Characterization of Diesel Aerosols in Underground Metal Mine

By Aleksandar Bugarski[1]

Introduction

Approximately 13,000 underground coal and 7,500 underground metal/nonmetal miners in U.S. are exposed to concentrations of diesel particulate matter (DPM) that are significantly exceeding those of any other occupation. In January 2001 the Mining Safety and Health Administration (MSHA) set interim limits for exposure of metal and nonmetal underground miners to DPM, i.e., 400 μg/m^3 of total carbon [30 CFR 57.5060 2001]. The total carbon standard was amended later with equivalent elemental carbon standard, 308 μg/m^3 [68 Fed. Reg. 48668 2003]. Controlling DPM emissions at their source using diesel particulate filter (DPF) systems and other advanced diesel emission control technologies was considered to be one of the potential solutions to the problem, but the rather limited knowledge on the performance of those technologies in underground environment significantly held up the wider acceptance and implementation of those technologies.

NIOSH conducted in an underground metal mine to determine the in-situ effectiveness of selected control technologies in reducing particulate matter and gaseous emissions from diesel-powered equipment and to characterize aerosols in the mine air. The primary objective was to evaluate the effects of the DPF systems and different fuel formulations on (1) the mass concentrations of elemental carbon (EC) particles under 800 nm, (2) the mass concentrations of total particulate matter under 800 nm, and (3) the number concentration and size distribution of aerosols between 10 and 392 nm.

Methodology

The control technologies were tested using an isolated zone methodology in which the contribution of the mining vehicles to the pollutant concentrations in mine air, were measured both before and after the tested vehicles were outfitted with the selected control technology. The vehicles were operated individually under conditions that closely resembled actual production scenarios. The effects of other diesel-powered vehicles on the quality of the air in the isolated zone were eliminated by physically isolating the test zone from the rest of the mine and ventilating it with fresh air from an adjacent portal. The test vehicles performed a structured, repeatable duty cycle devised for each of two types of vehicles used, the load-haul-dump vehicle and haul trucks.

While the vehicle performed the duty cycles, both the upstream and downstream ambient concentrations of particulate matter and selected gases were sampled. The DPM samples were collected using a high volume sampler and analyzed at the NIOSH PRL analytical laboratory for EC content using the NIOSH 5040 Analytical Method. Two TEOM Series 1400a ambient particulate monitors from Rupprecht & Patashnick Co. Albany, NY, were used to continuously measure concentrations of total particulate matter (TPM) under 0.8 μm in mine air at the downstream and upstream sampling stations. A scanning mobility

[1] National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory, phone: 412.386.5912, fax: 412.386.4917, e-mail: abugarski@cdc.gov

particle sizer (SMPS) Model 3936 from TSI Inc., St. Paul MN, consisting of an electrostatic classifier Model 3080L and a condensation particle counter (CPC) Model 3025A, was used at the downstream sampling station to periodically measure the size distribution and number of particles in the range between 10 and 392 nm.

Results

The carbon analysis performed on the collected samples showed that the tested DPF systems reduced the mass concentrations of EC in the mine air by 88 to 99%. The tested biodiesel blends, B20 (20% biodiesel / 80 % #2 diesel) and B50 (50% biodiesel / 50 % #2 diesel), were found to reduce EC concentrations in the mine air by 26 and 48 percent, respectively.

The TEOM measurements revealed that the DPF systems reduced the mass concentrations of total DPM in mine air by 74 to 89 %. The mass concentrations of total particulate matter under 800 nm in mine air were 9 and 24 % lower when biodiesel blends B20 and B50, respectively were used instead of diesel fuel.

The size selective measurements revealed that reductions in the mass concentrations were not necessarily accompanied by reductions in the particle number. For the tests with selected catalyzed DPF systems, the distributions of the particles were found to be characterized with significantly lower geometric means (D_{50}) and higher peak concentrations than the corresponding size distributions observed during the tests with unfiltered engines/vehicles. A substantial increase in the total number of particles in the mine air, of up to 80%, was observed during the tests when DPF systems with platinum catalysts were tested. Increase in the number of particles and lower D_{50} of measured aerosols was also observed in the cases when the test vehicle was fueled with B20 and B50 instead with diesel.

The results of the NO_2 measurements showed that the average normalized concentrations of NO_2 increased by 266 and 164 % when vehicles equipped with platinum catalyzed DPF systems were operated in the isolated zone. This increase in NO_2 emissions is recognized as a major technical problem limiting the implementation of catalyzed DPF systems in underground mines.

References

30 CFR 57.5060 [2001]. Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners. Limit on Concentration of Diesel Particulate Matter. Code of Federal Regulations. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

68 Fed. Reg. 48668 [2003]. Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners; Proposed Rule, Mine Safety and Health Administration. Washington, DC: U.S. Government Printing Office, Office of the Federal Register.

Characterization of Diesel Aerosols in Underground Mine

By
Aleksandar Bugarski,
NIOSH Pittsburgh Research Laboratory

ETH Conference on Combustion Generated Nanoparticles
Zürich, August 16-18, 2004

Introduction - Diesels and Underground Mining

- Underground miners in U.S. are exposed to concentrations of diesel particulate matter (DPM) that are significantly exceeding those of any other occupation. The reasons are:
  - Relatively large number of diesel vehicles
  - Confined space
  - Limited supply of fresh air
  - Relatively outdate diesel fleet
  - Limited use of control technologies…
- In 2001 Mine Safety and Health Administration (MSHA) promulgated rule regulating exposure of metal/nonmetal (M/NM) underground miners to DPM [30 CFR 57.5060 2001]
  - Interim standard: 400 μg/m^3 of total carbon (TC)
  - Final standard: 160 μg/m^3 of total carbon (TC)

Introduction - Diesels and Underground Mining

- In 2003 MSHA introduced alternative interim standard of 308 μg/m^3 of elemental carbon (EC)
- Technology driving regulations
- Limited experience with advanced control technologies for underground mining applications
- 30 CFR 57.5001 [1995] that regulates exposure of surface and underground miners to airborne contaminants has individual standards for
  - Nitric Oxide (NO), ACGIH TLV-TWA is 25 ppm and
  - Nitrogen dioxide (NO2), ACGIH TLV-TWA is 3 ppm, ACGIH TLV-STEL is 5 ppm

Objectives of the study

- To measure the effects of selected diesel emissions control technologies on the concentrations and properties of aerosols and gases in mine air
  - diesel particulate matter filtration systems (DPFs)
    - Engelhard DPX, model 9308,
    - DCL MineX, model 5C5711…
  - diesel oxidation catalytic converter/muffler (DOC)
  - fuel formulations
    - 20% (B20) and 50% (B50) yellow grease biodiesel blends (B100 from Griffin Industries, KY, G3000, 25 ppm sulfur)
    - #1 Diesel (125 ppm sulfur) vs. #2 Diesel (366 ppm sulfur) (Cenex, Billings, MT)

Mention of any company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health

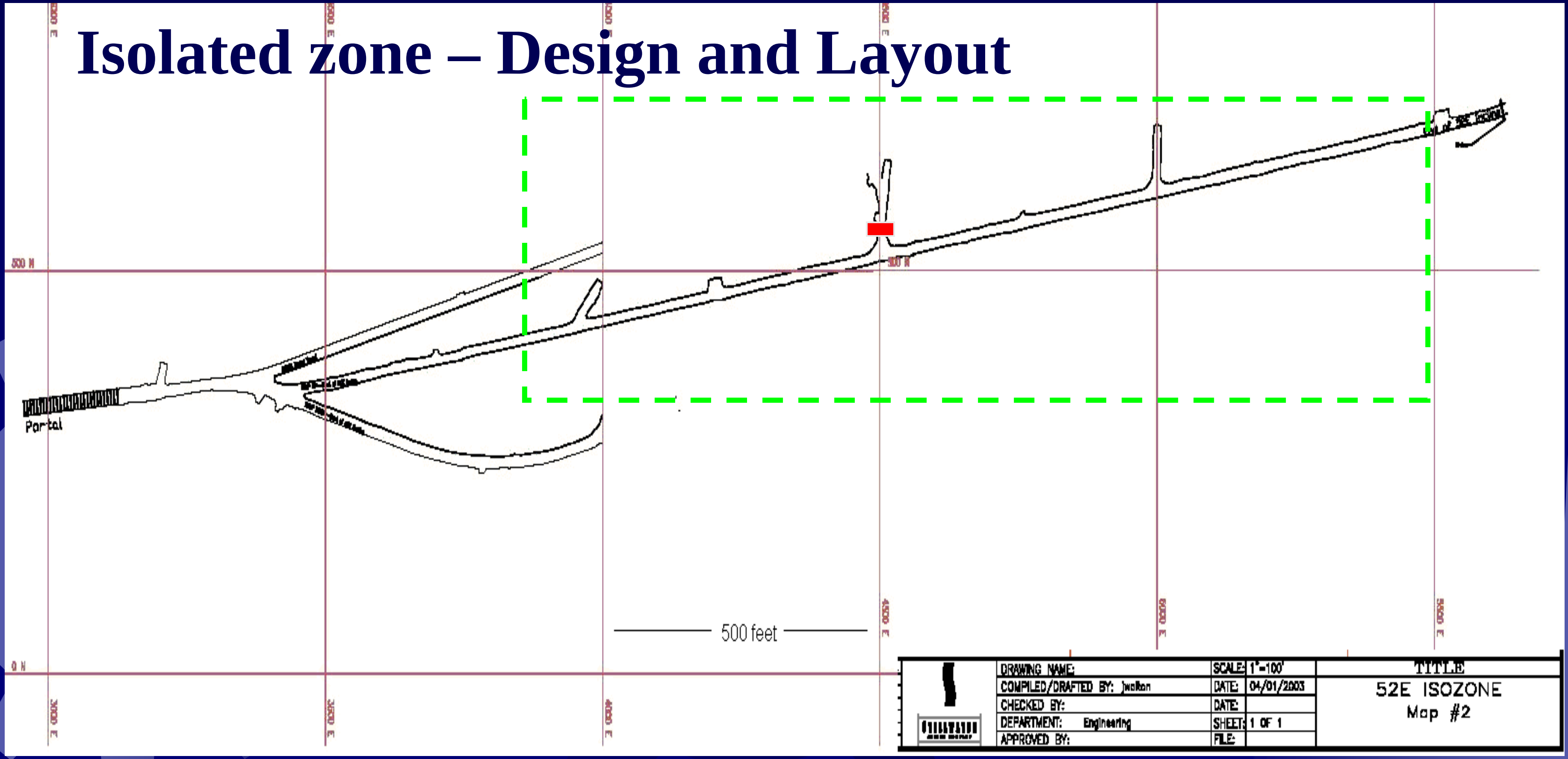
Methodology

- The study was conducted in an isolated zone at Stillwater Nye mine:
  - Nye, Montana
  - Precious metals mine (palladium, platinum, gold, silver,…)
  - Vein mining
  - Large inventory of diesel-powered equipment (~ 400 units)
  - Relatively small and low-power equipment
  - Main portal at 5000 feet above see level with production between 2900-7000 ft
  - Isolated zone between level 5000 and 5200
- Tests were conducted in a two-week period in May and June 2003

Rationale Behind Isolated Zone Testing

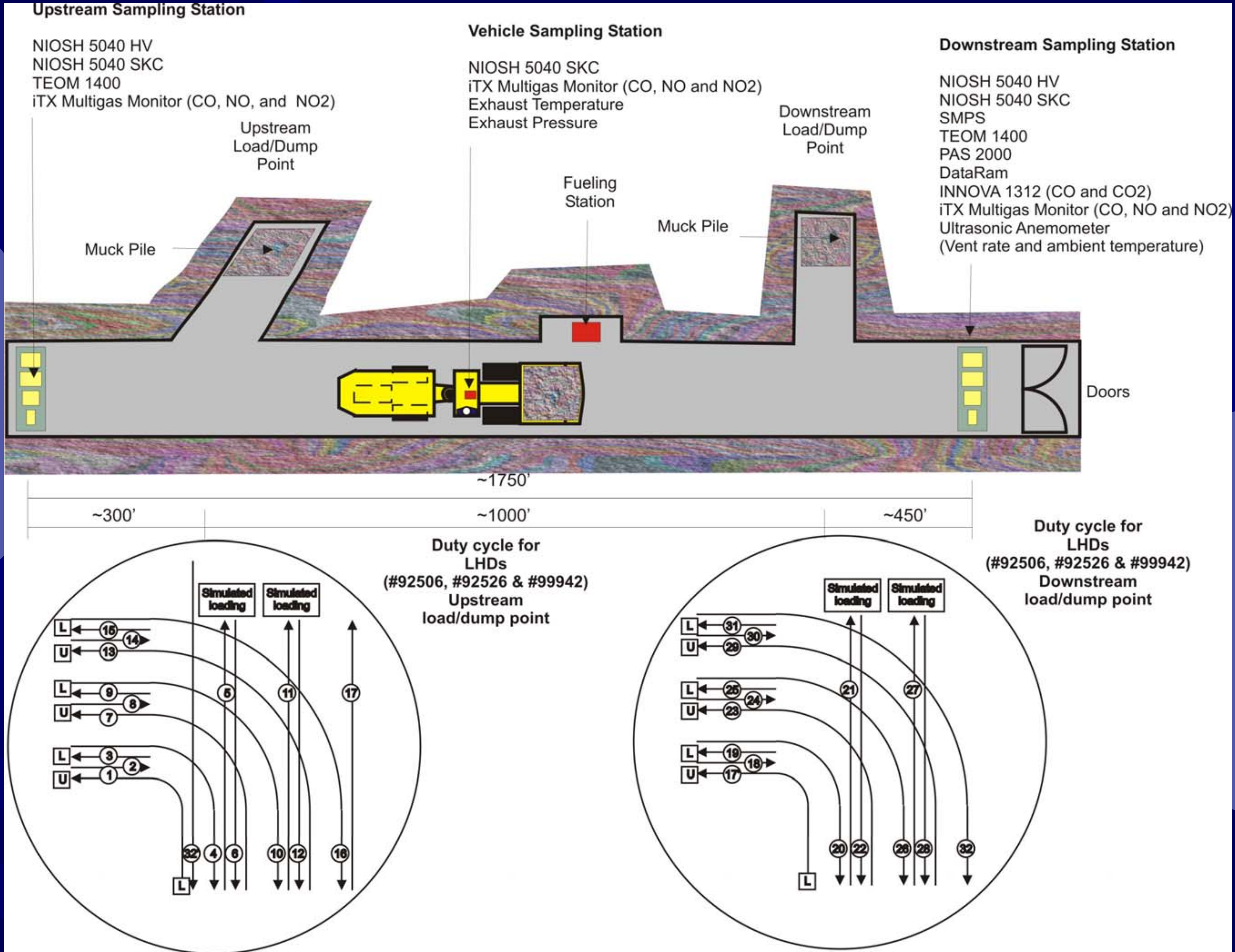
- Direct in-situ assessment of the effects of control technologies on quality of ambient air in occupational environment
- Vehicles operated over a simulated transient production cycle
- Interaction between vehicle, engine, and control technology
- Complements results of laboratory evaluations

Isolated zone – Design and Layout

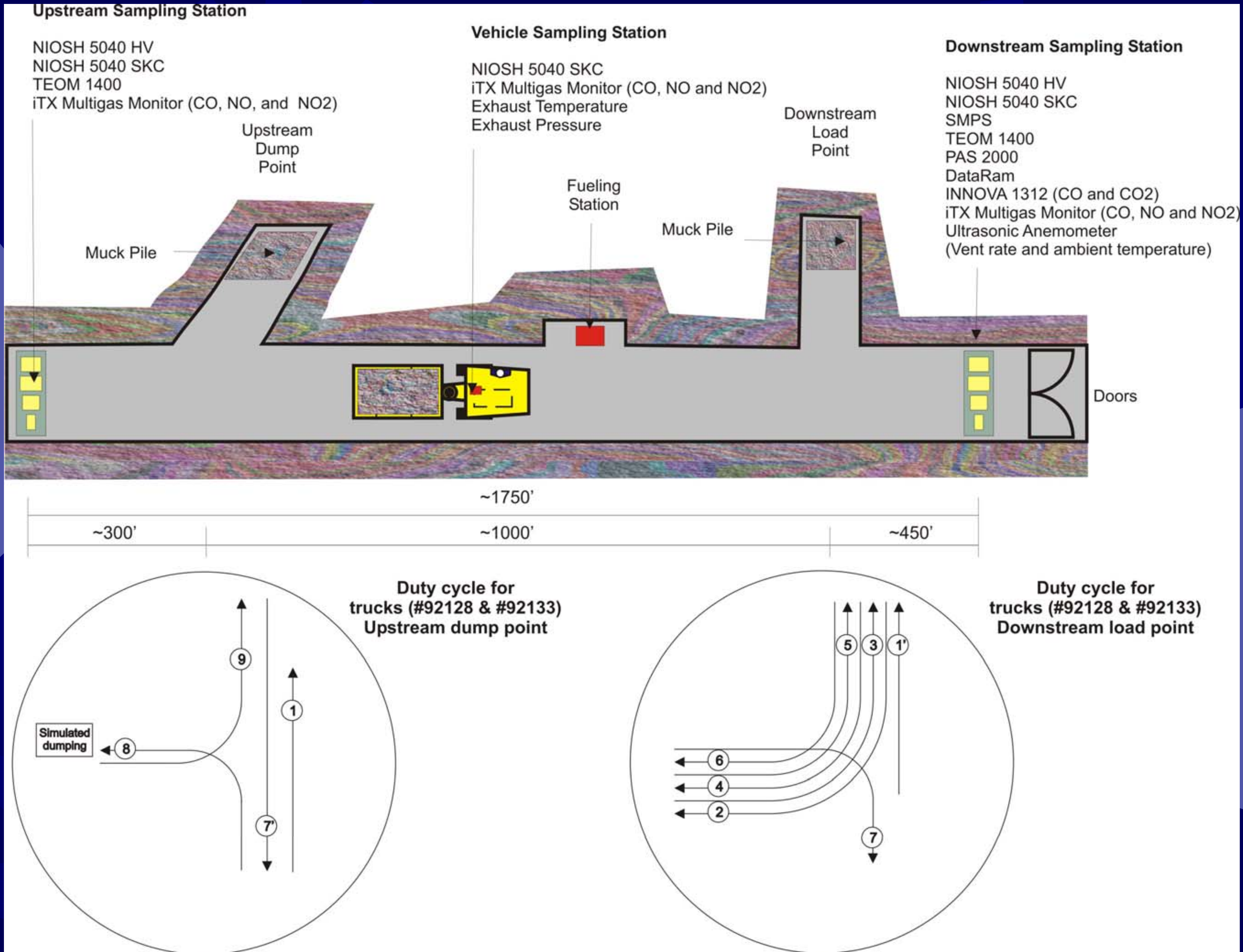


- ~1750 ft (533 m) long
- ~1000 ft (305 m) from portal
- 9% grade rising downstream
- ventilated with fresh air from portal

LHDs in Isolated Zone: Design, Layout and Duty Cycle



Haulage Trucks in Isolated Zone: Design, Layout and Duty Cycle



Sampling Strategy Used in IsoZone Tests

- Three sampling locations:
  - Upstream sampling station, ~ 300 ft (91 m) upstream of the upstream load/dump point
  - Downstream sampling station, ~ 450 ft (137 m) downstream of the upstream load/dump point
  - On-vehicle, ~ 6 ft (1.8 m) from the operator
- Contribution from the vehicles obtained by subtracting upstream from downstream concentrations. (As a rule, upstream concentrations were found to be negligible for every pollutant measured except CO_2.)

Sampling Methodology and Instrumentation Used in Isolated Zone Tests

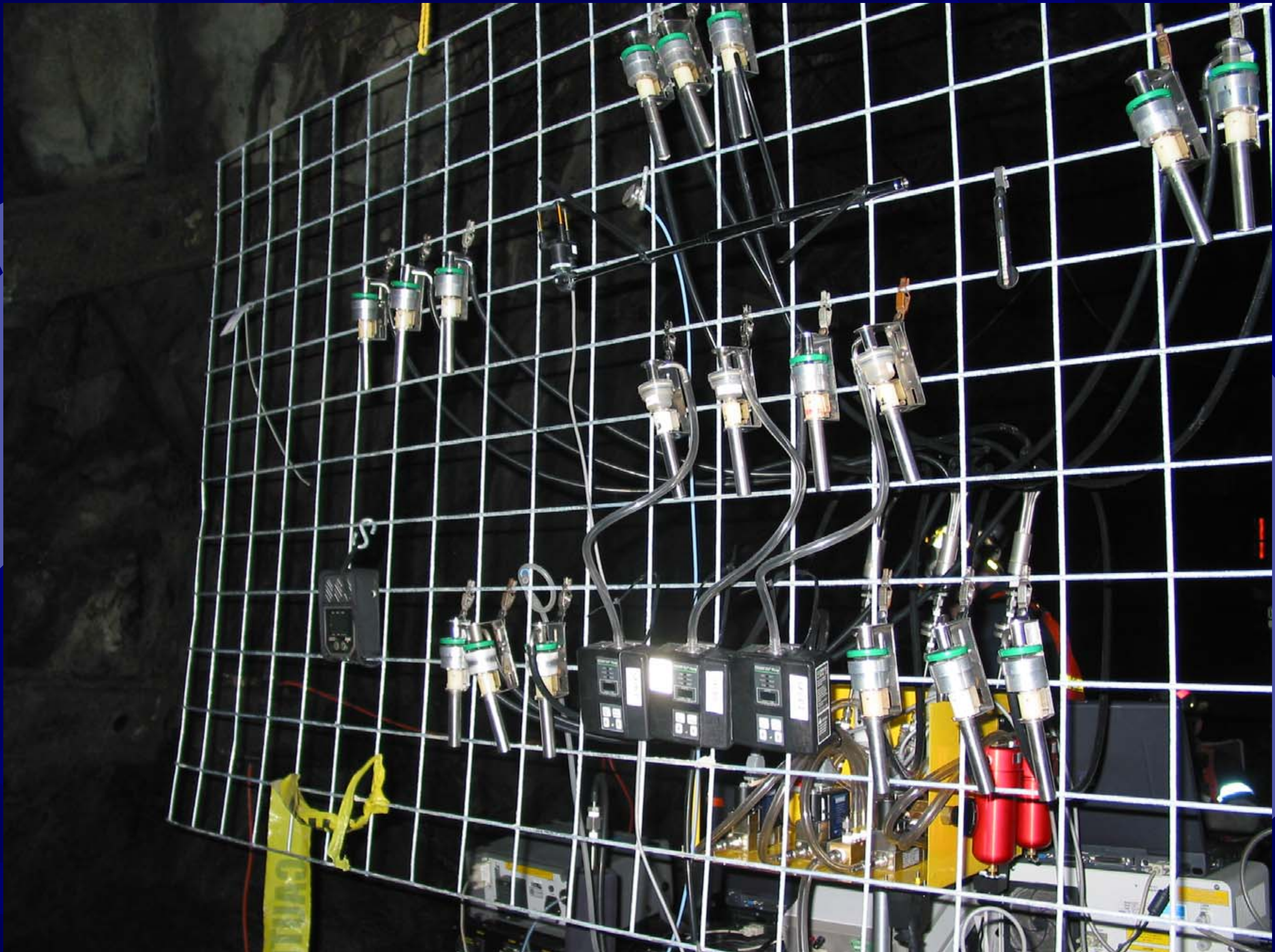
- **Particulate Matter**
  - Filter samples for NIOSH 5040 carbon analysis (elemental carbon with D_{50} under ~800 nm) were collected using:
    - Standard sampling train (10mm Dorr Oliver cyclone, SKC impactor, pump) at upstream, downstream, and on-vehicle sampling locations
    - High volume sampling train at upstream and downstream sampling station
  - Concentrations of particles were measured using:
    - TEOM 1400 (real-time, mass of total PM with D_{50} under 800 nm)
    - SMPS (steady-state, size distribution and number concentrations of aerosols with D_{50} between 10 and 392 nm)

Sampling Methodology and Instrumentation Used in Isolated Zone Tests (Continued)

- **Gases**
  - Concentrations of CO, NO, and NO_2 in mine air at upstream, downstream, and vehicle sampling station were continuously measured using:
    - Industrial Scientific iTX multigas monitors
  - Concentrations of CO and CO_2 in mine air at downstream sampling station were continuously measured using:
    - INNOVA 1312
- **Ventilation Rates**
  - Ultrasonic anemometer

Instrumentation at Downstream Sampling Station

Sampling Grid at Downstream Sampling Station



Results and Discussion

- Effects of DPF systems and DOC on:
  - mass concentrations of elemental carbon particles under 800 nm
  - mass concentrations of total particulate matter under 800 nm
  - number concentrations and size distribution of aerosols between 10 and 392 nm

- Effects of different fuel formulations on:
  - mass concentrations of elemental carbon particles under 800 nm
  - mass concentrations of total particulate matter under 800 nm
  - number concentrations and size distribution of aerosols between 10 and 392 nm

The Effects of Selected Diesel Particulate Filters (DPFs) and Diesel Oxidation Catalytic Converter (DOC) on Concentrations of Particulate Matter and Gases in Mine Air

The Effects on Mass Concentrations of Elemental Carbon (EC)

Test Vehicle and Test Type	Net Elemental Carbon Concentrations <0.8 µm (USBM Impactor) NIOSH Method 5040		Change in Elemental Carbon
	Average [µg/m^3]	CV [%]	[%]
#92128 Haul Truck, MSHA ventilation rate 5.66 m^3/s (12000 ft^3/m)			
Baseline	1182	5.3	-96
Engelhard DPX	51	3.2	
#92133 Haul Truck, MSHA ventilation rate 5.66 m^3/s (12000 ft^3/m)			
Baseline + CDT	1038*	10.6	-99
CleanAir + CDT	15*	5.3	
#92526 LHD, MSHA ventilation rate 4.96 m^3/s (10500 ft^3/m)			
Baseline	1265	1.6	3
DOC	1300	2	
#99942 LHD, MSHA ventilation rate 7.08 m^3/s (15000 ft^3/m)			
Baseline	1112	7.7	-88
DCL MineX	149	2.6	

- Tested DPFs reduced concentrations of EC below current standards (308 µg/m^3).
- Tested DOC did not significantly affect EC concentrations.

The Effects on Mass Concentrations of Total Particulate Matter (TPM)

Test Vehicle and Test Type	Concentrations of TPM <0.8 µm [µg/m³]		Change in TPM [%]
	Average	Maximum	Average
#92128 Haul Truck, MSHA vent rate 5.66 m³/s (12000 ft³/m)			
Baseline	1343.9	1536.3	-75
Engelhard DPX	342	411.6	
#92133 Haul Truck, MSHA vent rate 5.66 m³/s (12000 ft³/m)			
Baseline + CDT	1133.6	1331.7	-89
CleanAir + CDT	122.6	158.1	
#92526 LHD, MSHA vent rate 4.96 m³/s (10500 ft³/m)			
Baseline	1554.2	1983.8	15
DOC	1785	2213.9	
#99942 LHD, MSHA vent rate 7.08 m³/s (15000 ft³/m)			
Baseline	1433.6	2140.2	-74
DCL MineX	370	588.1	

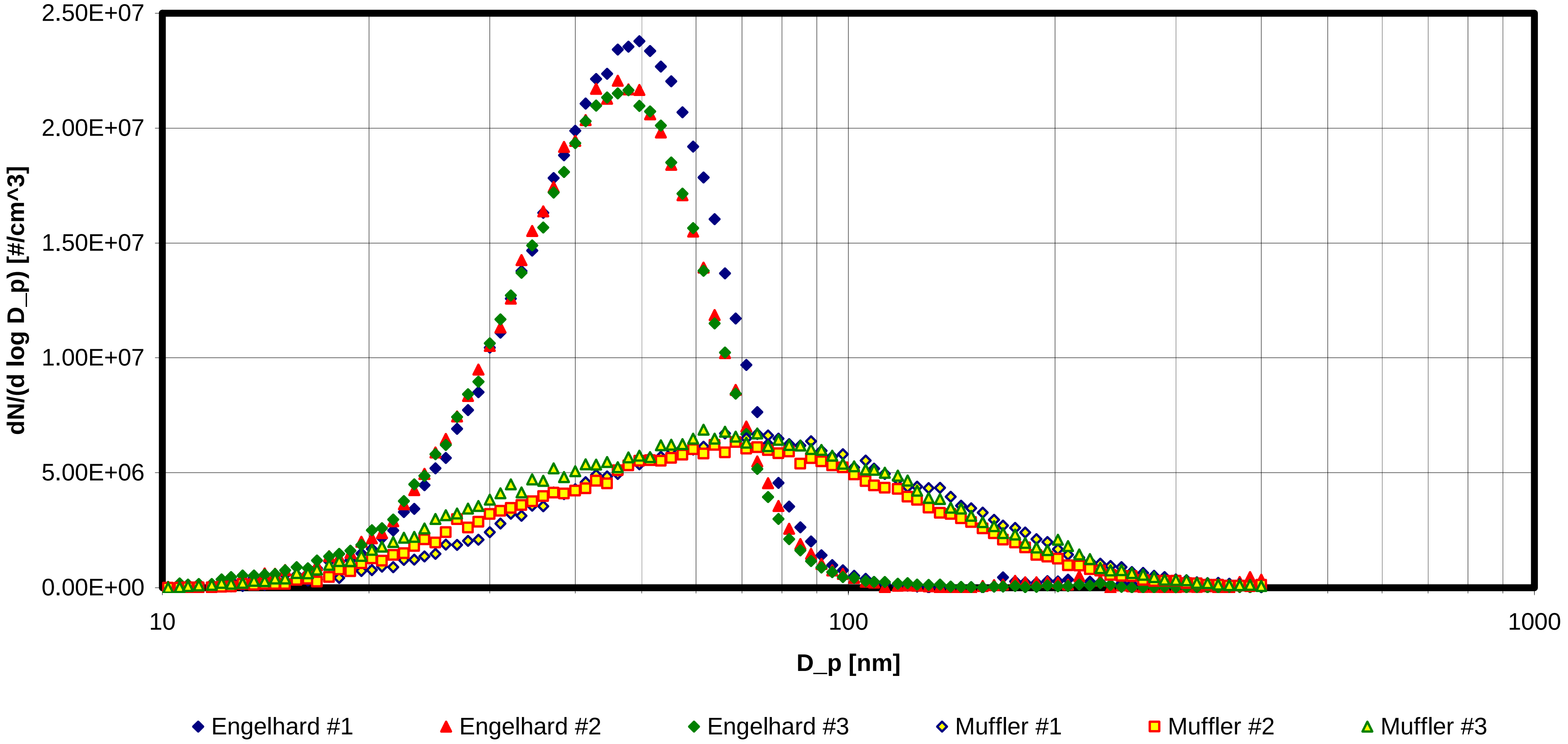
- Tested DPFs reduced TPM concentrations less than EC concentrations (sulfate and/or other artifact?)

The Effects on Concentrations of Aerosols with Electrical Mobility Diameter Between 10 and 392 nm in Mine Air

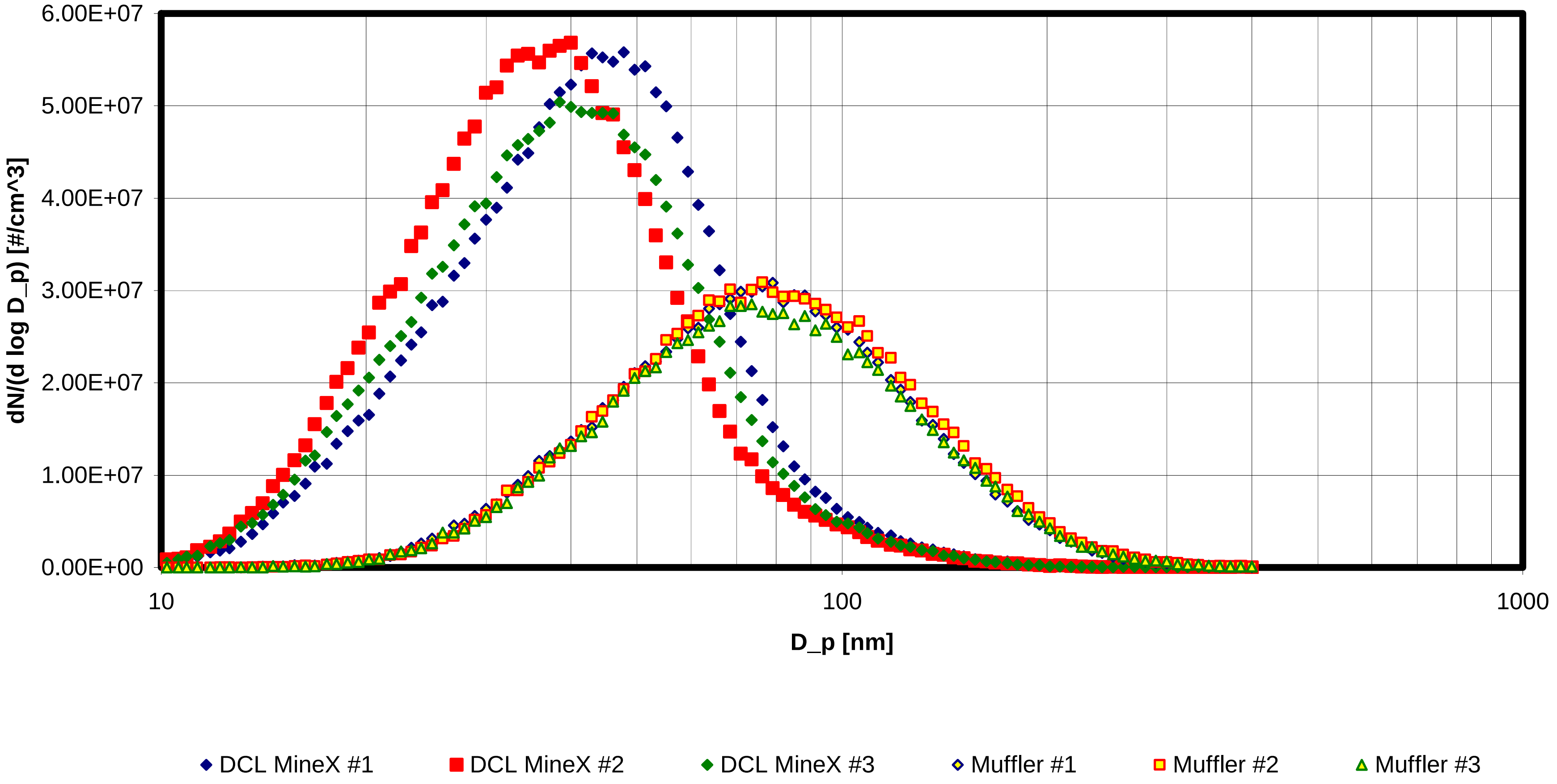
Test Vehicle and Test Type	Average Geometric Mean, D_{50} [nm]	Average Total Particle Conc. at MSHA Vent Rate	Change in Total Particle Concentration
	[nm]	[#/cm³ x 10^7]	[%]
#92128 Haul Truck, MSHA ventilation rate 5.66 m^3/s (12000 ft^3/m)			
Baseline	67 vs. 44	28.8	80
Engelhard DPX		51.7	
#92526 LHD, MSHA ventilation rate 4.96 m^3/s (10500 ft^3/m)			
Baseline	86 vs. 72	6.82	7
DOC		7.32	
#99942 LHD, MSHA ventilation rate 7.08 m^3/s (15000 ft^3/m)			
Baseline	75 vs. 38	3.97	79
DCL MineX		7.09	

- Tested DPFs greatly increased the aerosol number concentrations.
- Tested DPFs reduced D_{50} of the aerosols.
- Tested DOC slightly increased aerosol number concentrations.
- Tested DOC slightly reduced D_{50} of the aerosols.

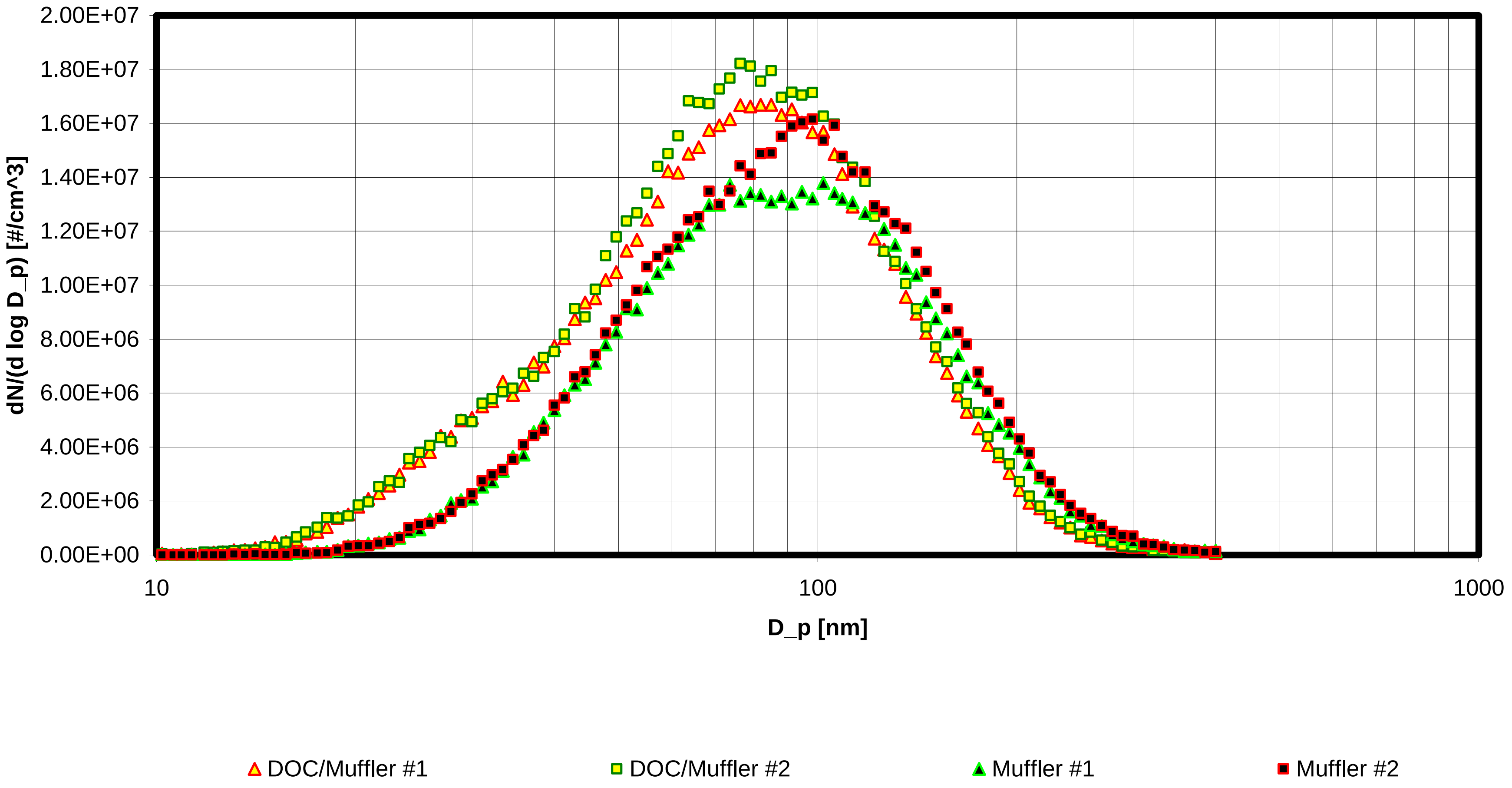
Size distribution of aerosols in mine air
Truck #92128: Engelhard DPX DPF vs. Muffler



Size distribution of aerosols in mine air
LHD #99942 - DCL MineX vs. Muffler



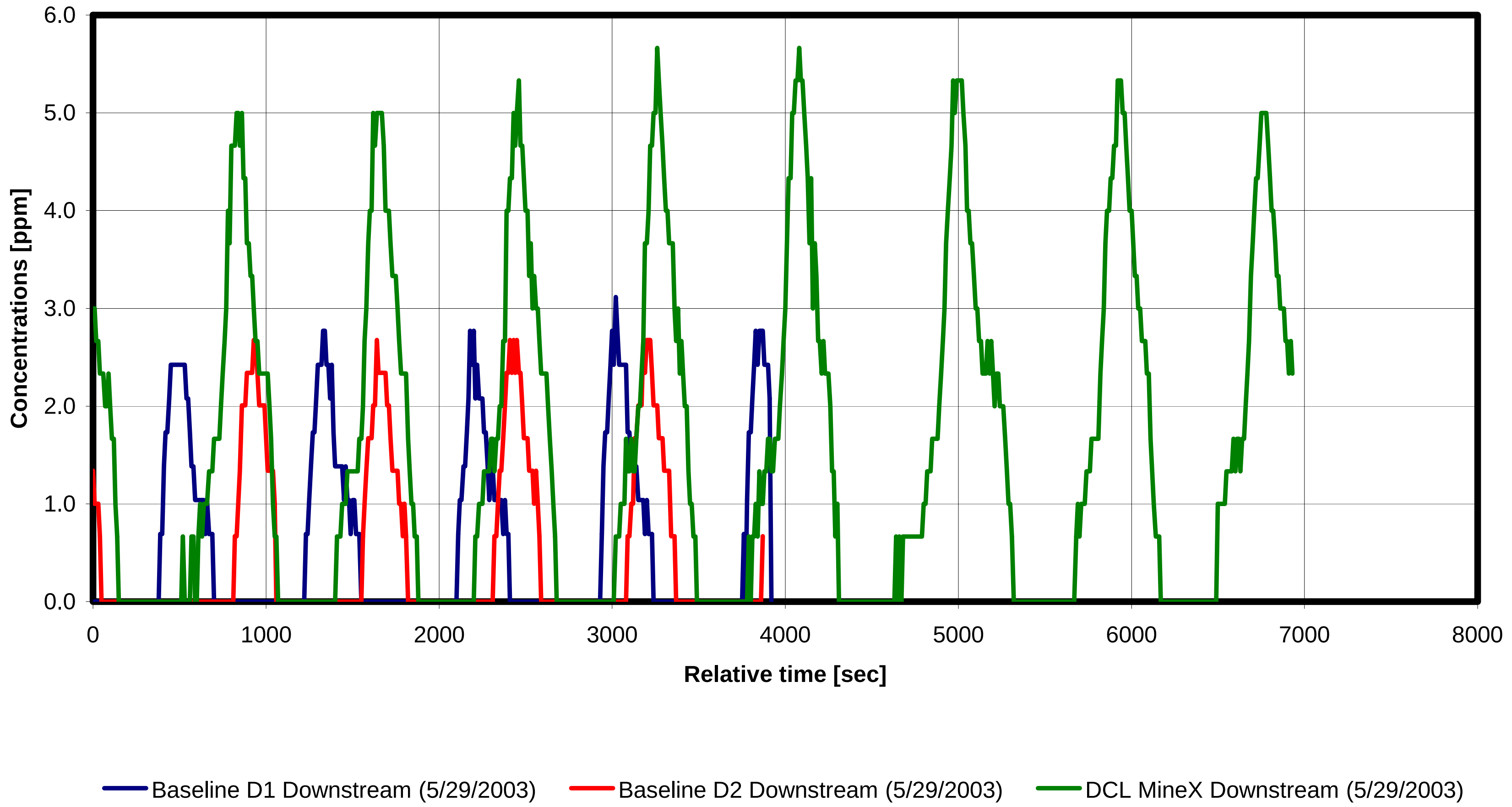
Size distribution of aerosols in mine air
LHD #92526 –DOC/Muffler vs. Muffler



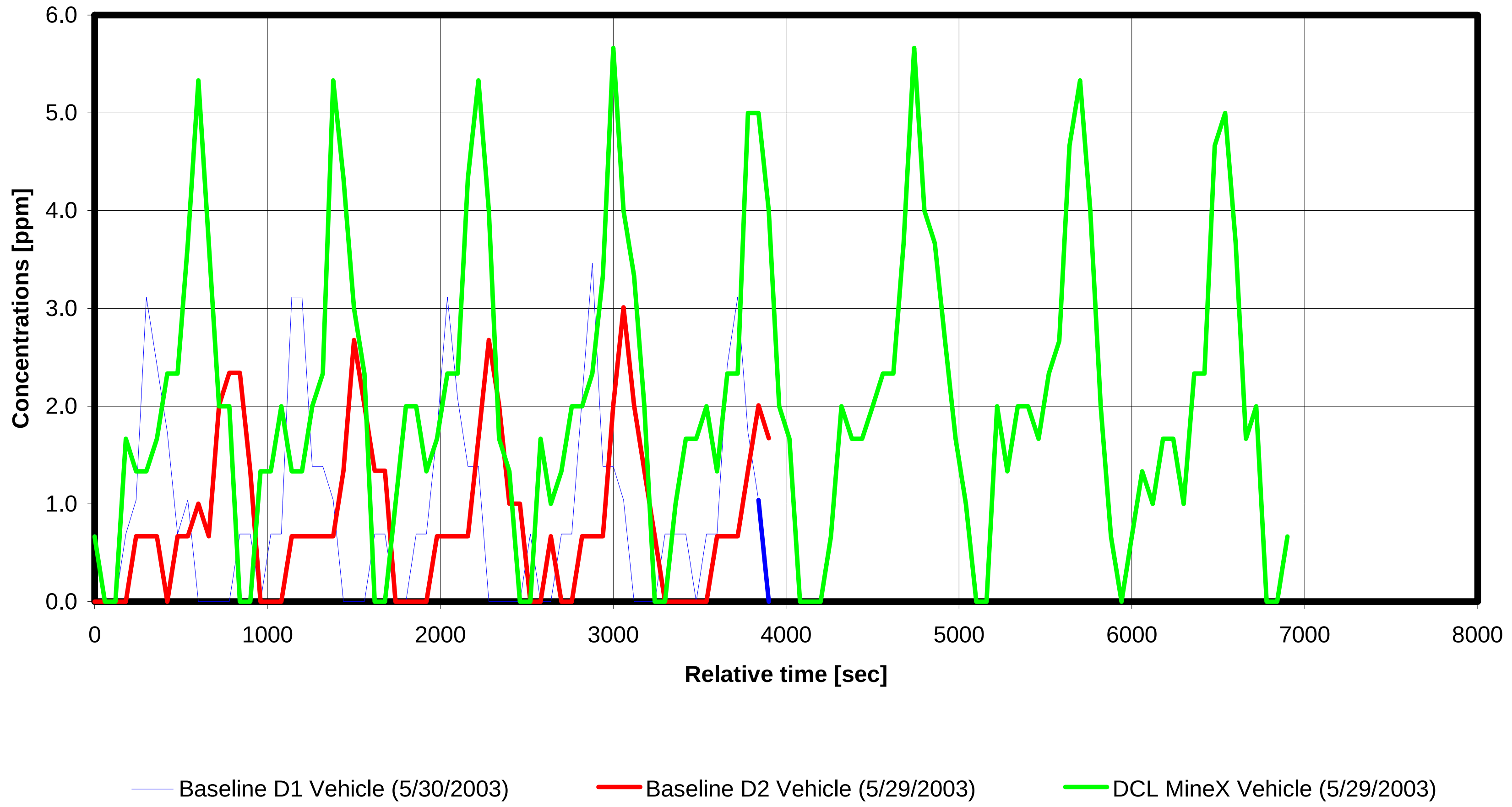
Concentrations of Nitrogen Dioxide (NO_2)

Test Vehicle and Test Type	Average NO_2 Concentrations at MSHA Vent. Rate	Change in NO_2 by Control Technology
	[ppm]	[%]
#92128 Haul Truck, MSHA ventilation rate 5.66 m^3/s (12000 ft^3/m)		
Baseline	0.6	--
Engelhard DPX	2.1	269
#92526 LHD, MSHA ventilation rate 4.96 m^3/s (10500 ft^3/m)		
Baseline	0.9	--
DOC	1.1	26
#99942 LHD, MSHA ventilation rate 7.08 m^3/s (15000 ft^3/m)		
Baseline, D1	0.5	--
DCL MineX	1.5	180

- The ambient concentrations of NO_2 increased when vehicles with platinum coated DPFs were tested.
- Tested DOC did not significantly affect ambient concentrations of NO_2.



Ventilation-normalized NO_2 concentrations at downstream sampling station observed during the tests with LHD #99942



Ventilation-normalized NO_2 concentrations at vehicle sampling station observed during the tests with LHD #99942

Effects of Tested Fuel Formulations on Concentrations of Particulate Matter and Gases Mine Air

The Effects on Mass Concentrations of EC

Test Vehicle and Test Type	Net Elemental Carbon Concentrations <0.8 µm (USBM Impactor) NIOSH Method 5040		Change in Elemental Carbon
	Average [µg/m^3]	CV [%]	[%]
#92506 LHD, MSHA vent rate 4.01 m^3/s (8500 ft^3/m)			
Baseline, 90% D2, 10% D1	1269	3	--
Baseline, D2	1422	6.6	12
#92526 LHD, MSHA vent rate 4.96 m^3/s (10500 ft^3/m)			
Baseline with DOC	1300	2	--
Biodiesel B20 with DOC	967	4.7	-26
Biodiesel B50 with DOC	669	4.3	-48
#99942 LHD, MSHA vent rate 7.08 m^3/s (15000 ft^3/m)			
Baseline, D1	1112	7.7	--
Baseline, D2	1222	4	10

- Biodiesel (‘yellow grease”) blends B20 and B50 reduced the concentrations of EC in mine air by 26 and 48 %, respectively.
- Fueling #99942 with # 2 diesel (D2) resulted in 10% increase in EC concentrations in mine air over the case when the same vehicle was fueled with # 1 diesel (D1).

The Effects on Mass Concentrations of TPM in Mine Air

Test Vehicle and Test Type	Concentrations of TPM <0.8 μm [μg/m^3]		Change in TPM [%]
	Average	Maximum	Average
#92526 LHD, MSHA vent rate 4.96 m^3/s (10500 ft^3/m)			
Baseline with DOC	1786	2213.9	--
Biodiesel B20 with DOC	1618	1985.5	-9
Biodiesel B50 with DOC	1349	1714.9	-24
#99942 LHD, MSHA vent rate 7.08 m^3/s (15000 ft^3/m)			
Baseline D1	1434	2140.2	--
Baseline D2	1735	2739.2	21

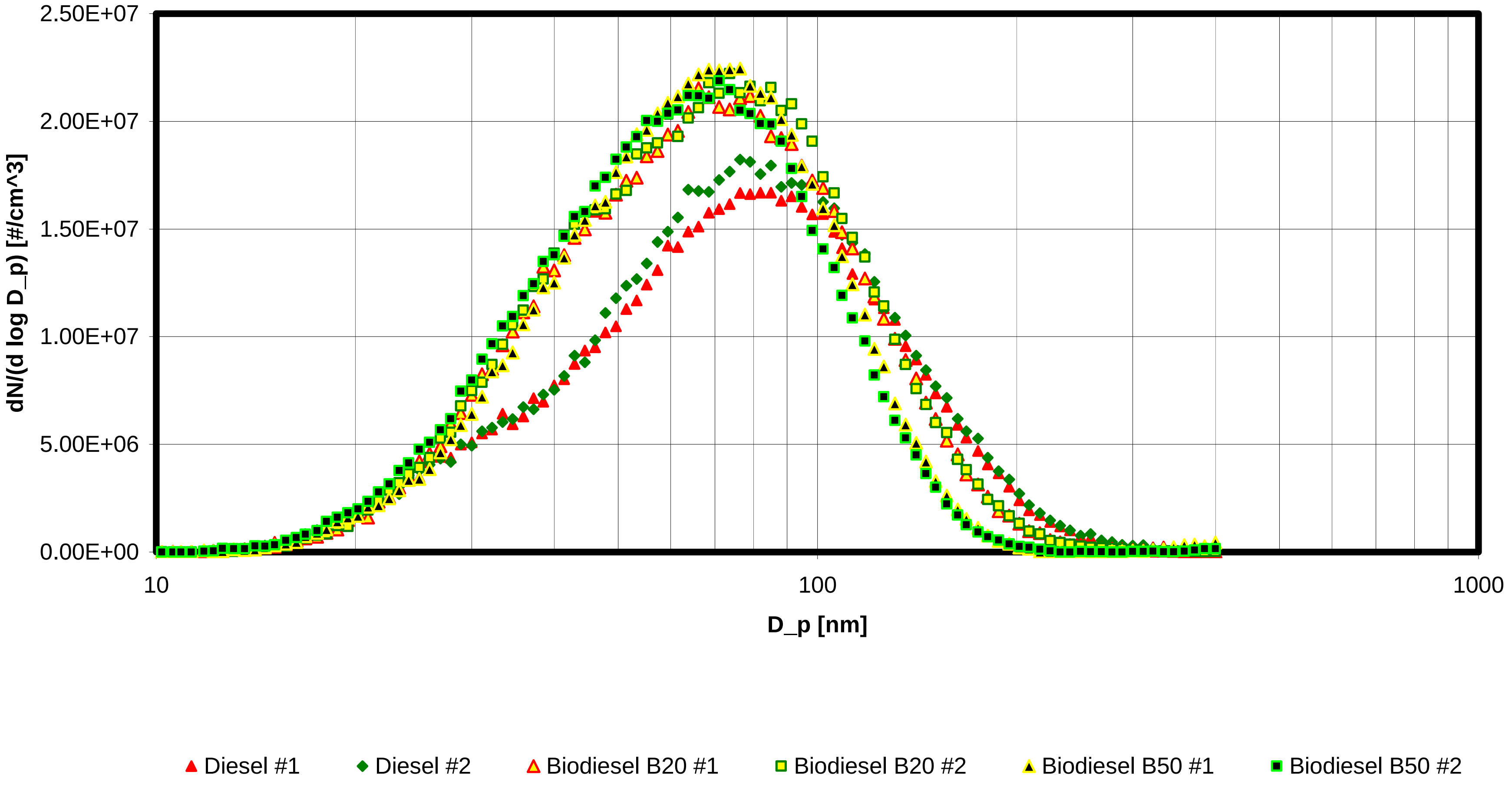
- Biodiesel blends B20 and B50 reduced concentrations of TPM in mine air by 9 and 24 %, respectively.
- Fueling #99942 with #2 diesel resulted in 21% increase in TPM concentrations in mine air over the case when the same vehicle was fueled with #1 diesel.

The Effects on Concentration of Aerosols with Electrical Mobility Diameter Between 10 and 392 nm in Mine Air

Test Vehicle and Test Type	Average Geometric Mean, D50 [nm]	Average Total Particle Conc. at MSHA Vent Rate	Change in Total Particle Concentration
	[nm]	[#/cm³ x 10^7]	[%]
#92526 LHD, MSHA ventilation rate 4.96 m^3/s (10500 ft^3/m)			
Baseline with DOC	72	7.32	--
Biodiesel B20 with DOC	66	9.72	33
Biodiesel B50 with DOC	62	9.11	24
#99942 LHD, MSHA ventilation rate 7.08 m^3/s (15000 ft^3/m)			
Baseline D1 (Muffler)	75	3.97	--
D2 (Muffler)	82	4.85	22

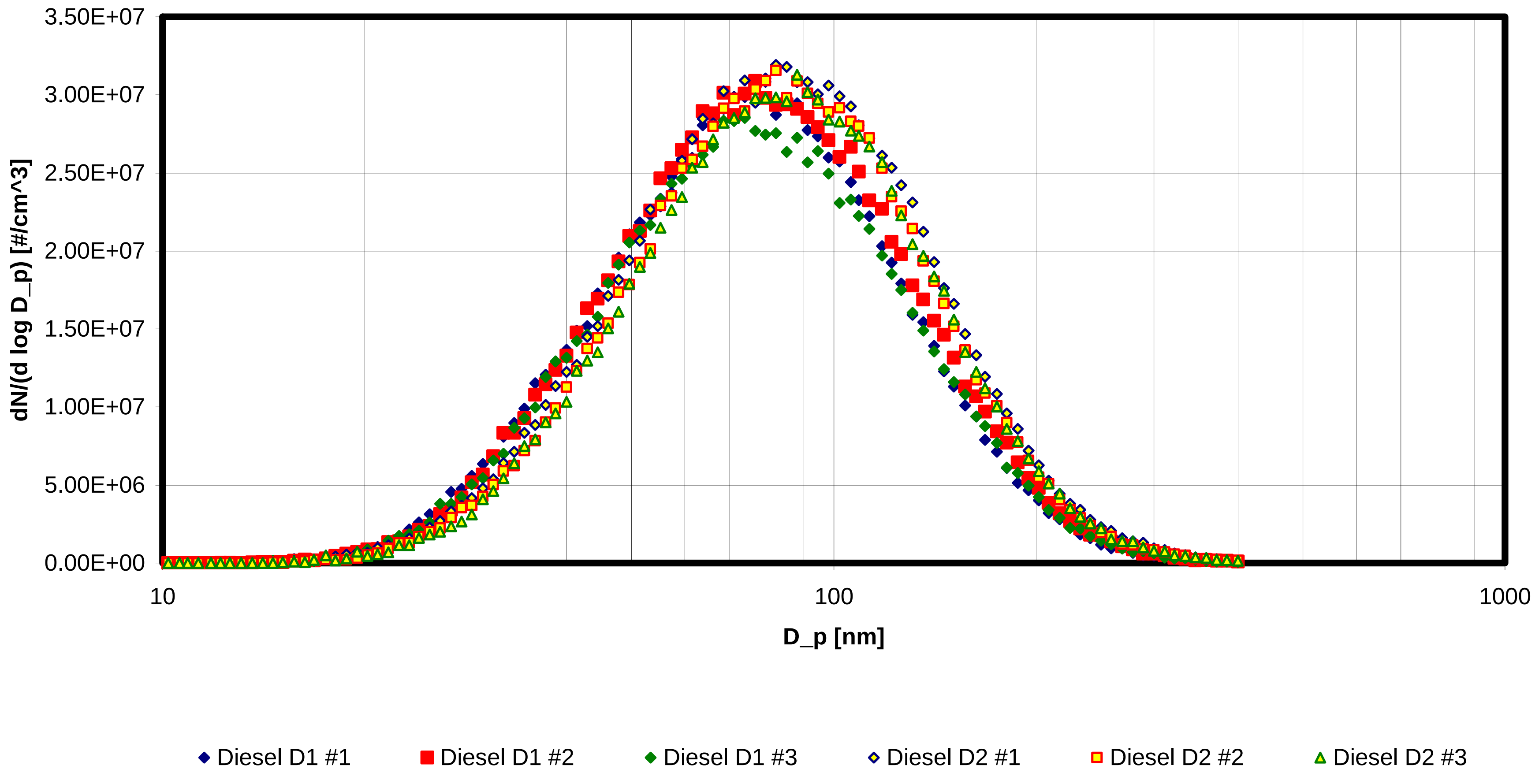
- Fueling with B20 and B50 instead of #2 diesel resulted in an increase in the number concentrations and lower D_{50} of measured aerosols.
- Fueling with #2 diesel instead of #1 diesel resulted in an increase in the number concentrations and higher D_{50} of measured aerosols.

Size distribution of aerosols in mine air
LHD #92526 with DOC and muffler:
#1 Diesel vs. Biodiesel B20 vs. Biodiesel B50



Size distribution of aerosols in mine air

LHD #99942 equipped with muffler: #1 Diesel vs. # 2 Diesel



The Effects on Concentration of Nitrogen Dioxide (NO_2)

Test Vehicle and Test Type	Average NO_2 Concentrations at MSHA Vent. Rate	Change in NO_2 by Control Technology
	[ppm]	[%]
#92506 LHD, MSHA vent rate 4.01 m^3/s (8500 ft^3/m)		
90% D2, 10% D1	0.0	--
D2	0.0	--
#92526 LHD, MSHA ventilation rate 4.96 m^3/s (10500 ft^3/m)		
Baseline with DOC	1.1	--
Biodiesel B20 with DOC	1.1	5
Biodiesel B50 with DOC	1.3	21
#99942 LHD, MSHA ventilation rate 7.08 m^3/s (15000 ft^3/m)		
Baseline, D1	0.5	--
D2	0.5	-13

- The average NO_2 concentration increased when biodiesel blends were used.

Summary

- Tested DPF systems reduced substantially ambient concentrations of EC and TPM in mine air
- But, tested platinum catalyzed DPF systems increased ambient concentrations of NO_2 by 266 and 164 %
- And, the size distributions of aerosols generated the vehicles equipped with certain DPF systems were found to be characterized by a larger number of a smaller size particles and higher peak concentrations than the size distributions of aerosols generated by the same vehicles when equipped with mufflers.
- Tested biodiesel blends B20 and B50 resulted in reductions of EC concentrations of 26 and 48%, respectively

Acknowledgements

- Stillwater Mining Co. for hosting the study.
- Larry Patts, Jon Hummer, and Shawn Vanderslice of NIOSH PRL for their long hours and great contribution to the study.
- Lee Melrose, Daniel Milton and other Stillwater Nye mine employees for their support in organizing and executing the study.

Questions???

Aleksandar Bugarski,
NIOSH PRL,
phone: 412.386.5912
e-mail: ABugarski@cdc.gov