Controlling Exposure to DPM: Diesel Particulate Filters vs. Biodiesel

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Introduction

- As of May 20, 2008 exposure of U.S. metal/nonmetal underground miners to diesel particulate matter (DPM) is limited to 160 μg/m³ (30 CFR 57.5060).
- In addition, exposure to airborne contaminants including gaseous pollutants emitted by diesel engines (primarily carbon dioxide (CO_2), carbon monoxide (CO), nitric oxide (NO), and nitrogen dioxide (NO_2)) are limited by 30 CFR 57.5001.
- Meeting the performance based requirements of these regulations necessitates a multifaceted, technology-forcing, and integrated approach toward reducing miner's exposure to DPM.

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Introduction

- Critical component of such approach is curtailment of DPM and toxic gaseous emissions at their source using advanced exhaust aftertreatment technologies:
  - Diesel particulate filter (DPF) systems
  - Filtration systems with disposable filter elements (DFEs)
  - Diesel oxidation catalyst (DOC)
- Changing fuel supply from petroleum diesel to biodiesel blends is considered by a number of underground mine operators to be viable alternative and/or supplement to using exhaust aftertreatment technologies.
- The results of series of the studies conducted at the NIOSH to evaluate the effects of aforementioned control technologies on properties of diesel aerosols were used to compare effects of those two approaches on aerosols emitted by diesel engine in mine air.

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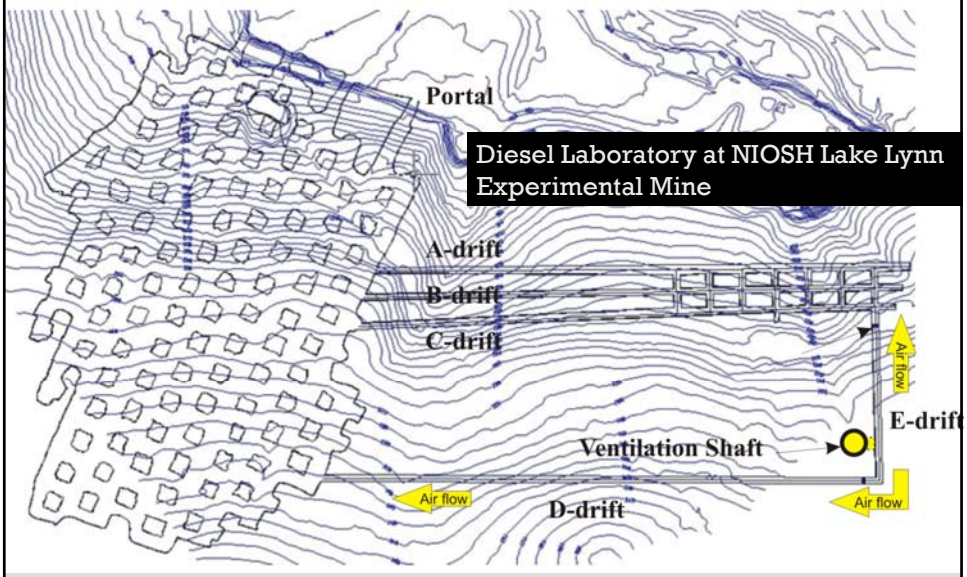
Methodology



Diesel Laboratory at NIOSH Lake Lynn Experimental Mine

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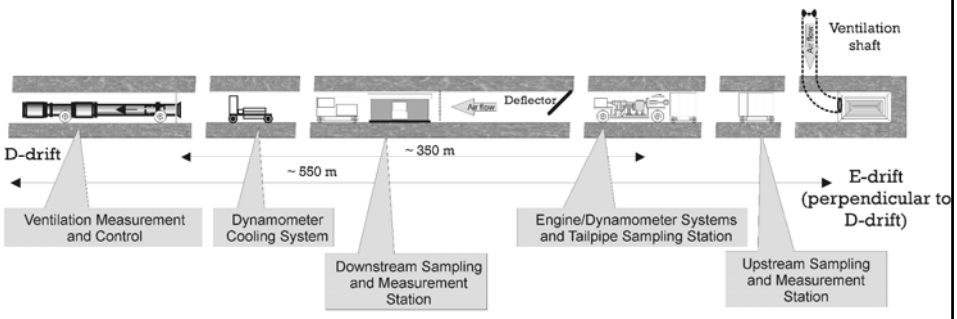
Methodology

Diesel Laboratory at NIOSH Lake Lynn Experimental Mine



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Engine/Dynamometer Systems: 150 kW Dynamometer Coupled to Isuzu C240 Engine (56hp)

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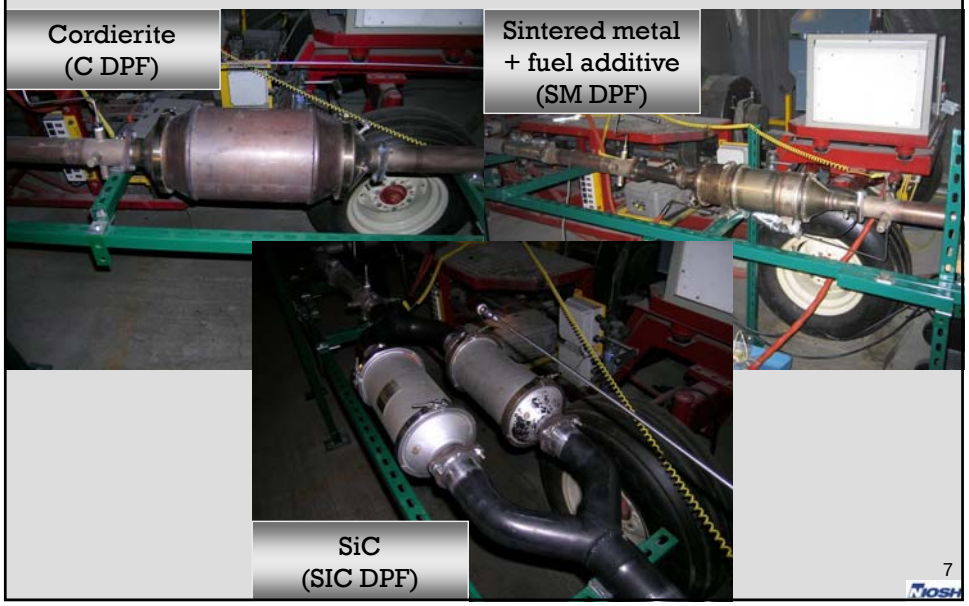
Evaluation of Uncatalyzed Diesel Particulate Filter (DPF) Systems: Exhaust Configurations



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Biodiesel Evaluation: Muffler and DOC/Muffler Exhaust Configurations

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Fuels

Ultra low sulfur petroleum diesel (ULSPD): Guttman Oil (Belle Vernon, PA);
Biodiesel (B100): Stepansol SB-W, Stepan Company (Northfield, IN);
B50 Blend (B50): 50% Biodiesel & 50% ULSD;

Fuel analysis done by Core Laboratories, Houston, TX.

Test	Method	Unit	B100	ULSPD
Energy, Net	ASTM D-240	kJ/kg (BTU/lb)	39975 (17198)	46486 (19999)
Cetane Number	ASTM D-613	-	49.2	58.1
Density	ASTM D-4052	g/ml	0.8835	0.8050
Oxygen Content	ASTM D-5291M	Wt. %	10.54	0.51
Flash Point, PMCC	ASTM D-93A	°C (F)	138 (280)	61 (142)
Sulfur Content	ASTM D-5453	mg/kg	5.1	10.0

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Biodiesel vs. ULSD

- Effects of biodiesel on regulated emissions (Schönborn et al. 2009):
  - lower particulate mass and CO emissions
    - fuel-bound oxygen
  - lower emissions of unburned hydrocarbons
    - high ignition quality
  - elevated NO_X emissions
    - advancement in fuel injection timing
      - lower compressibility and higher speed of sound
      - higher cetane number
    - higher flame temperature (less soot-radiative heat transfer)

Schönborn, A., Ladommatos, N., Williams, J., Allan, R., Rogerson, J. *Combustion and Flame* 2009, 156, 1396-1412.

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Steady-State Test Modes

Mode	Description	Engine Speed	Torque	Power
		rpm	Nm	kW
M1	Rated speed 50% load	2950	55.6	17.2
M2	Rated speed 100% load	2950	111.2	34.3
M3	Intermediate speed 50% load	2100	69.1	14.9
M4	Intermediate speed 100% load	2100	136.9	30.6

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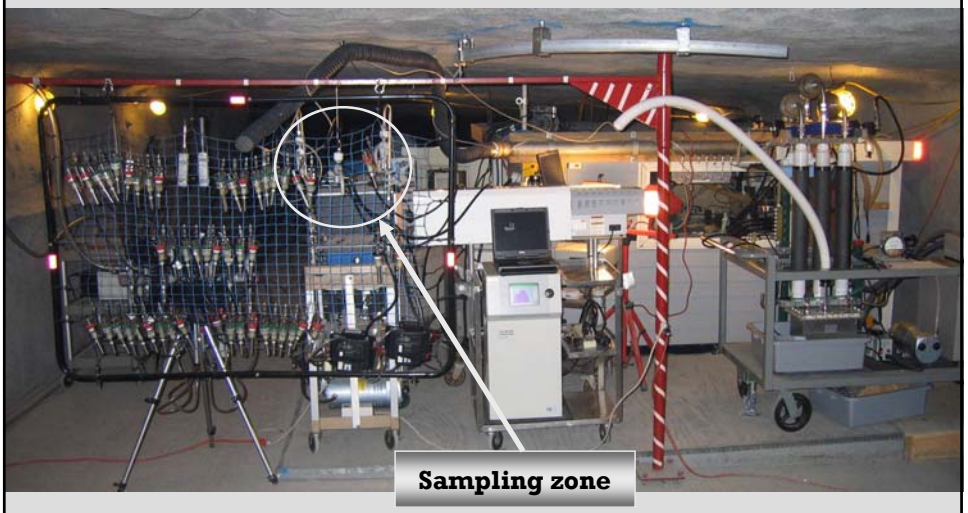
Downstream Sampling and Measurement Station



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Instrumentation for Physical Characterization of Diesel Aerosols

- Total mass: Tapered Element Oscillating Microbalance (Thermo TEOM 1400a);
- Total alveolar region deposited surface area: Nanoparticle Surface Area Monitor (TSI NSAM 3550);
- Total number and size distribution: Scanning Mobility Particle Sizer Spectrometer (TSI SMPS 3936).

TEOM

NSAM

SMPS

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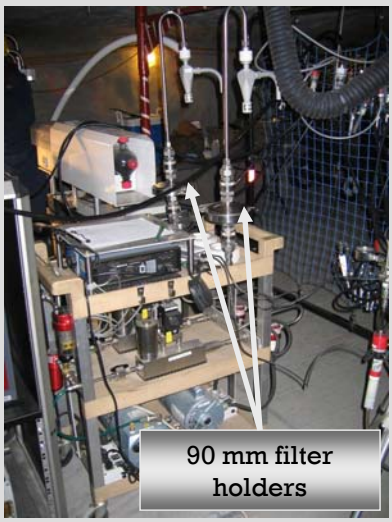
System Used to Sample DPM for Carbon Analysis and Mutagenic Activity Analysis



90 mm filter holders

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Mutagenic Activity Analysis of Solvent Extracted Filter Assays

- The samples were extracted using acetone.
- The samples analyzed for bacterial gene mutation.
- Bacterial tester strain TA98 previously shown to be sensitive to the genotoxicity of diesel exhaust and airborne particles was used in this study.
- Bacterial revertants per microgram of sample are compared to revertants of the same mass of a strong positive control, nitropyrene and for different test cases.

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Results:
1. Total Mass, Surface Area, and Number of Aerosols

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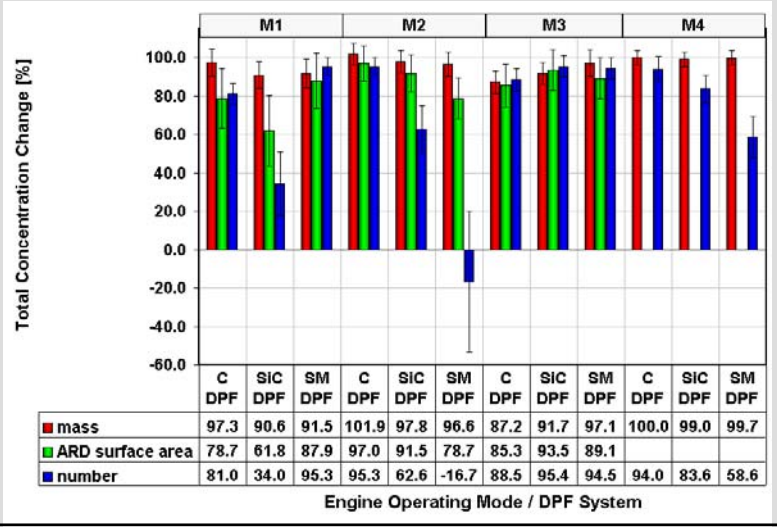
DPF systems effects on aerosols:
total mass concentrations - 5 to 100 fold reduction;
total alveolar region deposited (ARD) surface area – 2 to 20 fold reduction
total number concentrations – 20 fold reductions to slight increases.



	C DPF	SiC DPF	SM DPF	C DPF	SiC DPF	SM DPF	C DPF	SiC DPF	SM DPF	C DPF	SiC DPF	SM DPF
mass	97.3	90.6	91.5	101.9	97.8	96.6	87.2	91.7	97.1	100.0	99.0	99.7
ARD surface area	78.7	61.8	87.9	97.0	91.5	78.7	85.3	93.5	89.1			
number	81.0	34.0	95.3	95.3	62.6	-16.7	88.5	95.4	94.5	94.0	83.6	58.6

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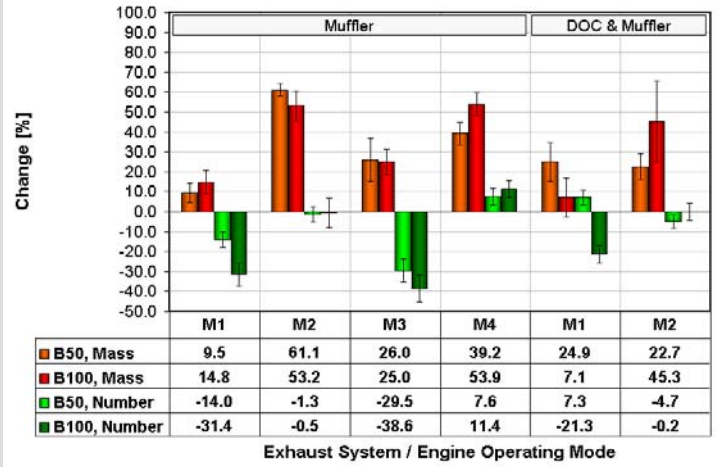
B50 and B100 reduced total mass concentrations up to 60 % (the increase was more pronounced heavy-load conditions).

B50 and B100 increased total number concentrations up to 40 % (the increase was more pronounced for light-load conditions.



	M1	M2	M3	M4	M1	M2
B50, Mass	9.5	61.1	26.0	39.2	24.9	22.7
B100, Mass	14.8	53.2	25.0	53.9	7.1	45.3
B50, Number	-14.0	-1.3	-29.5	7.6	7.3	-4.7
B100, Number	-31.4	-0.5	-38.6	11.4	-21.3	-0.2

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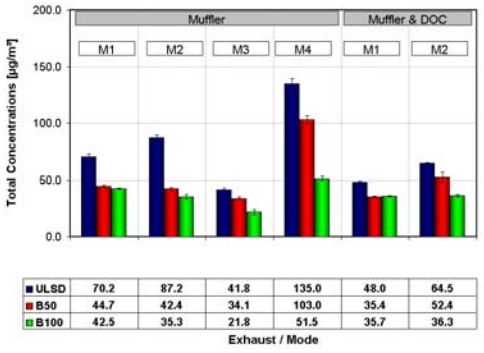
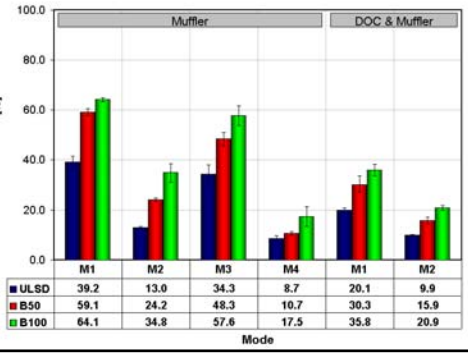


Biodiesel reduced elemental carbon (EC) concentrations in mine air.

Fraction of OC in TC on primary filter increased with fraction of biodiesel in the fuel.



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Results:
2. Size Distributions of Diesel Aerosols - Number

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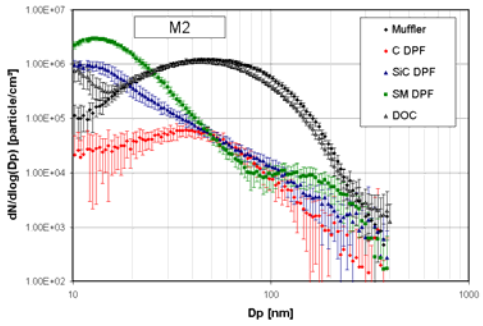
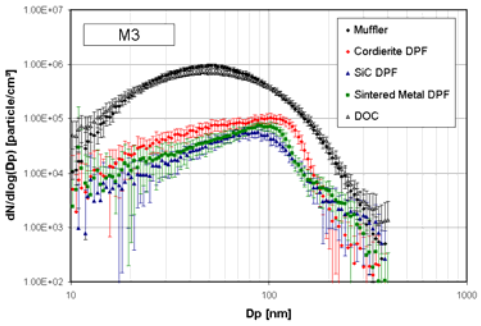


The high concentrations of nucleation mode aerosols were observed when the engine equipped with **DPFs** were operated at high-load engine operating conditions (M2), but not at light-load conditions (M3).



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Results indicate strong relationship between concentration of nucleation mode aerosols and exhaust temperatures.

Mode	DPFs, DOC, Muffler	
	Average Exhaust Temperatures at Inlet to Device	Average Exhaust Temperatures at Outlet from Device
	°C	°C
M1	**306**	**258**
M2	**529**	**436**
M3	**254**	**216**
M4	**485**	**402**

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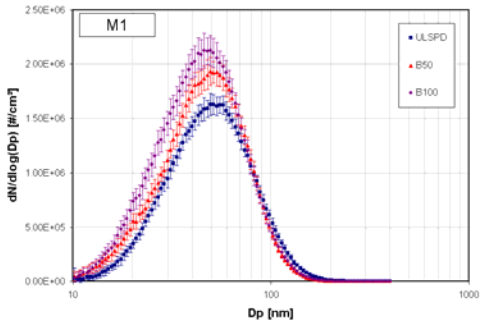
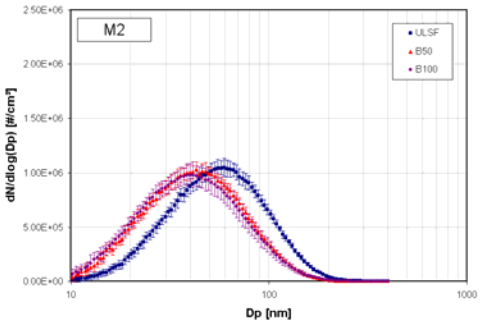


For M1 (muffler), peak concentrations increased and the median diameter slightly decreased with an increase in the fraction of biodiesel in the fuel.

For M2 (muffler), B50 and B100 did change median diameter, but did not substantially change the peak and total number concentrations.



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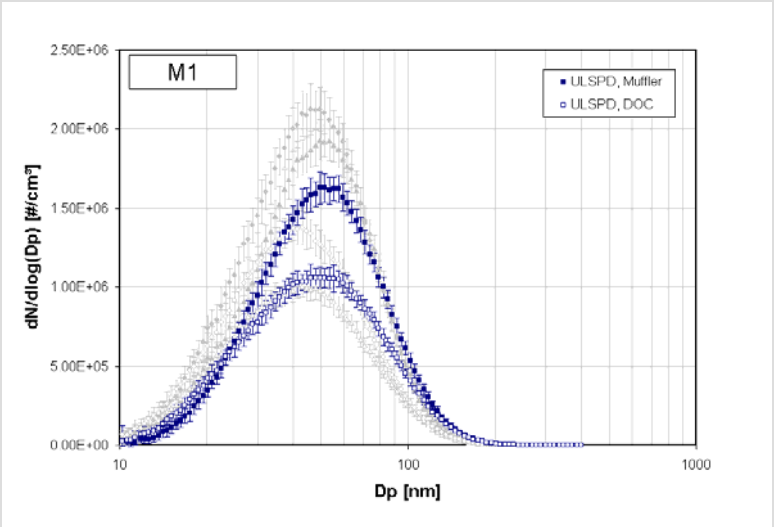
For M1, DOC had relatively major effect on aerosol concentrations: **ULSPD**



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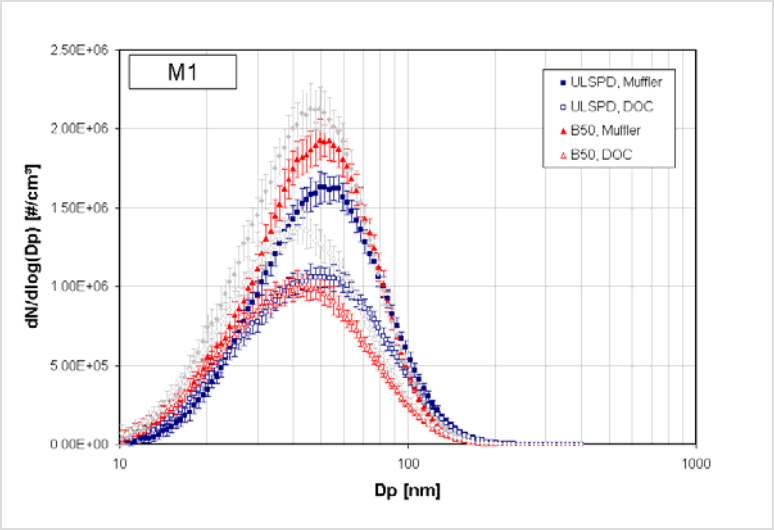
For M1, DOC had relatively major effect on aerosol concentrations: **B50**



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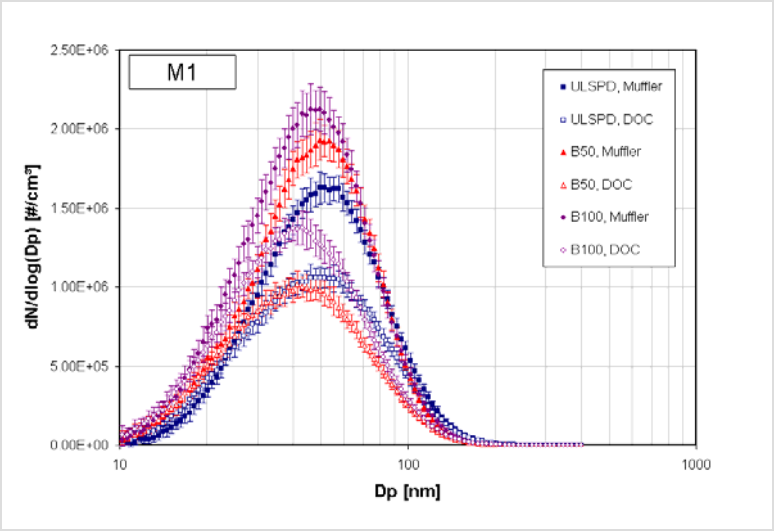
For M1, DOC had relatively major effect on aerosol concentrations: **B100**



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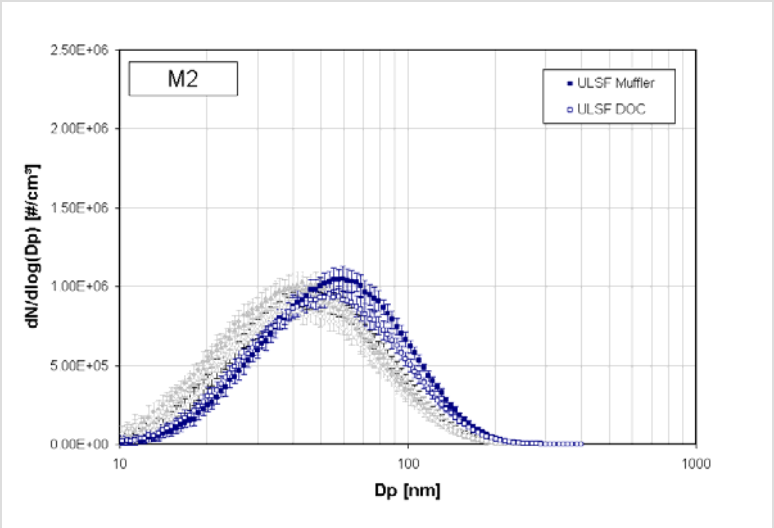
For M2, DOC had relatively minor effect on aerosol concentrations:
ULSPD



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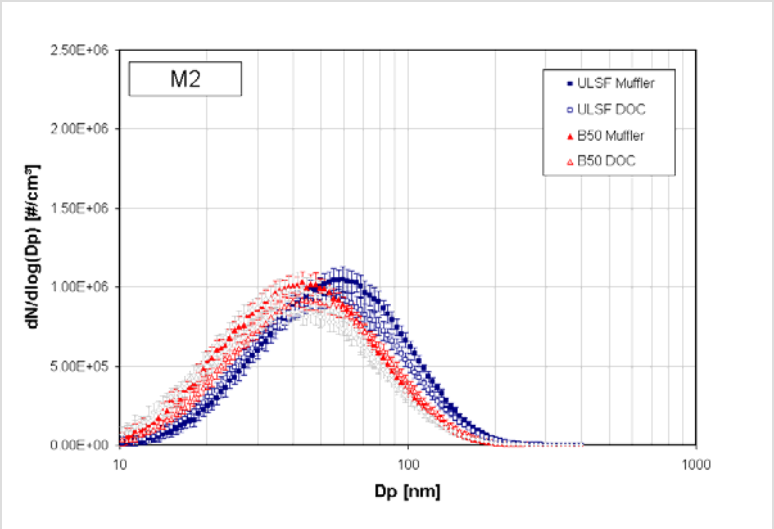
For M2, DOC had relatively minor effect on aerosol concentrations:
B50



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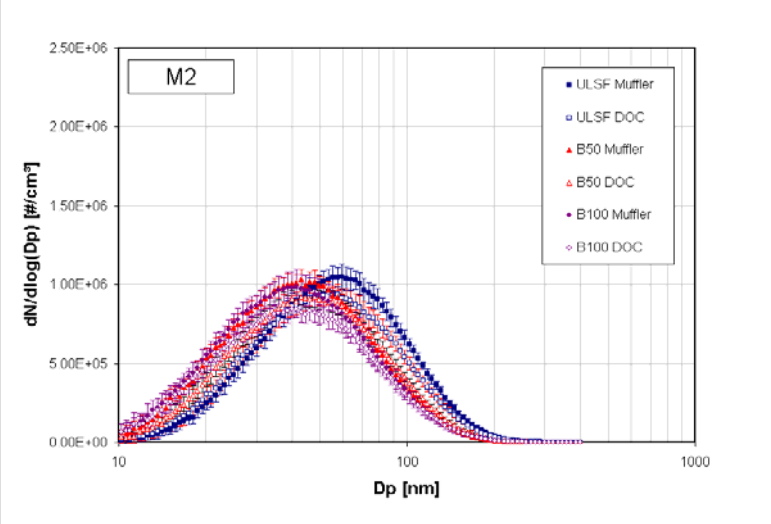
For M2, DOC had relatively minor effect on aerosol concentrations:
B100



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Results:
3. Mutagenic Activity

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Ames Salmonella assay mutagenic activity:

1. the muffler samples: M1 and M3 showed activity, M2 and M4 did not show activity;
2. the DOC samples: did not show activity;
3. the DFE and DPF samples: showed activity.

Sample	Exhaust Configuration	Engine Mode	Mutagenic Activity
1	Muffler	M1	++
2	Muffler	M2	
3	Muffler	M3	++
4	Muffler	M4	
5	DOC	M1	
6	DOC	M2	
7	DOC	M3	
8	DOC	M4	
9	DFE-A	M1	+
10	LDFE-A	M1	+
11	DFE-B	M1	+
12	SM DPF	M1	+

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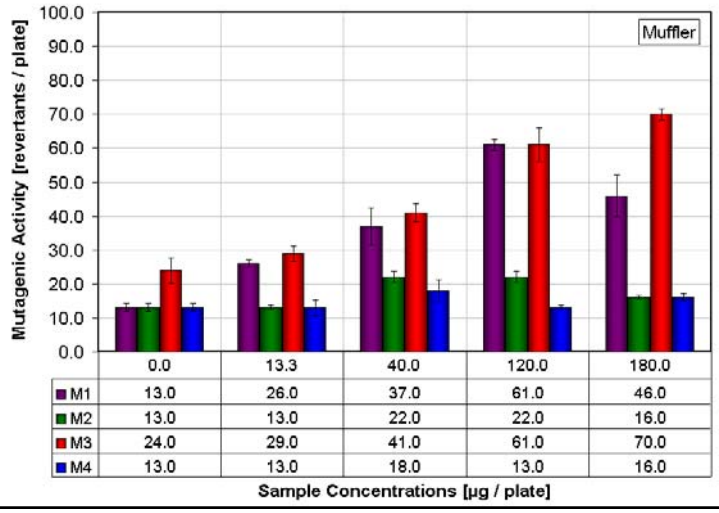
The mutagenic activity of the muffler samples was affected by engine operating conditions:

1. the samples collected at M1 and M3 showed positive dose response relation;
2. the samples collected at M2 and M4 did not show positive dose response relation.



	0.0	13.3	40.0	120.0	180.0
M1	13.0	26.0	37.0	61.0	46.0
M2	13.0	13.0	22.0	22.0	16.0
M3	24.0	29.0	41.0	61.0	70.0
M4	13.0	13.0	18.0	13.0	16.0

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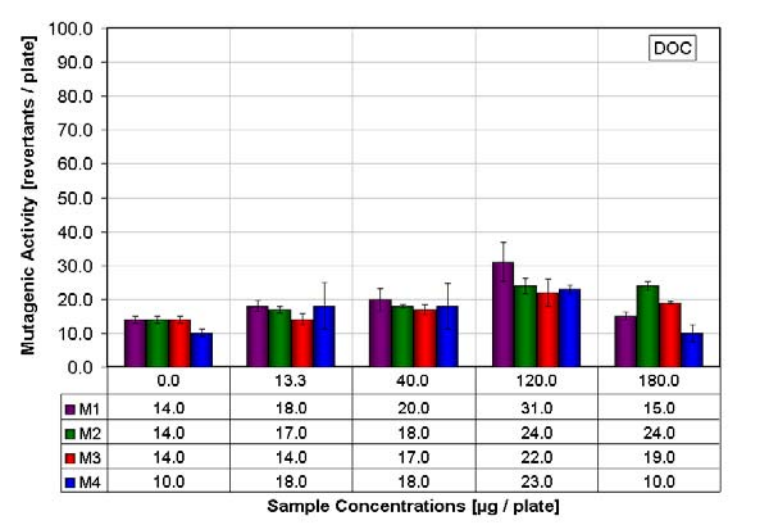
The samples collected for the DOC cases did not show positive dose response relation.



	0.0	13.3	40.0	120.0	180.0
M1	14.0	18.0	20.0	31.0	15.0
M2	14.0	17.0	18.0	24.0	24.0
M3	14.0	14.0	17.0	22.0	19.0
M4	10.0	18.0	18.0	23.0	10.0

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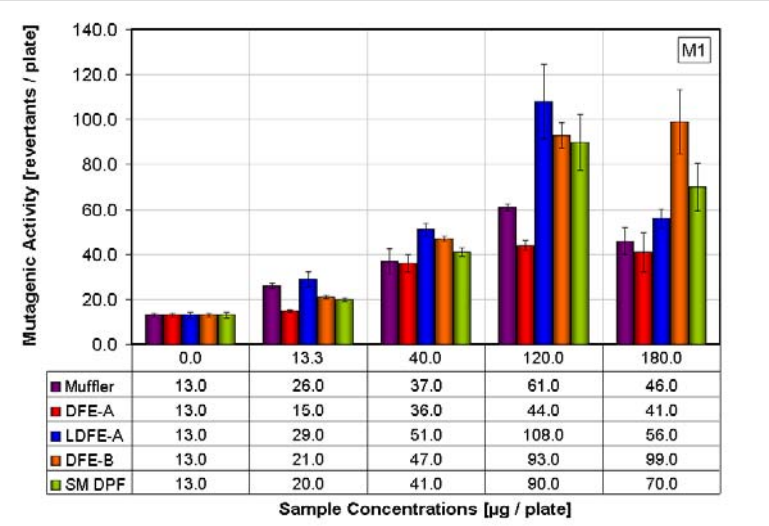
The samples collected for the DFEs and SM DPF at M1 showed positive dose response relation.



	0.0	13.3	40.0	120.0	180.0
Muffler	13.0	26.0	37.0	61.0	46.0
DFE-A	13.0	15.0	36.0	44.0	41.0
LDFE-A	13.0	29.0	51.0	108.0	56.0
DFE-B	13.0	21.0	47.0	93.0	99.0
SM DPF	13.0	20.0	41.0	90.0	70.0

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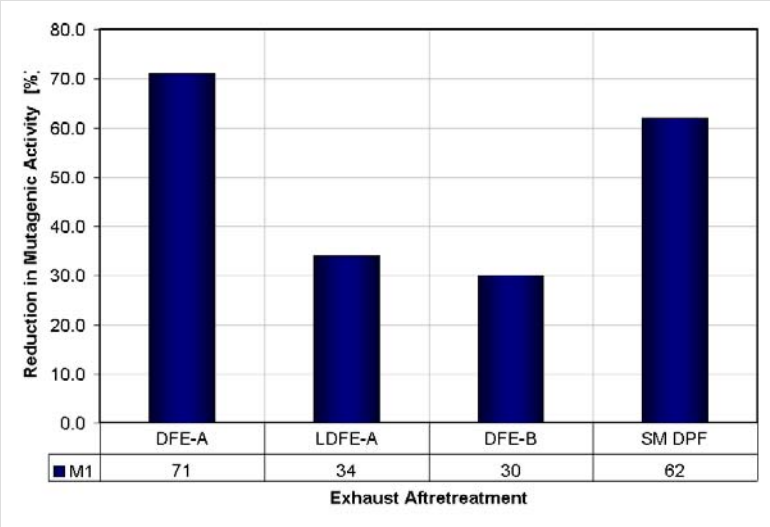
The DFE-A, LDFE-A, DFE-B, and SM DPF reduced Ames Salmonella assay mutagenic activity.



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Ames salmonella assay mutagenic activity:
1. the activity of B50 and B100 samples was higher that that of ULSD;
2. the DOC samples also showed activity for B50 and B100.

Fuel	Muffler				Muffler + DOC	
	M1	M2	M3	M4	M1	M2
ULSD	+	—	+	—	+	—
B50	+ +	+ +	+ +	—	+ +	+ +
B100	+ +	+ +	+	—	—	+ +

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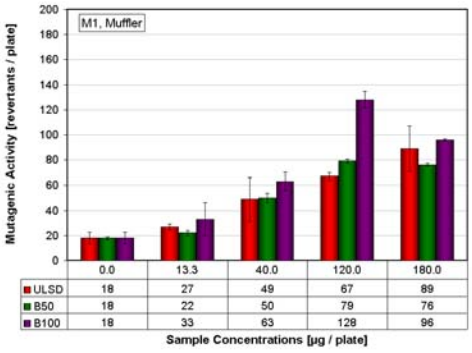


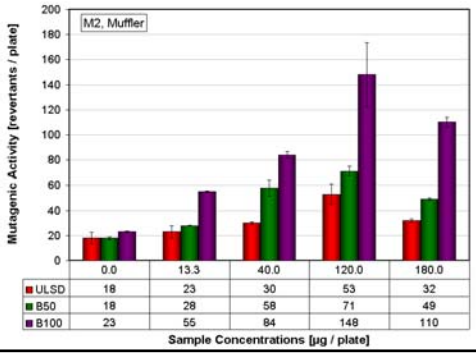
	0.0	13.3	40.0	120.0	180.0
ULSD	18	27	49	67	89
B50	18	22	50	79	76
B100	18	33	63	128	96

The samples collected for muffler at **M1** showed positive dose response relation.

The mutagenic activity **increased** with fraction of biodiesel in the fuel

The samples collected for muffler at M2 showed positive dose response relation.

The mutagenic activity **increased** with fraction of biodiesel in the fuel.



	0.0	13.3	40.0	120.0	180.0
ULSD	18	23	30	53	32
B50	18	28	58	71	49
B100	23	55	84	148	110

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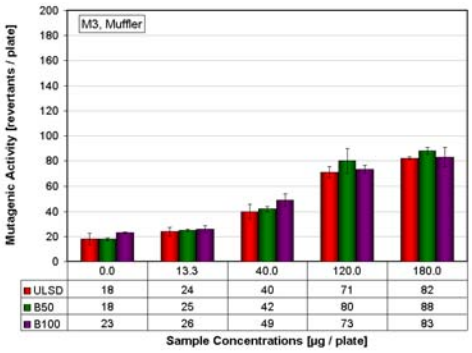
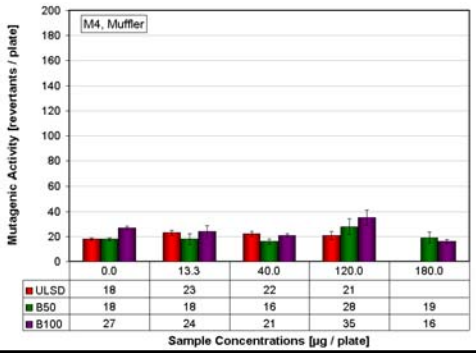


	0.0	13.3	40.0	120.0	180.0
ULSD	18	24	40	71	82
B50	18	25	42	80	88
B100	23	26	49	73	83

The samples collected for muffler at **M3** showed positive dose response relation.

The mutagenic activity **increased** with fraction of biodiesel in fuel.

The samples collected for muffler at **M4** did not exhibit positive dose response relation.



	0.0	13.3	40.0	120.0	180.0
ULSD	18	23	22	21	
B50	18	18	16	28	19
B100	27	24	21	35	16

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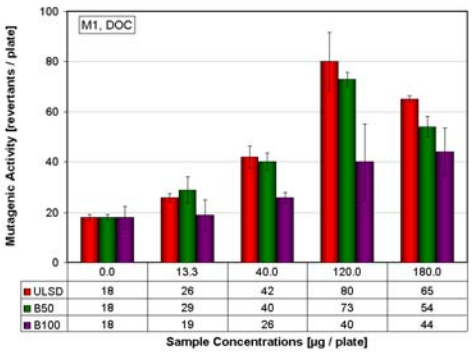
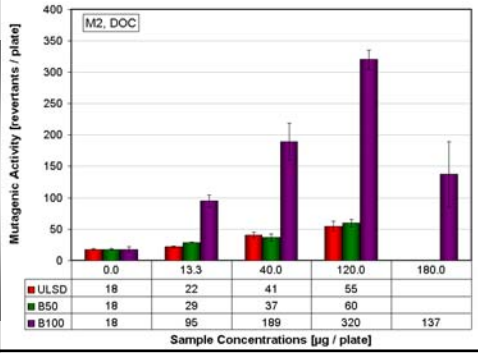


The samples collected for DOC at **M1** showed positive dose response relation.

The mutagenic activity **decreased** with fraction of biodiesel in fuel.

The samples collected for DOC at **M2** exhibited positive dose response relation.

The mutagenic activity **increased** with fraction of biodiesel in fuel.



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Discussion

1. Concentrations

2. Size

3. Chemical composition

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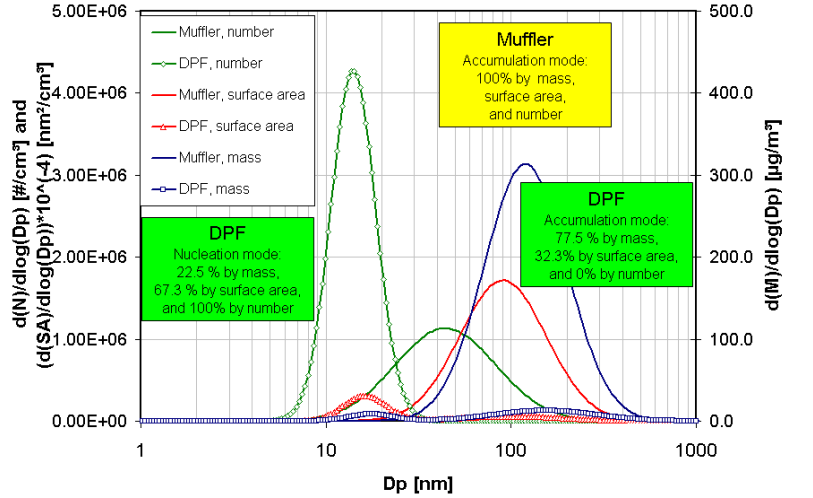
Example of the effects DPF system has on size distributions of diesel aerosols (number, surface area, and mass): Engine operated at **M2**.



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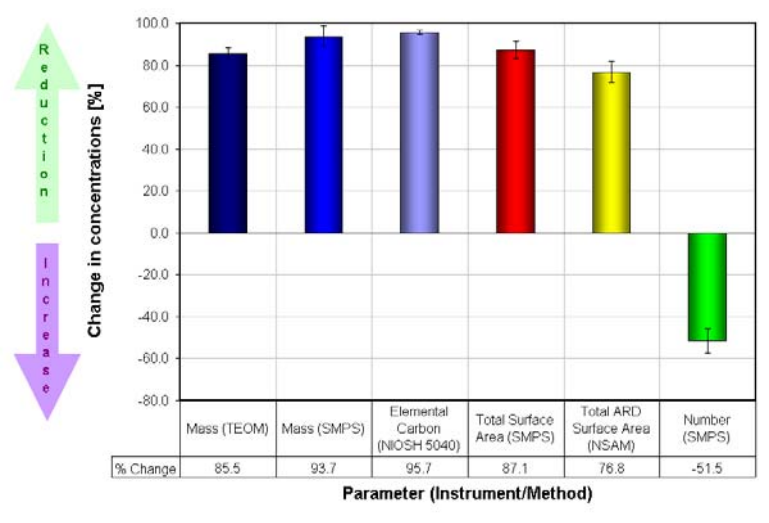
The effects of uncatalyzed DPF on concentrations of diesel aerosols differ with respect to the metric considered: mass, elemental carbon, total surface area, ARD total surface area, or number.



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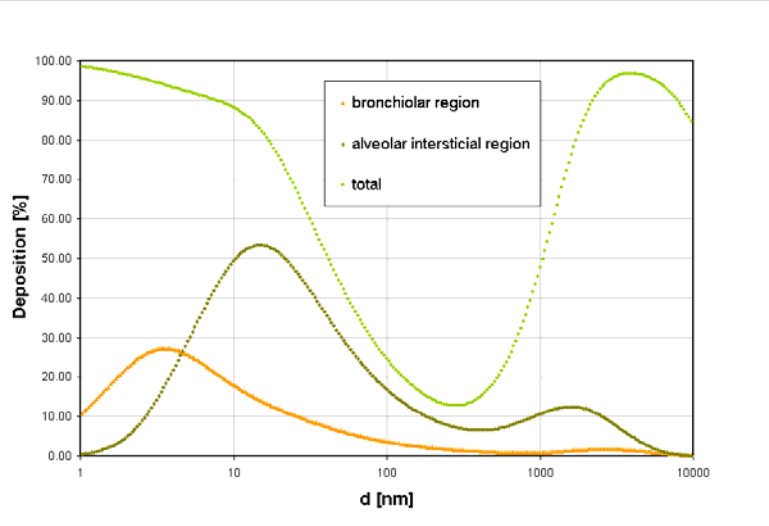
Size affects deposition of diesel aerosols in human respiratory tract.

LUDEP 2 deposition model (ICRP Pub 66):
Adult male, light exercise, nose breather, ventilation rate 1.5 m³/h, resp. freq. 20/min, tidal volume 1250 cm³, volumetric flow rate 833 cm³/s



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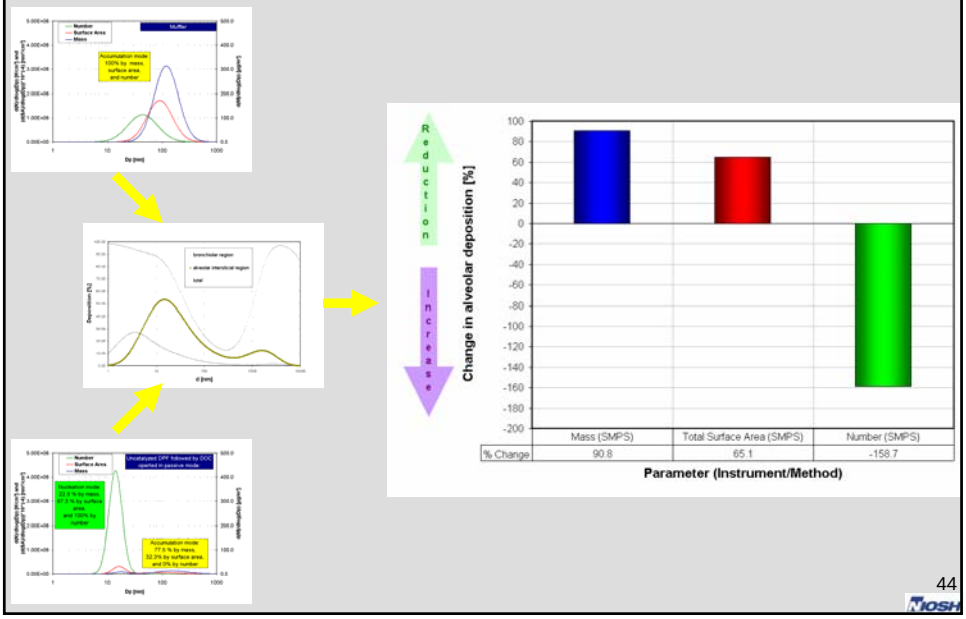
The effects of the changes in the aerosol size are even more important when deposition in respiratory tract is considered.



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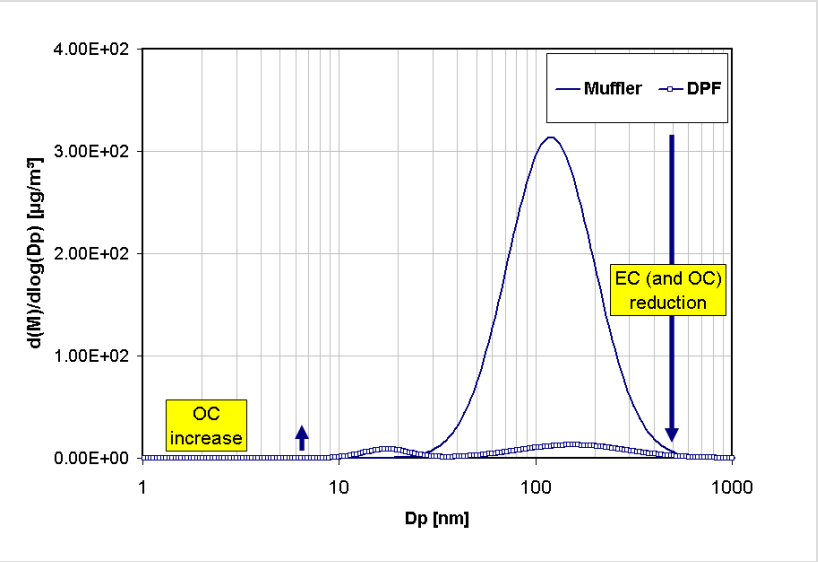
Chemical composition of DPM changes with implementation of DPF systems.



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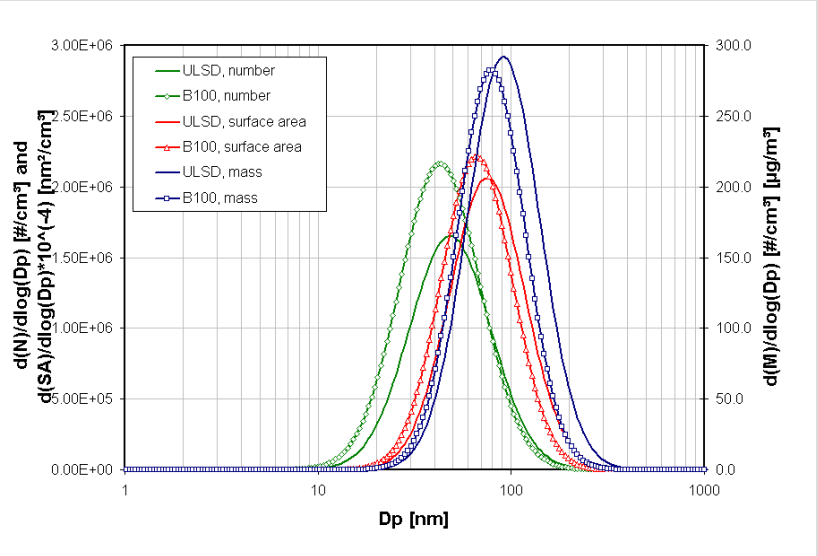
Example of the effects biodiesel has on size distributions of diesel aerosols (number, surface area, and mass): Engine operated at **M1.**



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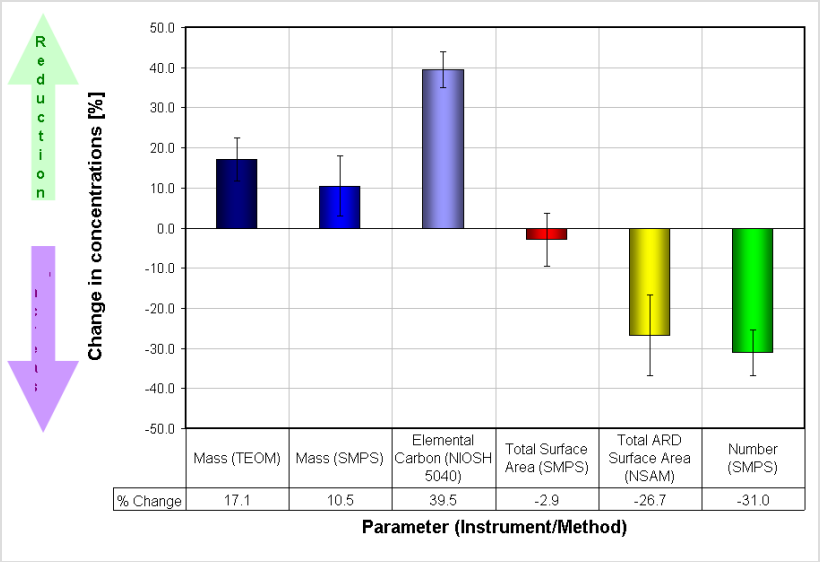
The effects of biodiesel on concentrations of diesel aerosols differ with respect to the metric considered: mass, elemental carbon, total surface area, ARD total surface area, or number.



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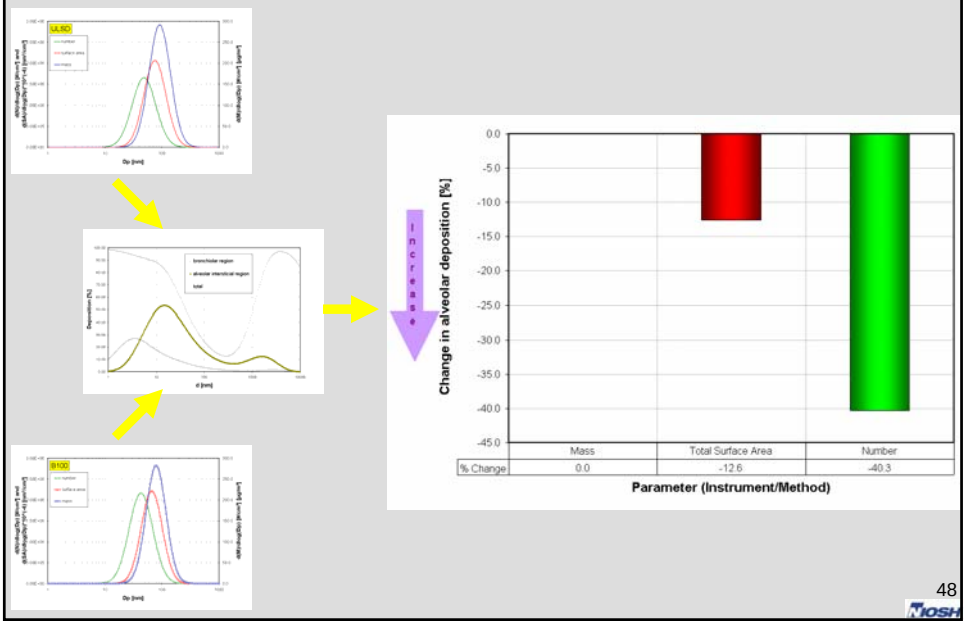
The effects of the changes in the aerosol size are even more important when deposition in respiratory tract is considered.



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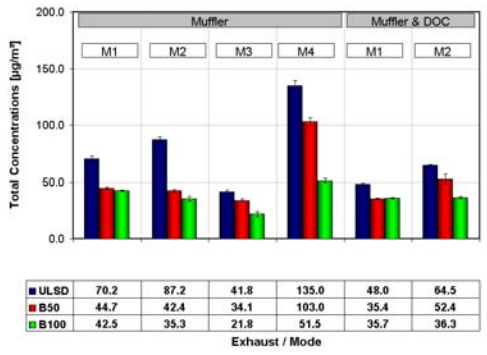
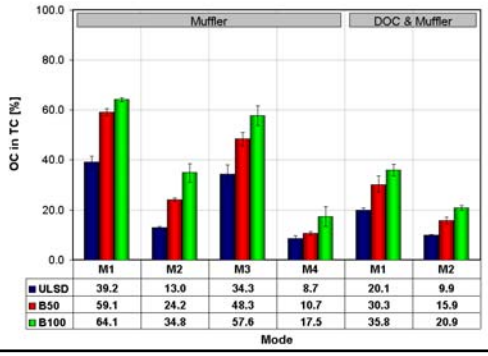


Biodiesel has profound effect on chemical composition of DPM:
1. reduction in EC conc.
2. increase in OC conc.

Trading EC for OC!!!



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Summary

- Both DPFs and biodiesel are found to be effective in reducing mass concentrations of DPM and EC can be effectively used to reduce miners' exposures to those pollutants,
- But, both DPFs and biodiesel altered profoundly other physical, chemical, and toxicological properties of aerosols emitted by diesel engine.
- The finding of these studies warrant further research on establishing relation between changes in physical, chemical and toxicological properties and risks associated with exposure to aerosols emitted by diesel engine.
- It appears that additional metric is needed to supplement mass measurements and allow for better monitoring, hazard assessment, and risk management related to the exposure to diesel and biodiesel aerosols.

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