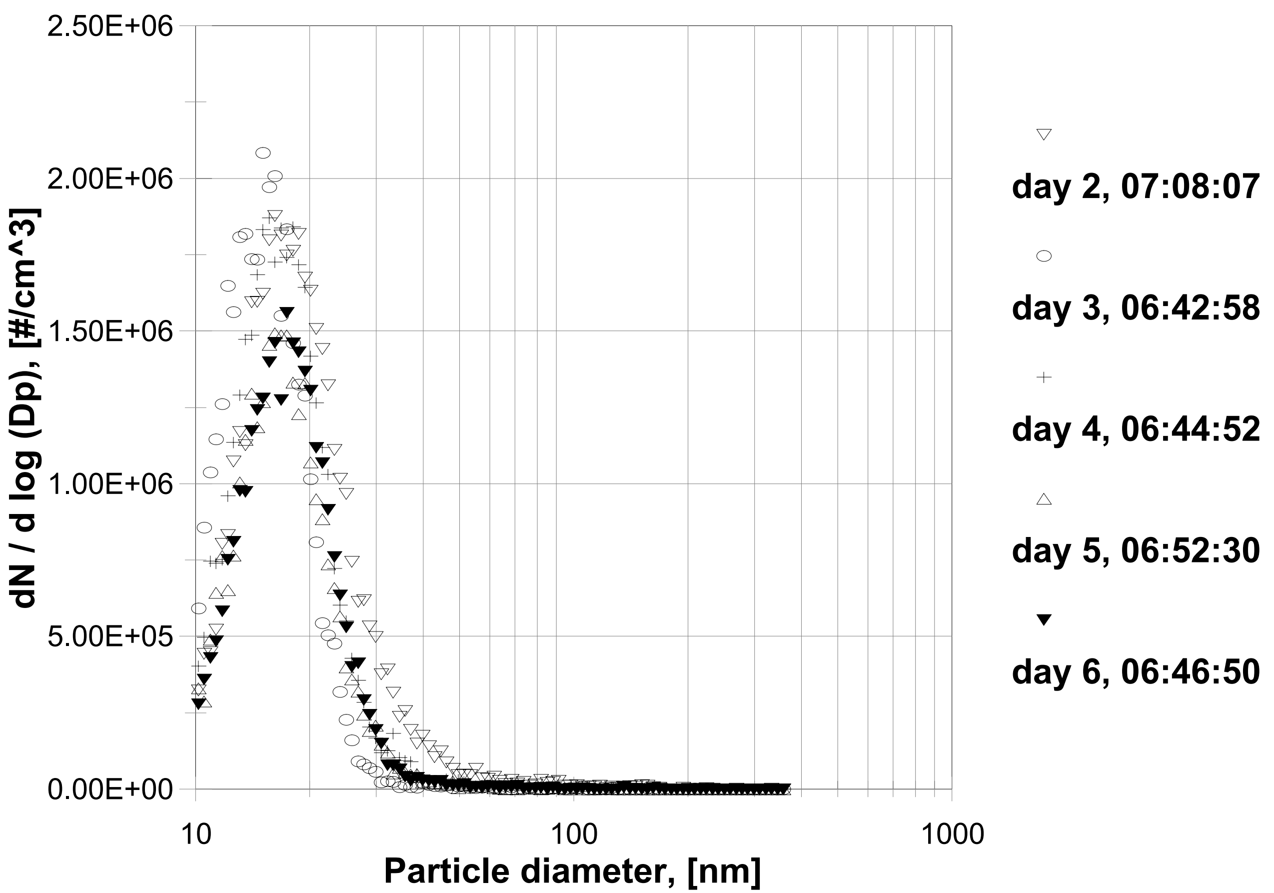


Figure 3. Truck 3 equipped with knitted fiber DPF, Vehicle performing load cycle (LC)

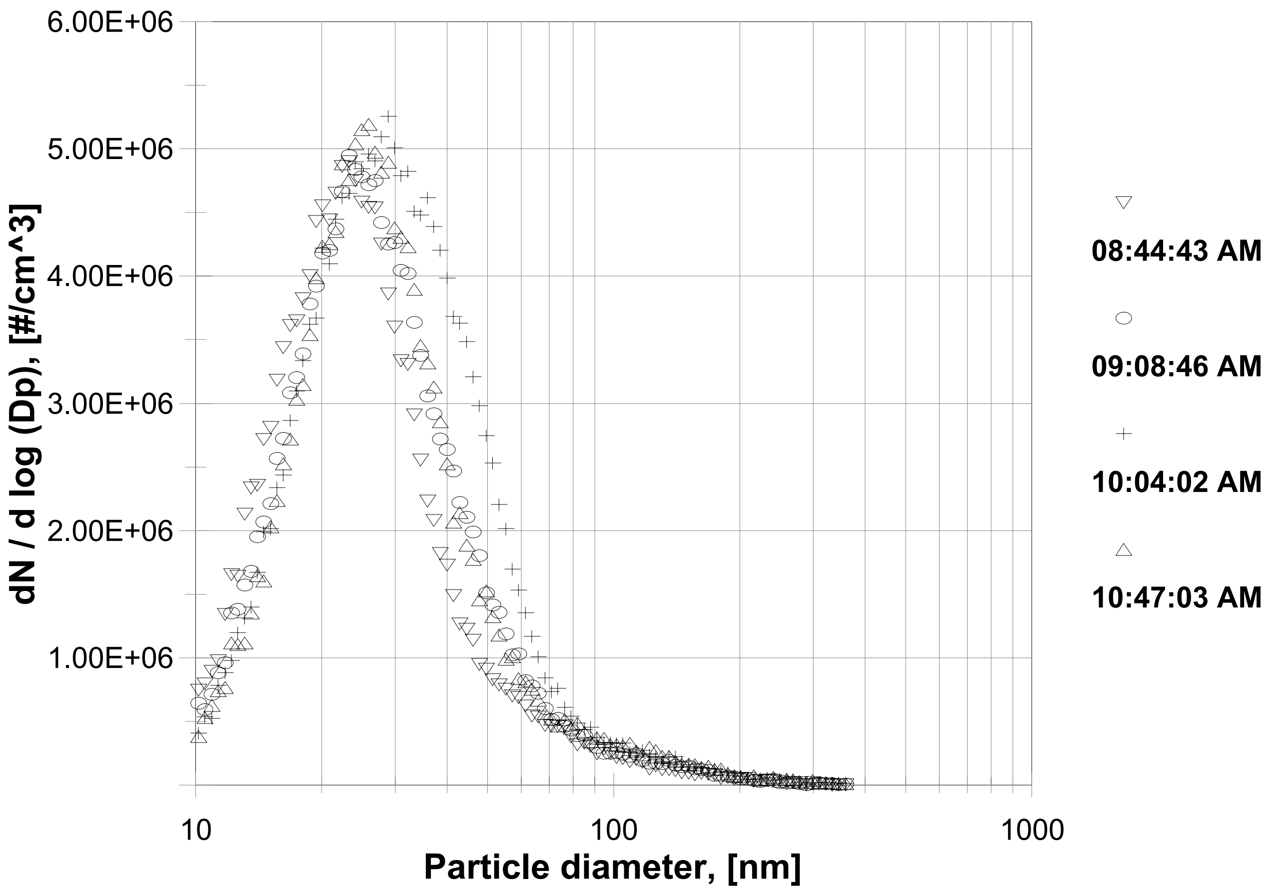


Figure 4. LHD 2 equipped with catalyzed ceramic monolith DPF, Vehicle performing load cycle (LC)

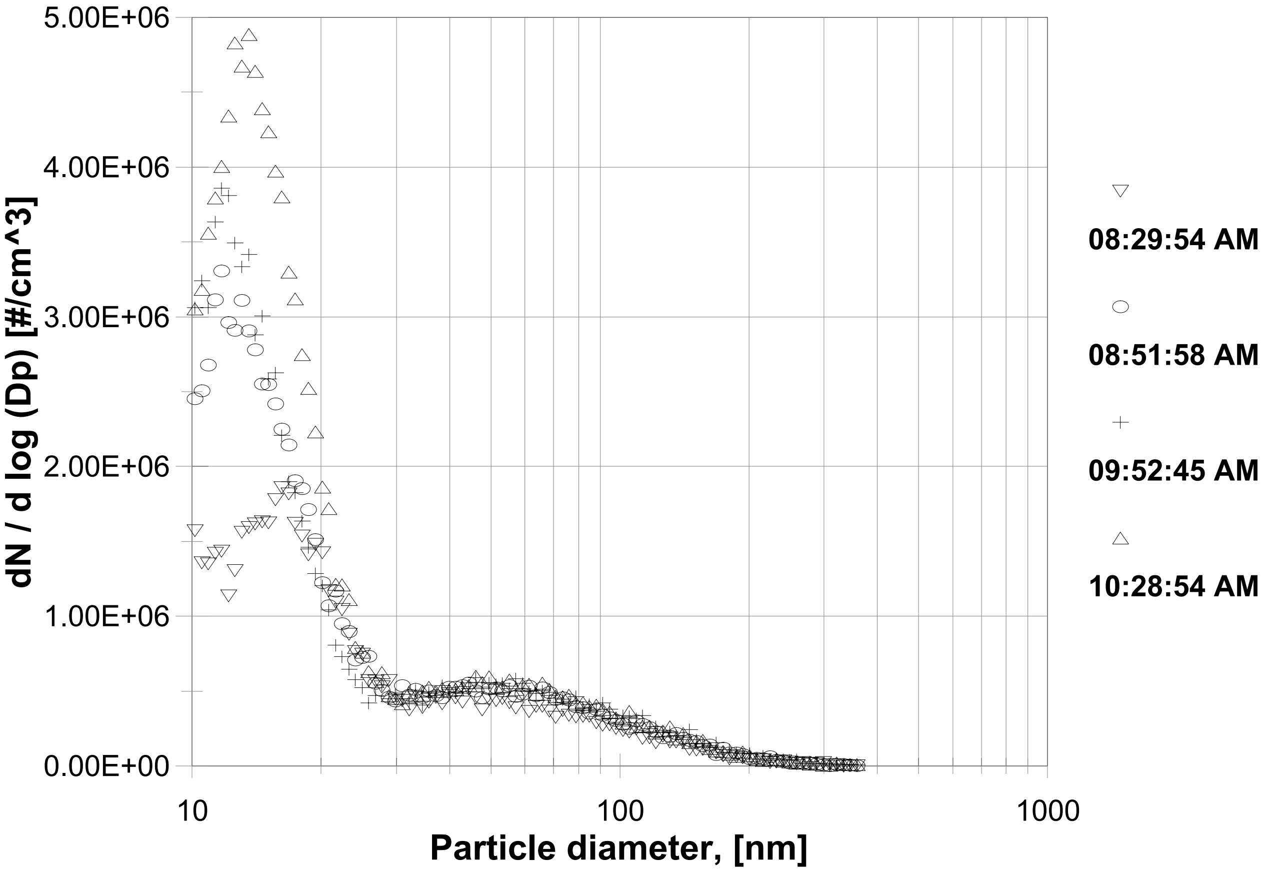


Figure 5. Truck 1 equipped with DOCC, Particle aging, Number

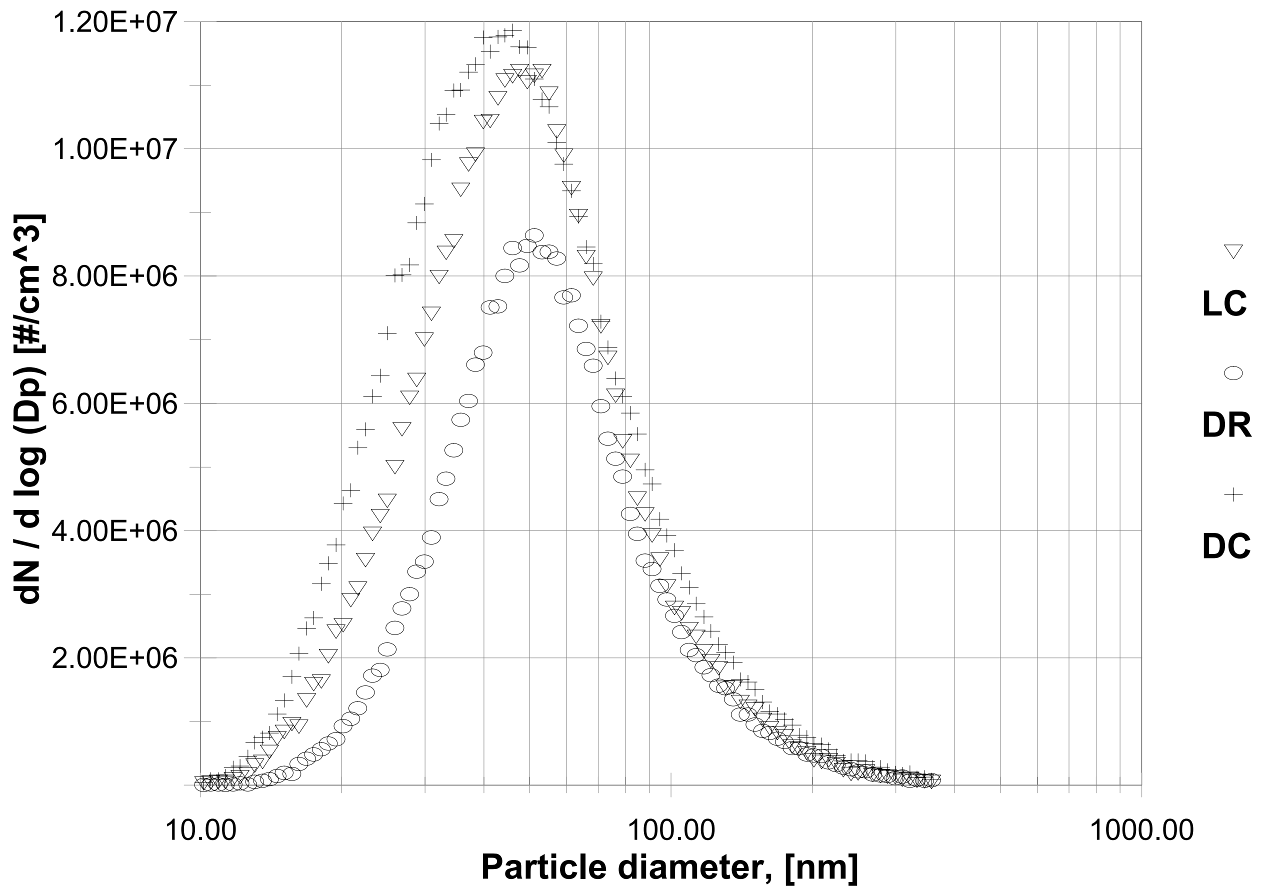


Figure 6. Truck 2 equipped with SiC DPF, Particle aging, Number

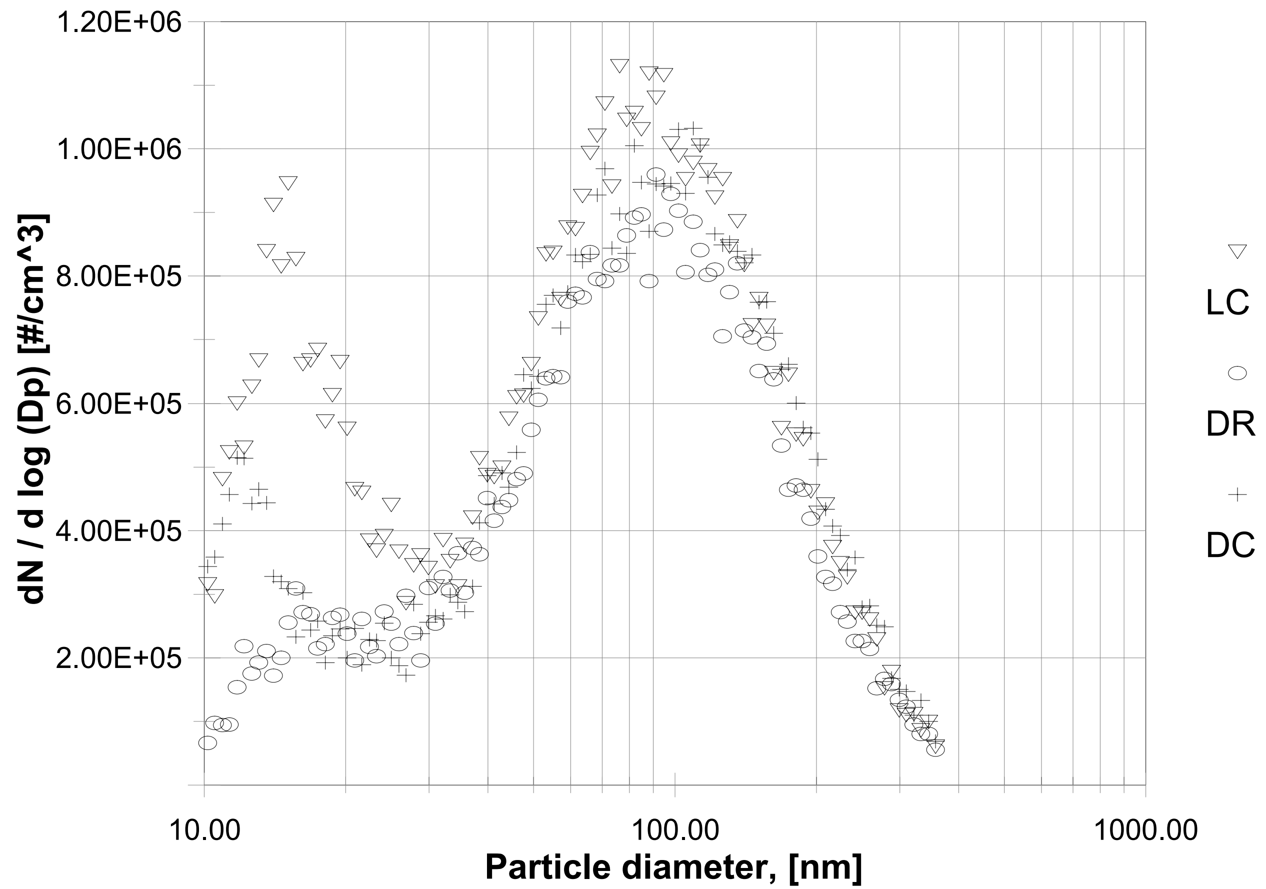


Figure 7. Truck 3 equipped with knitted fiber DPF, Particle aging, Number

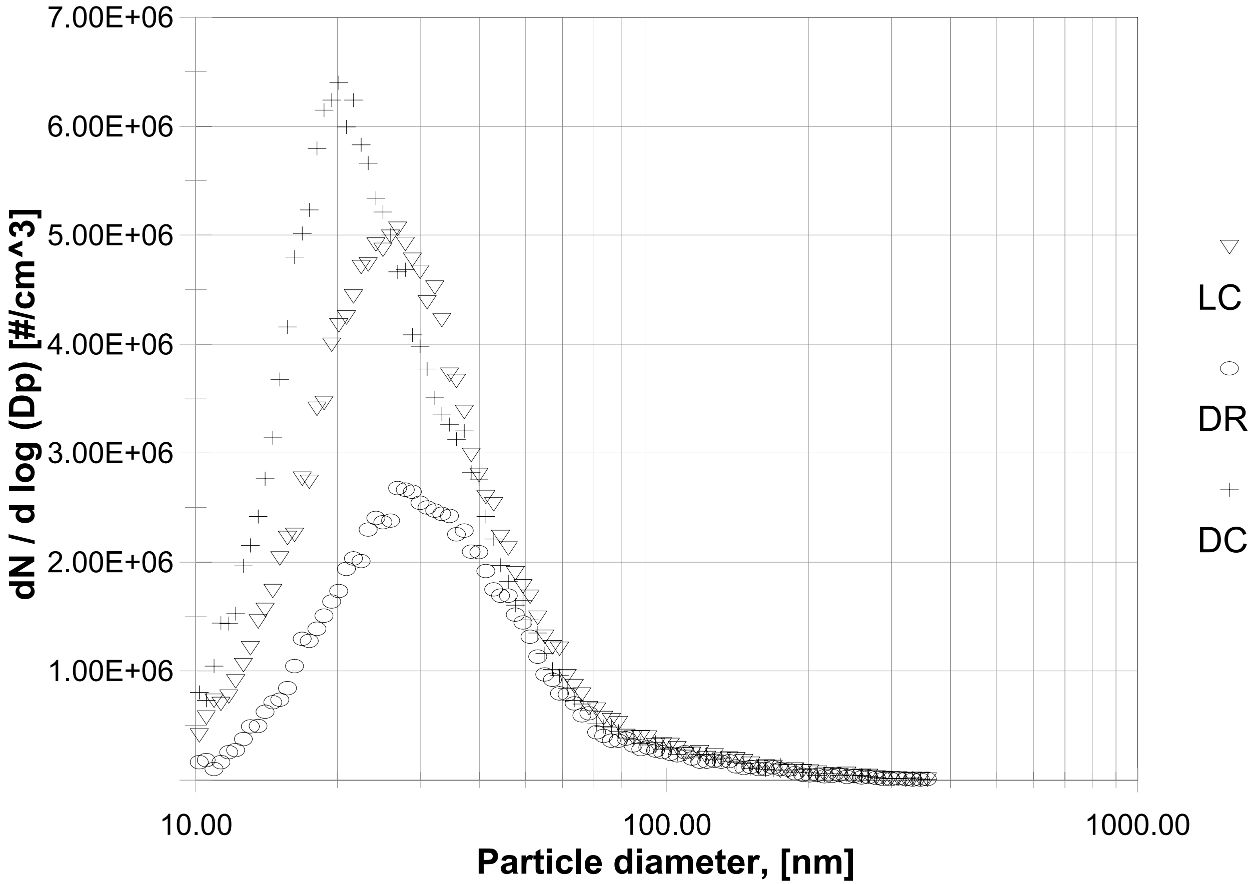


Figure 8. LHD 1 equipped with DOCC Particle aging, Number

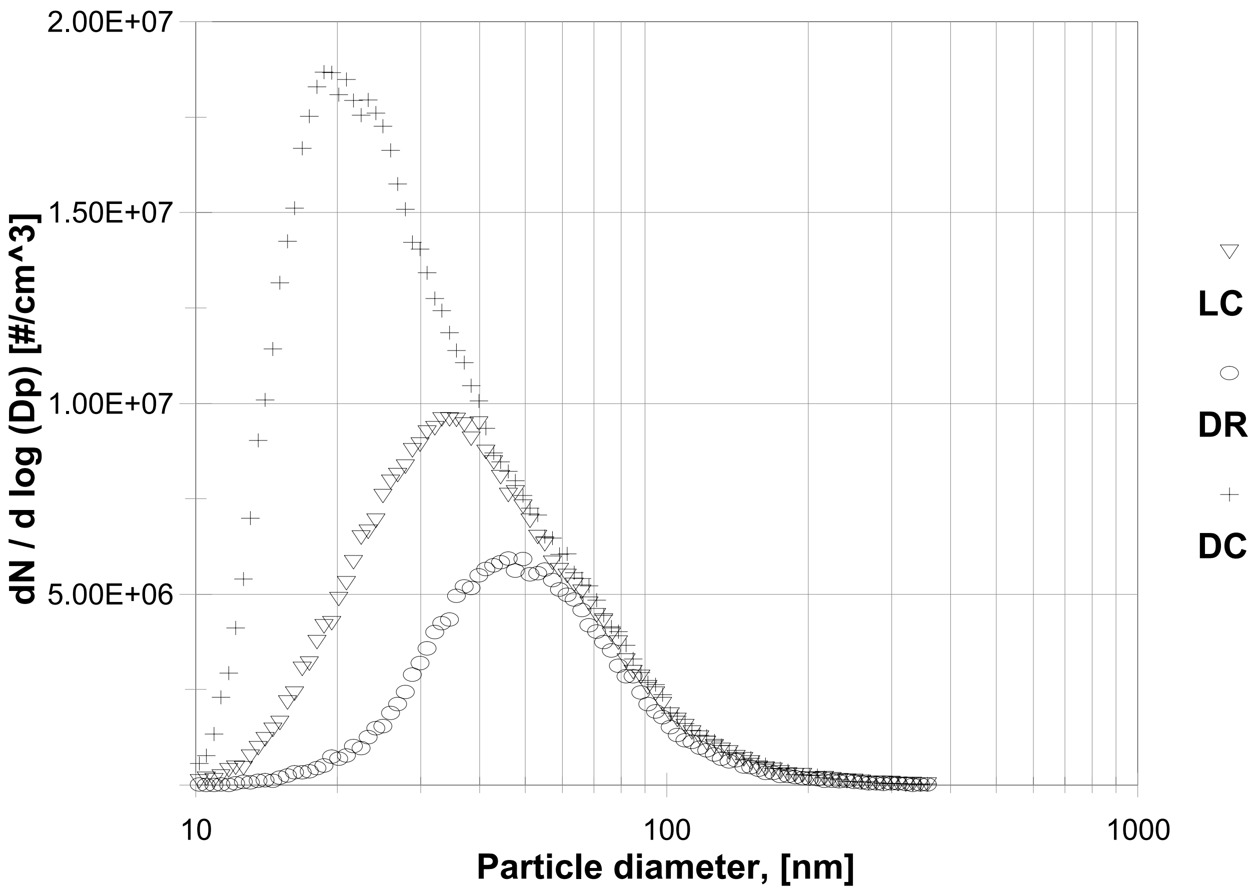


Figure 9. LHD 2 equipped with cat. ceramic monolith DPF, Particle aging, Number

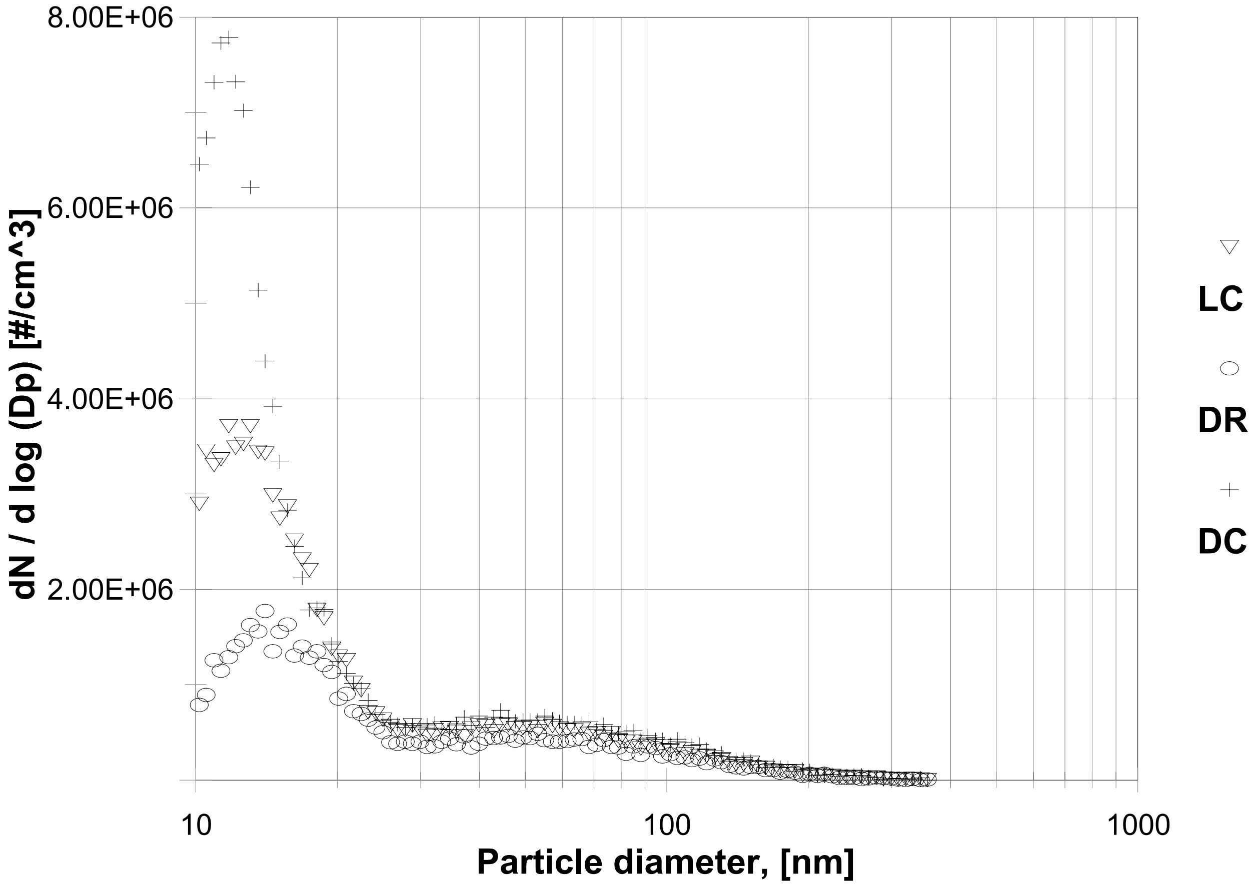


Figure 10. LHD 3 equipped with SiC monolith DPF, Particle aging, Number

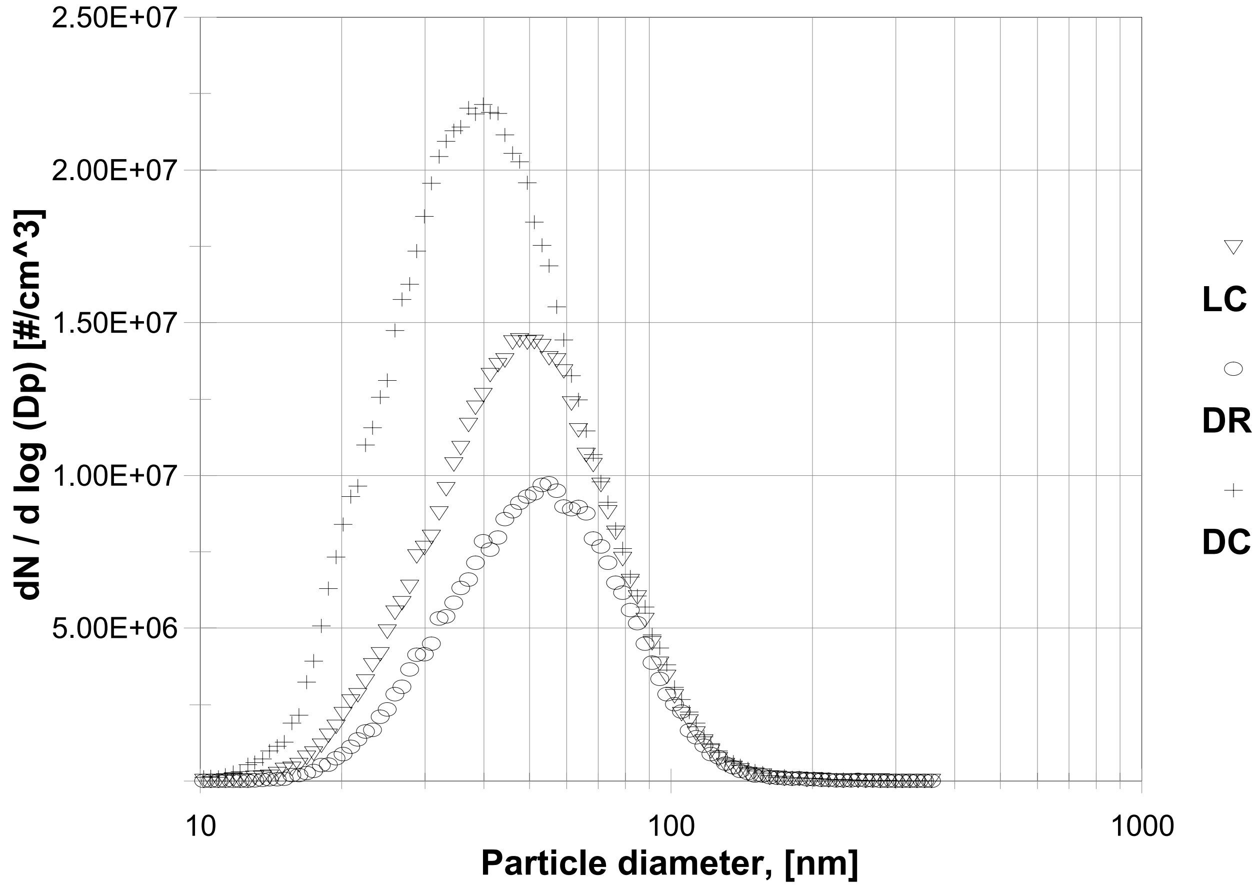


Figure 11. All Vehicles, Dump Cycle (DC), Particle Number

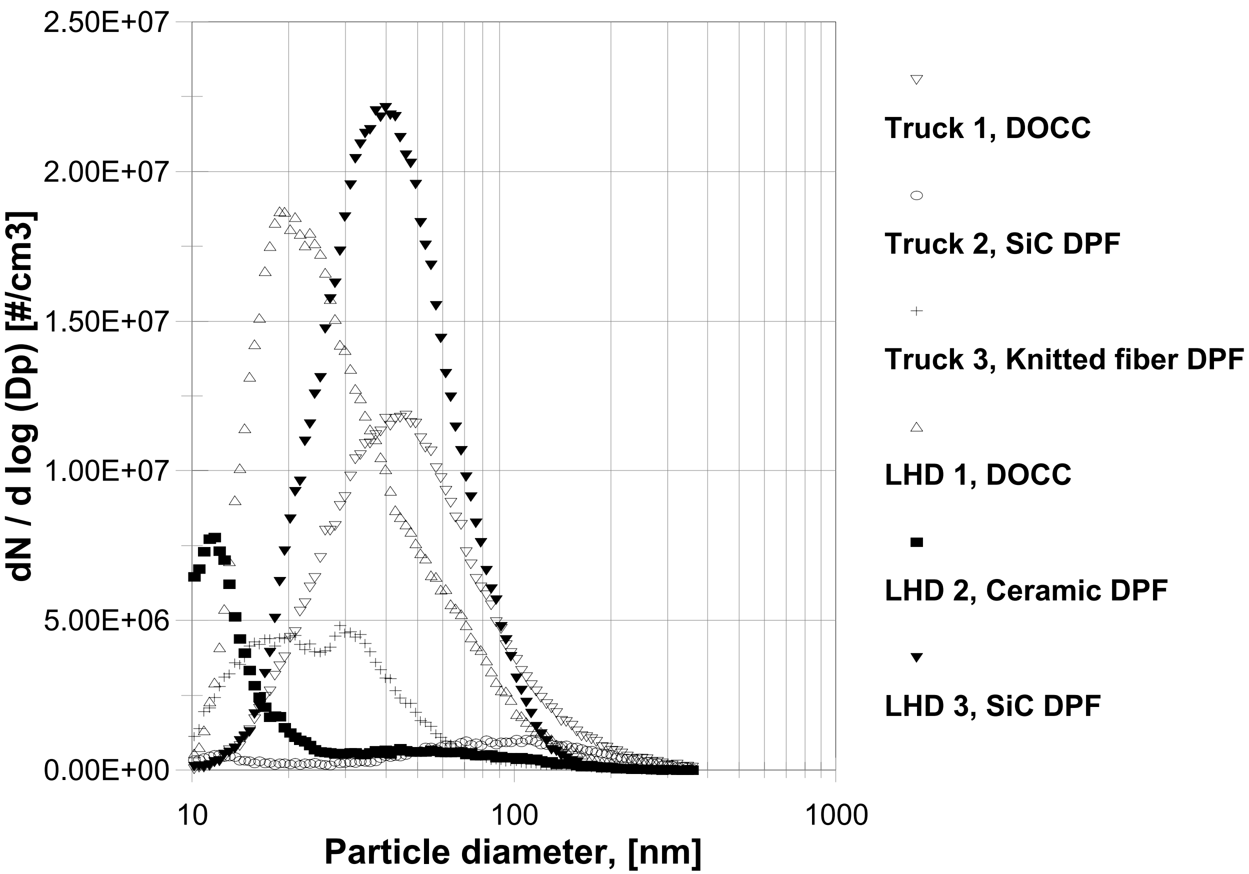


Figure 12. All Vehicles, Load Cycle (LC), Particle Number

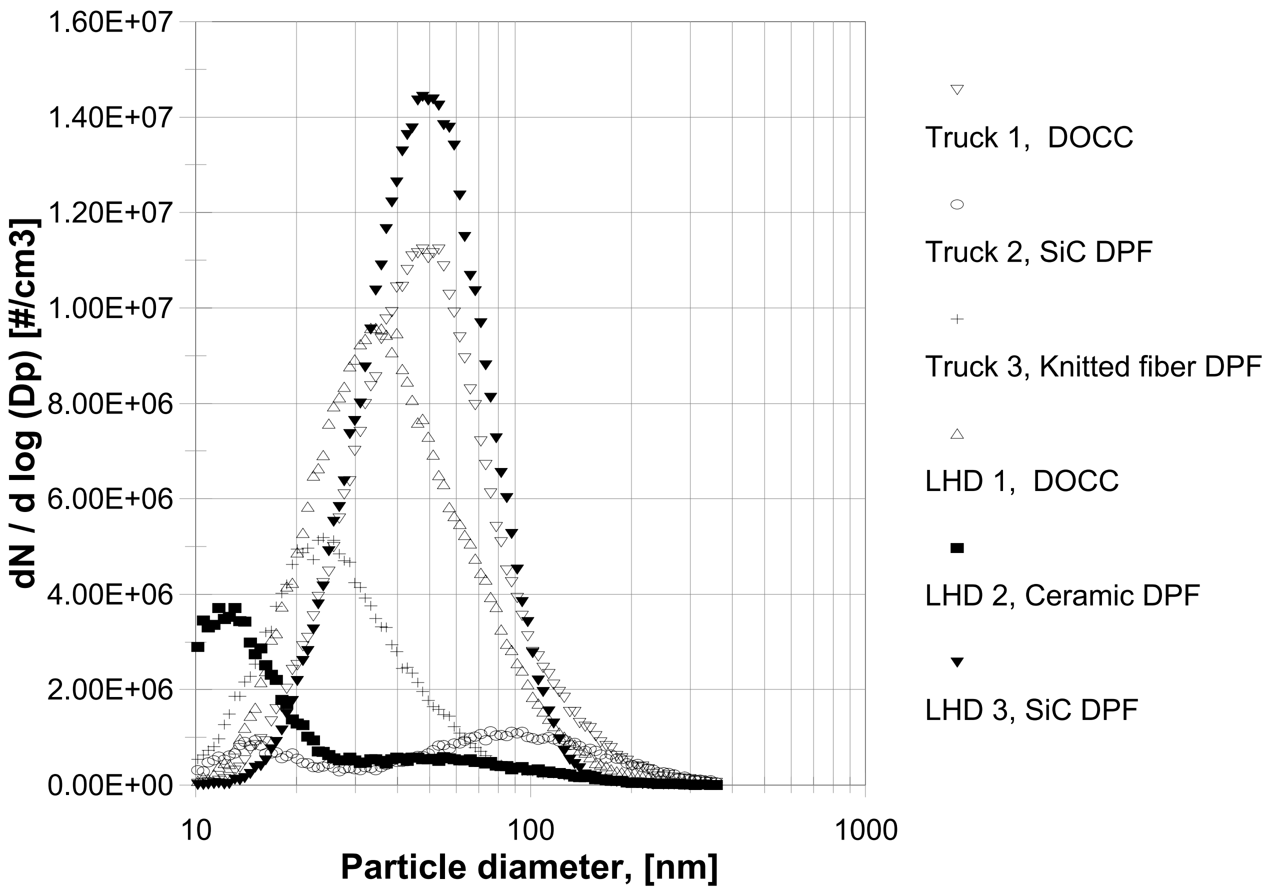


Figure 13. All Vehicles, Approaching dump point (DR), Particle Number

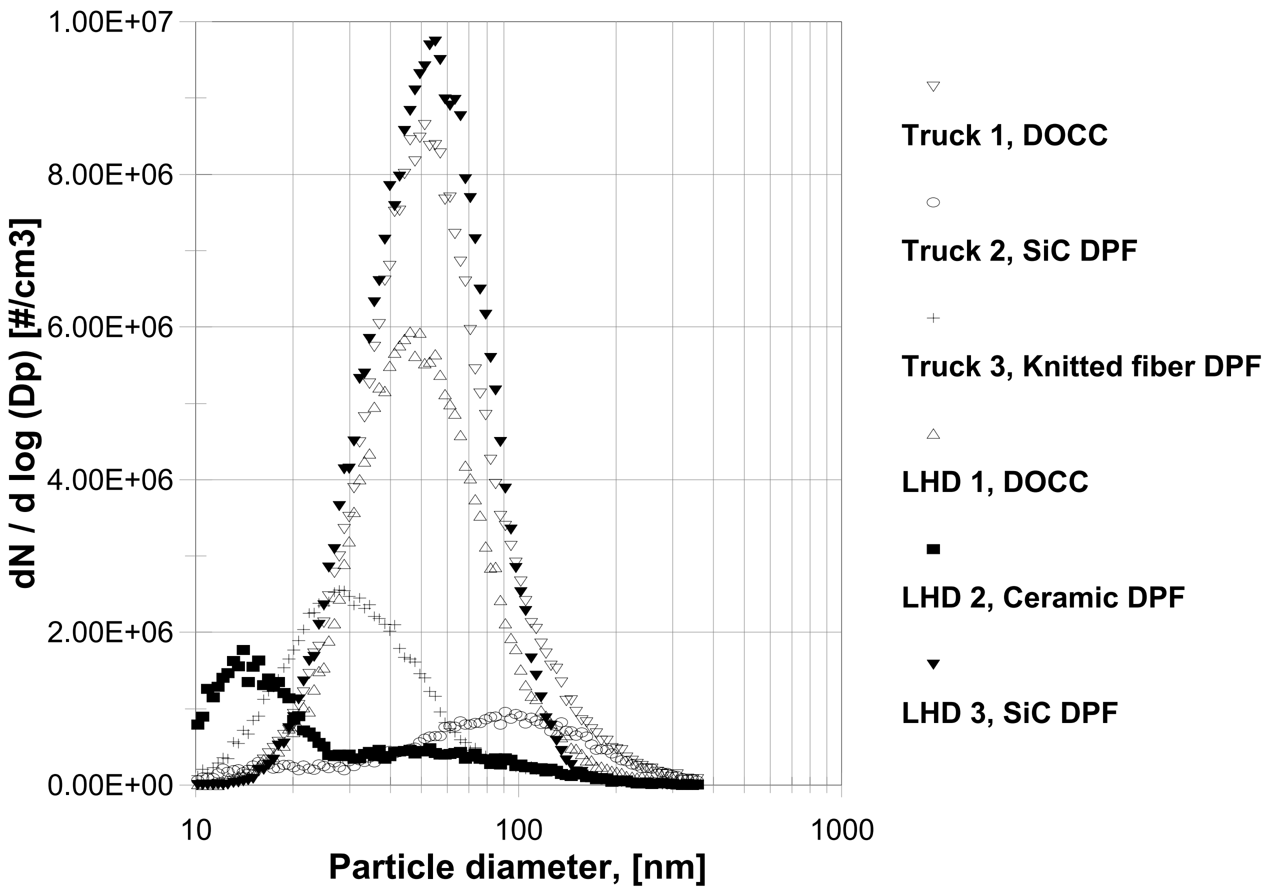
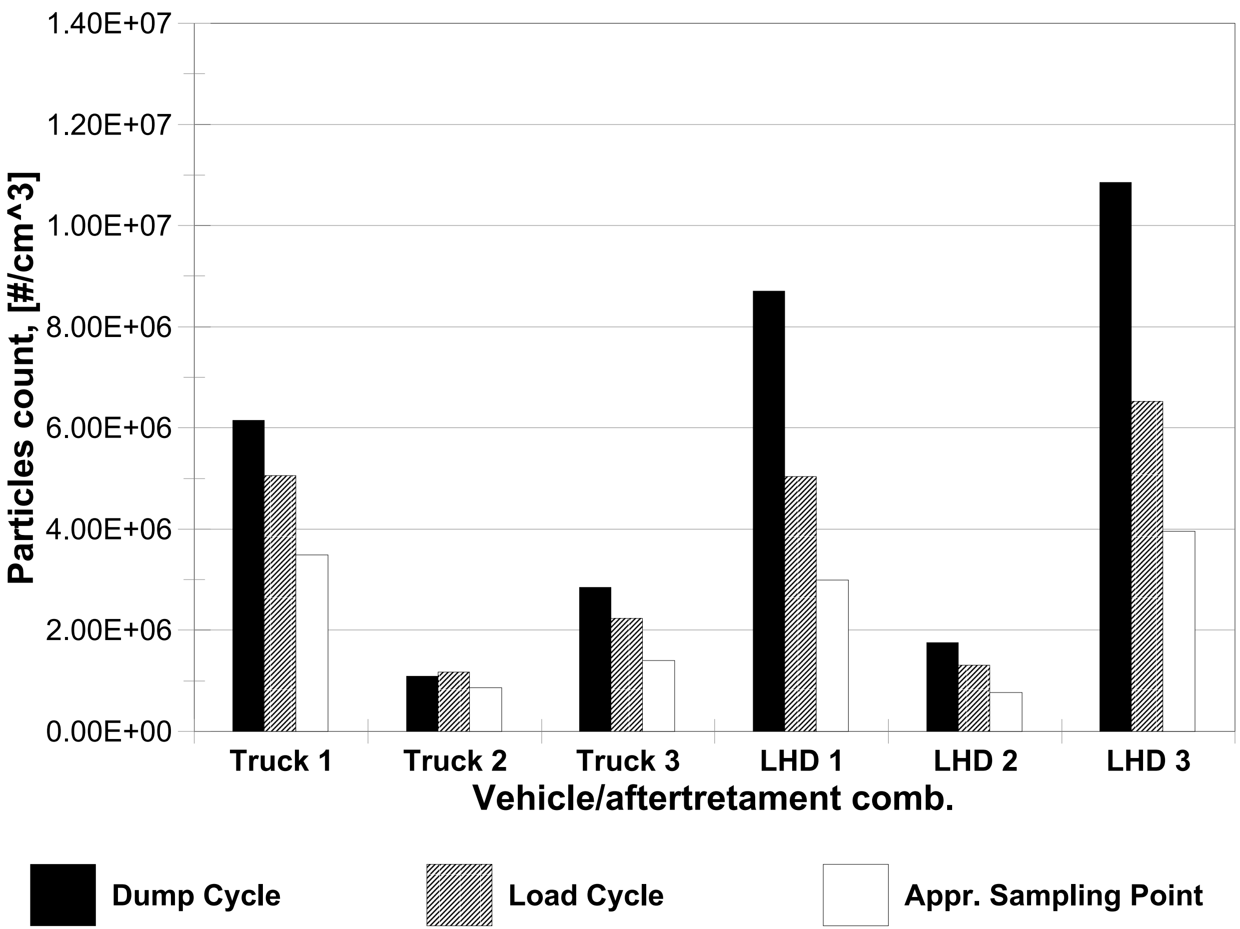
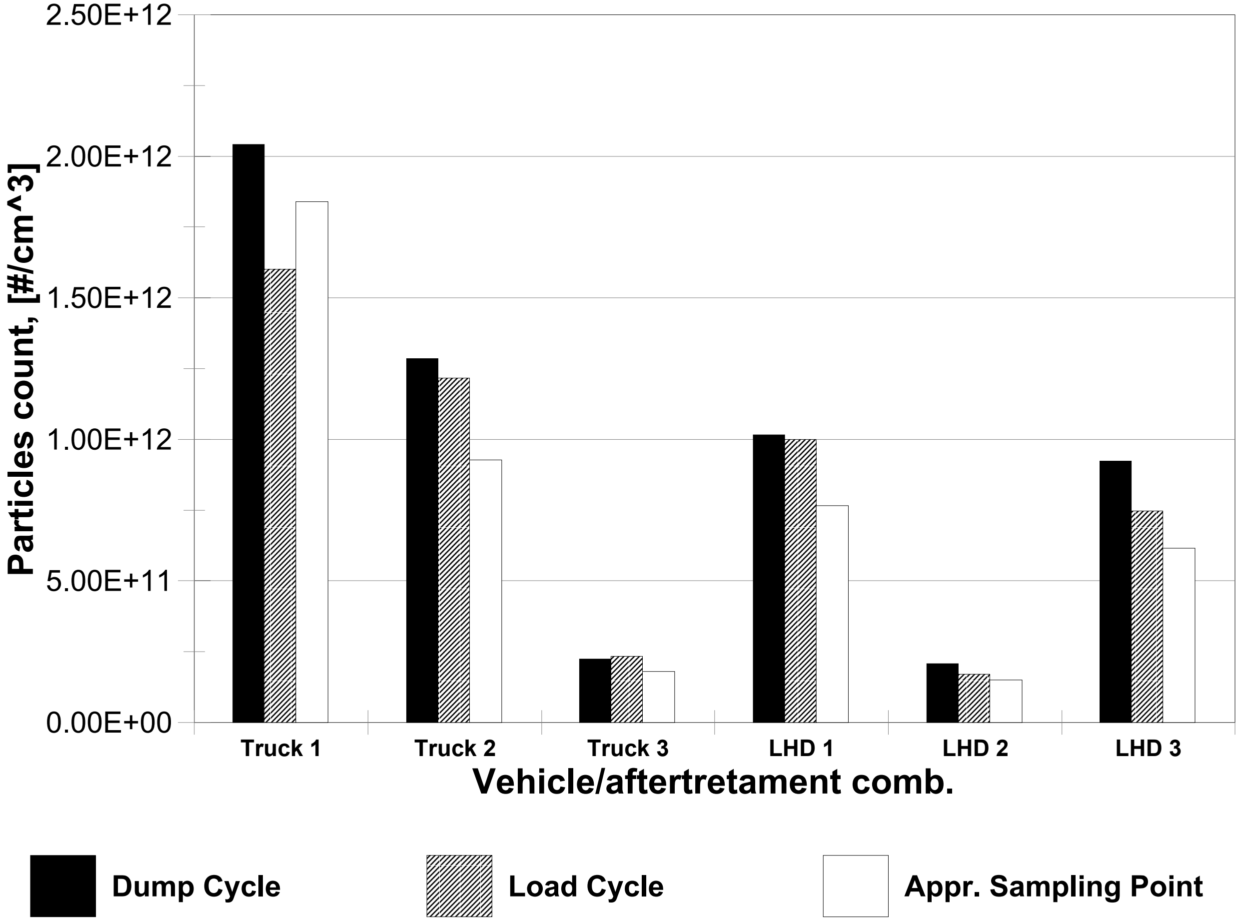


Figure 14. Effects of filters on total number of particles in mine air



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

Figure 15. Effects of filters on total concentration 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

Conclusion…

- **Performance of the filters**
- **All filters except filter installed on LHD #3 offered excellent reductions in particles number in the mine air (see Figure 14).**
- **Estimated reductions in particle volume/mass were bellow expectations for the filters installed on Truck #2 and LHD #3 (see Figure 15).**
- **Observation**
- **The exhaust systems on all the vehicles equipped with DPF showed evidence of leaks in the exhaust pipes between engine and filter. This diminished the effectiveness of the filters to reduce work place concentrations. Therefore, maintaining integrity of the exhaust system is crucial for meeting new DPM work place exposure standards.**

…Conclusions…

Size distribution of aerosols

- The results show evidence of nanoparticles in this underground mine which are attributable to diesel powered equipment and propane heaters (see Figures 2 – 13).
- High concentration of nanoparticles (D_{50} < 50 nm) were observed in mine air prior to introduction of diesel powered vehicles in the zone (see Figure 2). Those particles were attributed to incomplete combustion of propane in the cyclic heaters which are used for heating intake air during cold winter days.
- Size distribution of the DPM was found highly dependant on type and design of aftertreatment device (see Figures 11, 12, and 13).
- Relatively high concentration of ultra fine particles (D_{50} <100 nm) in mine air were observed when vehicles equipped with diesel oxidation catalytic converters were operated in the zone

…Conclusions

- **Relatively high concentrations of nanoparticles (D_{50} < 50 nm) in mine air were observed when vehicles equipped with certain types of diesel particulate filters were operated.**
- **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 (see Figures 5 – 10).**