Effects of Exhaust Aftertreatment Technologies on Concentrations of Diesel Particulate Matter and Gases in Underground Mines

Aleksandar Bugarski
NIOSH Pittsburgh Research Laboratory

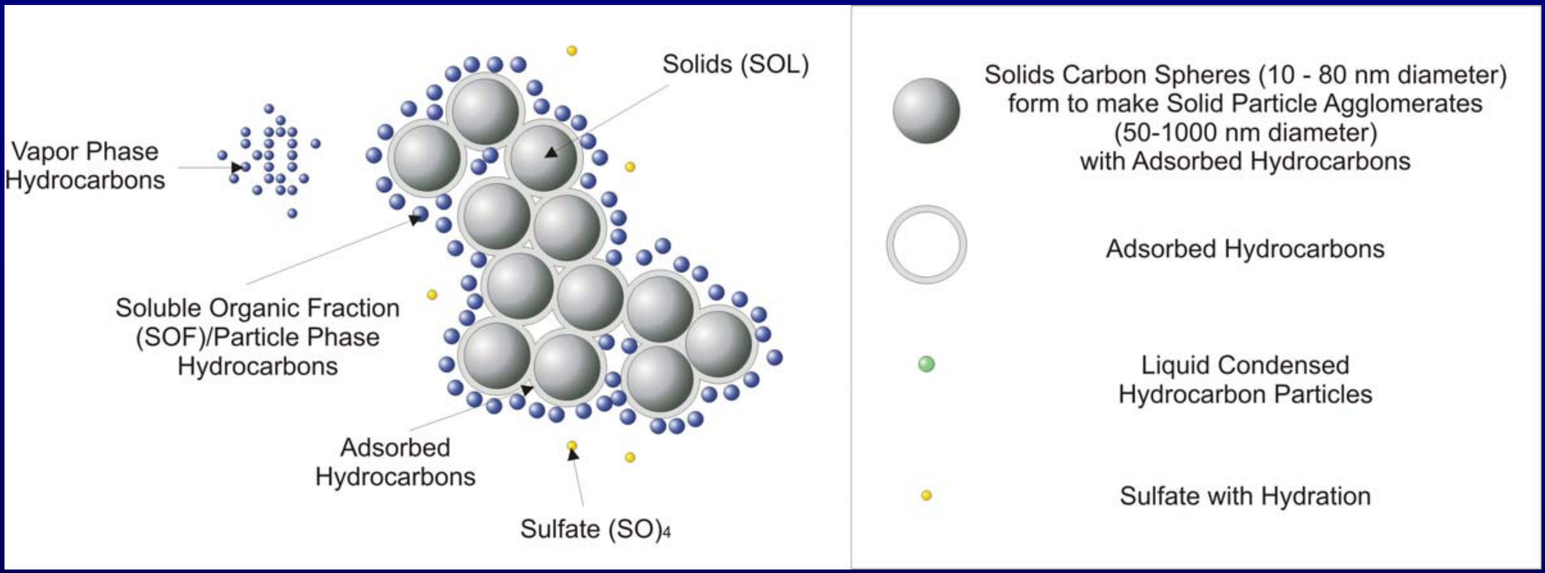
CDC Workplace Safety and Health

DPM Workshop, Reno, Nevada, January 24 & 25, 2007

NIOSH

Diesel Emissions from Underground Mining Equipment

- Diesel particulate matter (DPM) and elemental carbon (EC)
- CO
- NO and NO_2
- CO_2
- hydrocarbons



Aftertreatment Technologies in Underground Mines

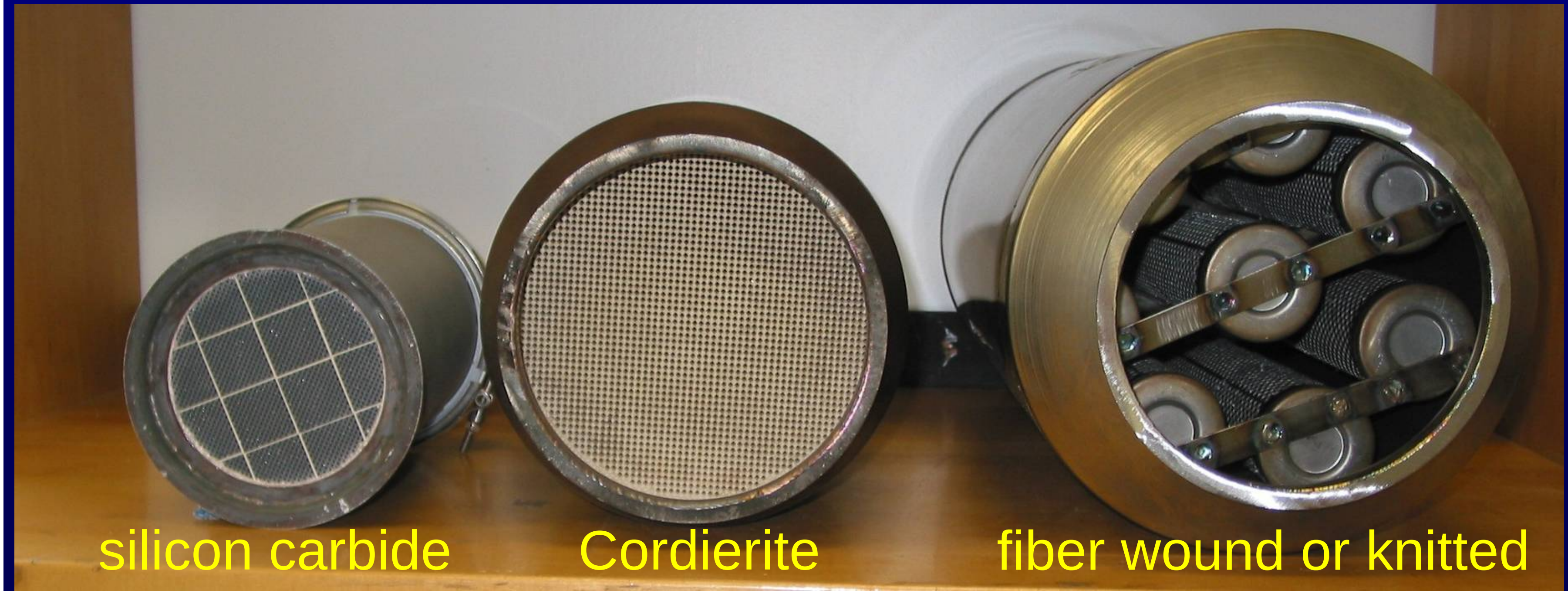
- CO and hydrocarbons:
  - Diesel oxidation catalytic converters (DOC)
- Diesel particulate matter (DPM) and elemental carbon (EC):
  - Diesel particulate filter (DPF) systems;
  - Filtration systems (FS) with disposable filter elements (DPEs);
  - Flow through filters
- NO and NO_2
  - Lean NO_x catalyst,
  - Selective catalytic reduction (SCR) systems
- Integrated aftertreatment systems

Aftertreatment Technologies in Underground Mines

- CO and hydrocarbons:
  - Diesel oxidation catalytic converters (DOC)
- Diesel particulate matter (DPM) and elemental carbon (EC):
  - **Diesel particulate filter (DPF) systems;**
  - **Filtration systems (FS) with disposable filter elements (DPEs);**
  - Flow through filters
- NO and NO_2
  - Lean NO_x catalyst,
  - Selective catalytic reduction (SCR) systems
- Integrated aftertreatment systems

DPF Systems
Elements

- Media
  - Wall flow monoliths
    - Cordierite
    - Silicon carbide (SiC)
  - Deep bed filters
    - Ceramic fiber
    - Sintered metal fiber
- Catalyst
  - Non-catalyzed DPF systems
  - Catalyzed DPF systems:
    - wash coat catalyst
    - fuel borne catalyst



NIOSH

DPF Systems
Regeneration

DPF Regeneration – burning off carbon collected on the filter media

- Regarding the regeneration concept, contemporary DPF systems available to mining industry can generally be classified into two groups:
  - Passive

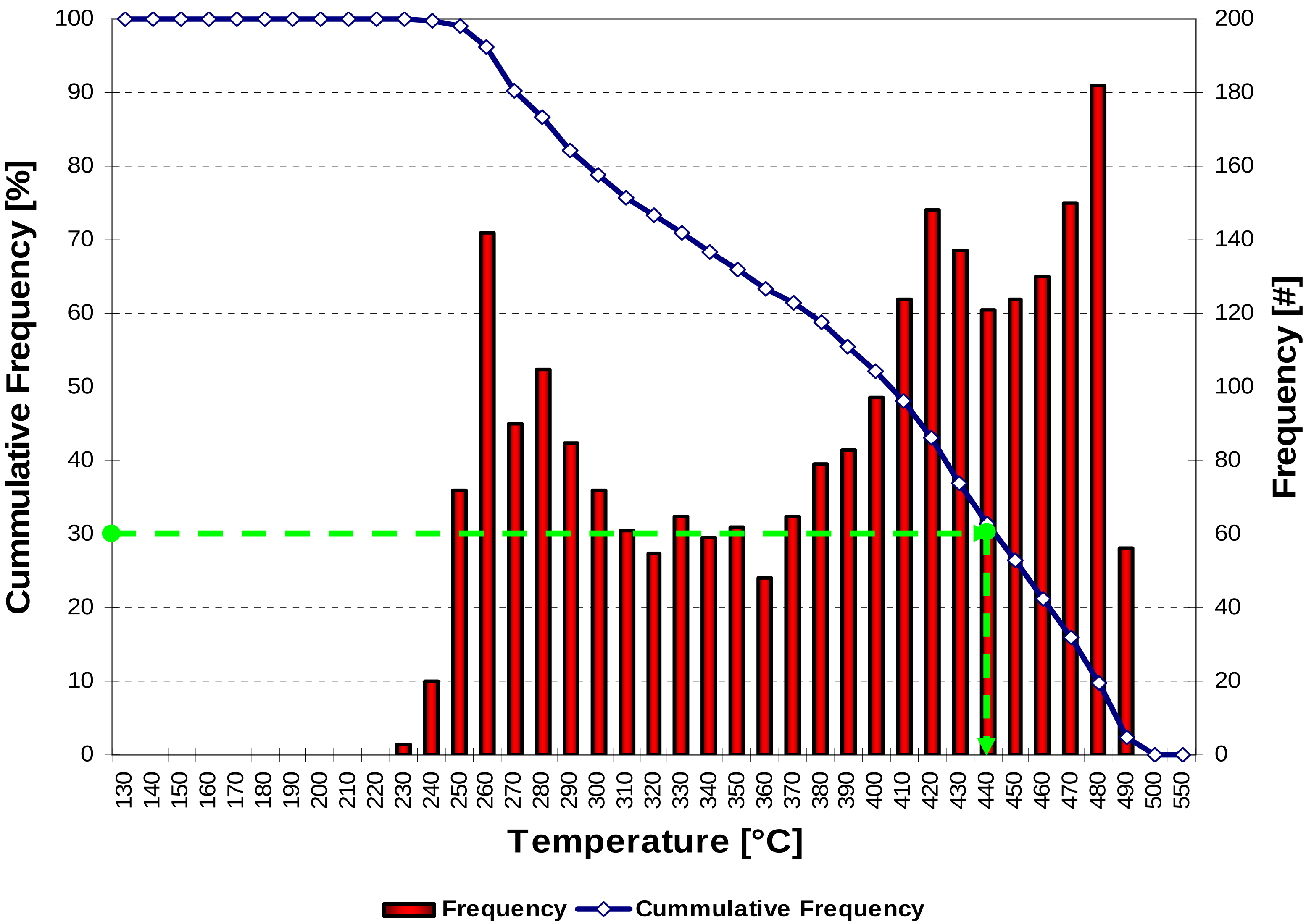
    Exhaust gas temperatures are favorable and a DPF is regenerated during a duty cycle without operator's involvement and need for external sources of heat.
  - Active

    DPF is sized to accumulate DPM between two active regenerations. Accumulated DPM is removed using an external source of energy:
    - electrical heaters;
    - fuel combustion.

DPF Systems
Passive Regeneration

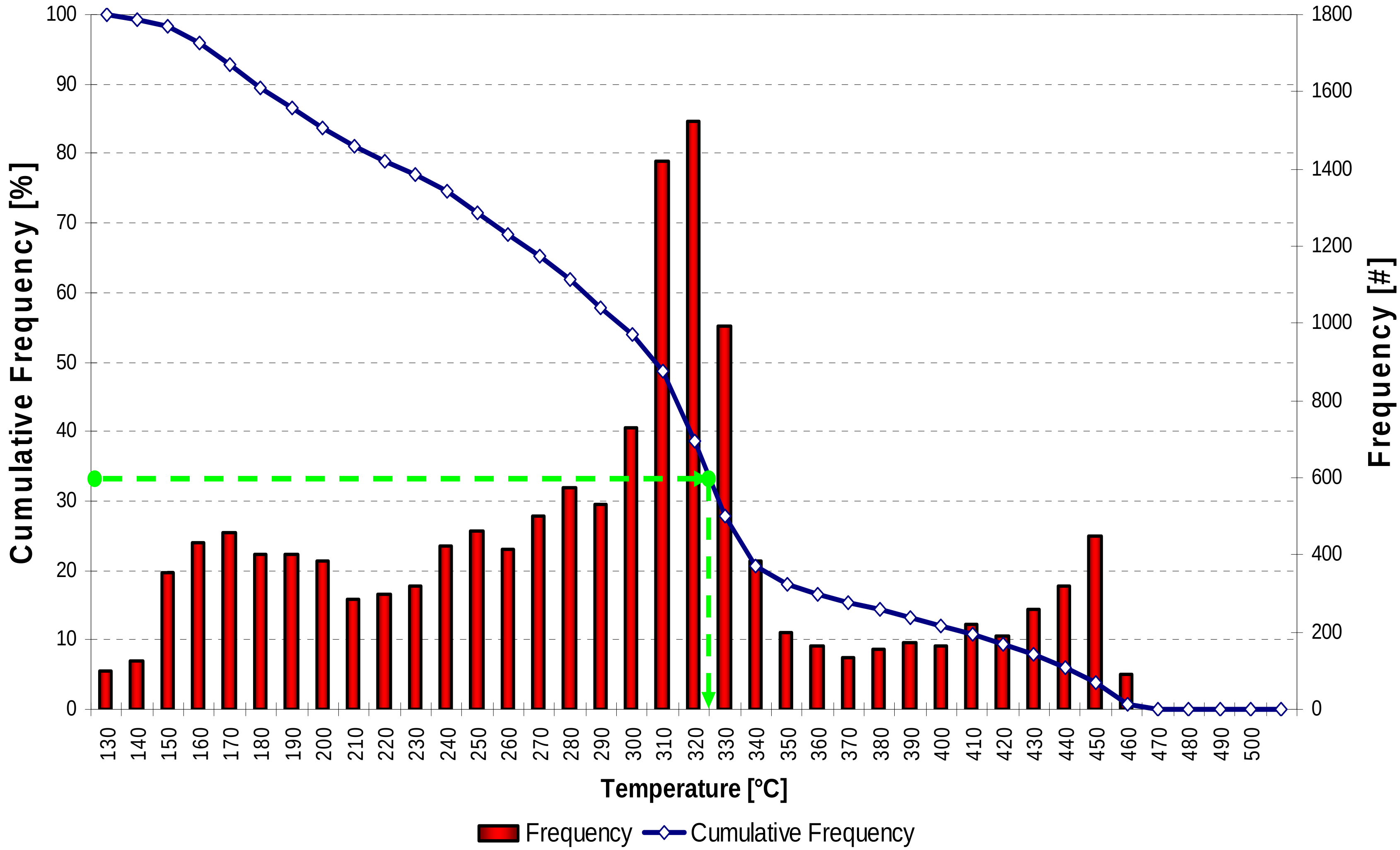
- Approximate minimum exhaust temperatures required to initiate regeneration process:
  - Non-catalyzed DPF – over 600 °C;
  - Base metal catalyst – over 390 °C;
  - Nobel metal catalyst – over 325 °C;
  - Continuously Regenerating Technology (CRT) - over 260 °C…
- 25-30% or more of a duty cycle on vehicle/engine should be operated at loads generating exhaust temperatures exceeding minimum regeneration temperatures.
- Frequency and duration of the favorable temperature occurrences are playing important role in initiating and supporting regeneration process.

Regeneration of DPF Systems
Exhaust Temperature Histogram



NIOSH

Regeneration of DPF Systems
Exhaust Temperature Histogram



NIOSH

DPF Systems
Active Regeneration

- Electrical Heating
  - On-board heaters
    - Air/exhaust gas heating
    - substrate heating (sintered metal)
  - Off-board heaters
    - Air heating
- Fuel combustion
  - Flame combustion
    - Automated full flow fuel burner system
    - Stationary partial flow fuel burner system
  - Catalytic combustion

DPF Systems
Passive vs. Active Regeneration Concept

- Passive DPF systems:
  - relatively simple
  - low operational requirements;
  - low maintenance requirements;
  - lower initial cost;
  - regeneration depend on exhaust heat!!!
  - In some cases potential for increase in NO_2 and sulfates emissions.

DPF Systems
Passive vs. Active Regeneration Concept

- Active DPF systems:
  - regeneration does not depend on exhaust heat;
  - no long-term effects on secondary emissions;
  - might require changes in way vehicles are operated;
  - higher initial cost;
  - relatively complex;
  - higher maintenance requirements;
  - require change in operator’s attitude;

DPF Systems
Regeneration Concepts

- Underground mining stigma:
  - Passive=transparent="business as usual"
  - Active systems=downtime="trouble"
- Advanced DPF regeneration strategies are constantly emerging:
  - Integration of DPF systems into engine management system
- DPF systems evaluated by MSHA are posted at http://www.msha.gov/01-995/Coal/DPM-FilterEfflist.pdf

Filtration Systems (FS) with Disposable Filter Elements (DFE)

- Systems designed to control diesel emissions from permissible underground coal mining equipment:
  - Surface temperature requirements (30 CFR § 7.98):
    - < 302 °F (150 °C)
  - Exhaust temperature requirements (30 CFR § 7.102)
    - wet exhaust conditioner: < 170 °F (76 °C);
    - dry exhaust conditioner: < 302 °F (150 °C).

Filtration Systems (FS) with High Temperature Disposable Filter Elements (DFE)

- Systems designed to control diesel emissions from non-permissible underground coal mining and other equipment:
  - No surface temperature requirements
  - Exhaust temperature requirements:
    - DFE efficiency;
    - Potential for spontaneous combustion of accumulated soot.

Equivalent Disposable Filter Elements (DFE)

- List of the DFE evaluated by MSHA is available in Table 1 at http://www.msha.gov/01-995/Coal/DPM-FilterEfflist.pdf
  - Equivalency with respect to efficiency recognized only if DFE is used below manufacture specified exhaust temperature limits (185, 302, 650 °F)

NIOSH

DFE Life

- The elements should be replaced when engine backpressure exceeds engine manufacture recommended limit:
  - DDEC Series 60 - 41 in H_2O
  - Caterpillar 3306 PCNA - 34 in H_2O

- Low emissions extend life of the DFE
  - Emissions assisted engine maintenance directly benefits DFE life.

Useful References on DPF and DFE Systems

- DieselNet Technology Guide. http://www.dieselnet.com/tg.html#other
- Schnakenberg-GH, Bugarski-AD [2002]. Review of Technology Available to the Underground Mining Industry for Control of Diesel Emissions. U.S. Department of Health and Human Services, DHHS (NIOSH) Publication No. 2002-154, Information Circular 9462, 2002 Aug :1-51 http://www.cdc.gov/niosh/mining/pubs/programareapubs8.htm
- Mine Safety and Health Administration (MSHA) Diesel Particulate pages:

  http://www.msha.gov/01-995/dieselpart.HTM

NIOSH

DPF and DFE Systems in Underground Mines

Achieving substantial reductions in the exposure to DPM depends on the ability of the industry to widely implement advanced diesel emissions control technologies primarily DPF systems.

Design, selection, and implementation of DPF systems for underground mining presents unique challenges:

- Wide variety of application with specific operational, engineering and maintenance issues.
- MSHA regulations
  - Confined space:
    - (NO_2 + NO) vs. NO_x
- Retrofit systems vs. OEM.
- Harsh environment.
- "Business as usual" philosophy vs. reality
  - Human factor;
  - High expectations.

Selection of DPF Systems for Underground Mining Applications

Considerations:

- Effects on DPM/EC and gaseous emissions
  - Reductions in
    - total diesel particulate matter (DPM)
    - elemental carbon
  - Secondary emissions
  - Laboratory vs. in-use emissions

- Regeneration strategy

- Implementation issues

- Cost.

Effects of DPF systems and DFEs of DPM emissions

- MSHA posted the following total DPM removal efficiencies at http://www.msha.gov/01-995/Coal/DPM-FilterEfflist.pdf :
  - Cordierite DPF elements – 85%
  - Silicon carbide DPF elements – 87%
  - DFE – equivalency criteria

Effects of DPF Systems on Gaseous Emissions

- NO to NO_2 conversion
- Ventilation rate requirements might be higher for the engines equipped with certain types of DPF systems

Dilution Ratios

MODE	Engine-out Emissions					DPF-out Emissions				
	CO_2	CO	NO	NO_2	PM	CO_2	CO	NO	NO_2	PM
	---	---	---	---	---	---	---	---	---	---
1	16.3	0.9	25.5	13.0	65.4	15.7	0.4	22.8	33.4	6.9
2	14.3	1.0	18.4	11.5	46.2	13.9	0.3	14.2	37.6	5.2
3	11.5	1.3	14.8	14.2	48.3	11.7	0.3	8.0	52.3	5.6
4	5.7	4.0	16.8	33.2	27.0	5.5	0.3	9.7	13.8	---
5	20.5	1.8	43.3	16.5	72.0	19.9	0.4	36.2	28.5	9.9
6	18.7	1.5	32.6	13.1	72.7	18.3	0.3	26.2	36.9	3.5
7	15.9	1.6	26.8	15.1	56.5	15.9	0.3	19.1	52.3	3.6
8	2.3	2.1	7.6	17.4	20.1	1.9	1.8	8.3	7.2	---

Effects of DPF Systems and DFEs on Concentrations of DPM in Mine Air

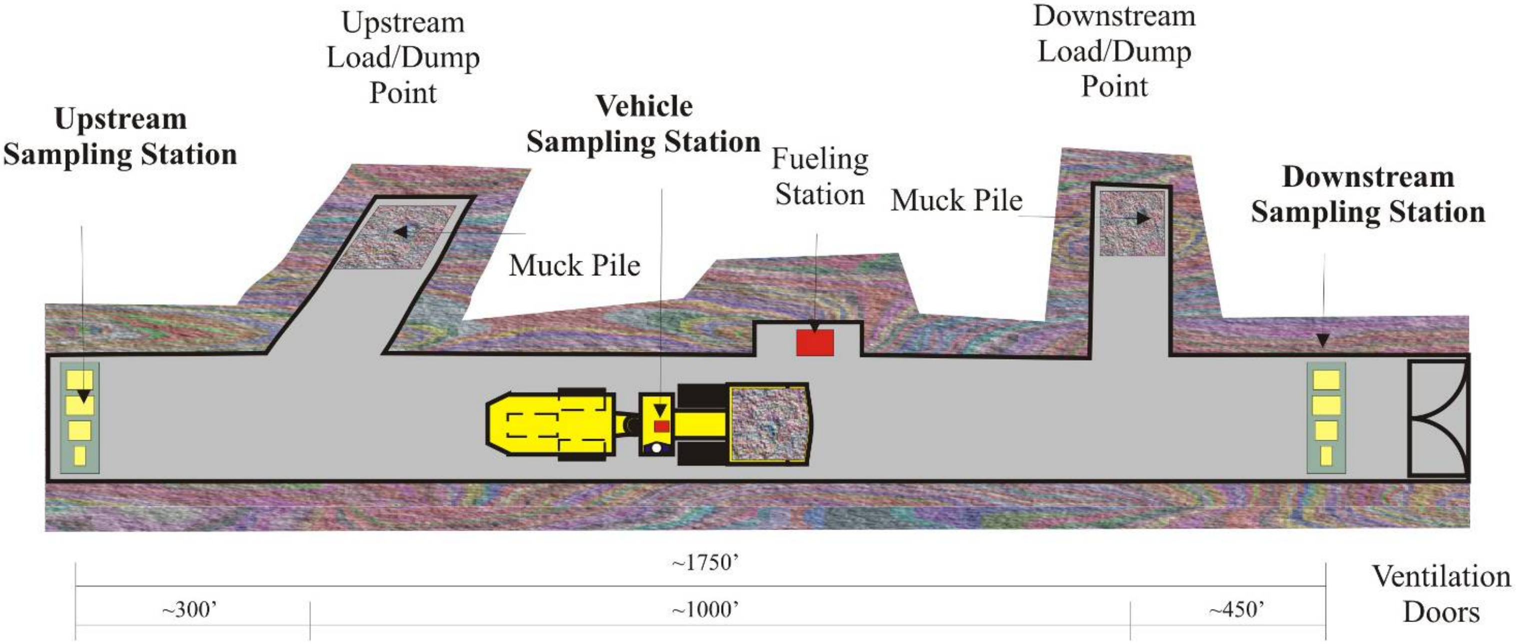
- **Isolated Zone Studies at Stillwater Nye Mine**
  - May/June 2003, and **2003**
  - August/September 2004. **2004**

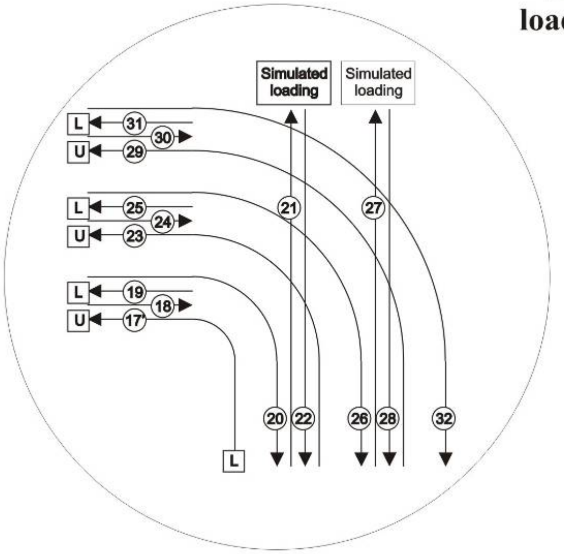
- To measure the effects of selected diesel emissions control technologies on the concentrations and properties of aerosols and gases in mine air:
  - DPF systems;
  - DFEs;
  - DOCs and;
  - Reformulated fuels.

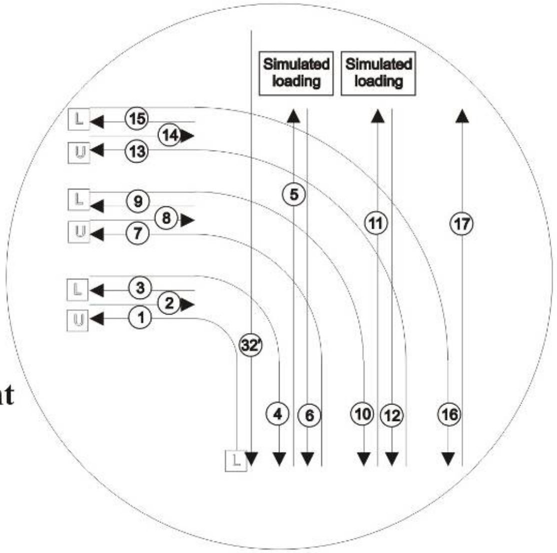
Rationale Behind Isolated Zone Testing

- 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.

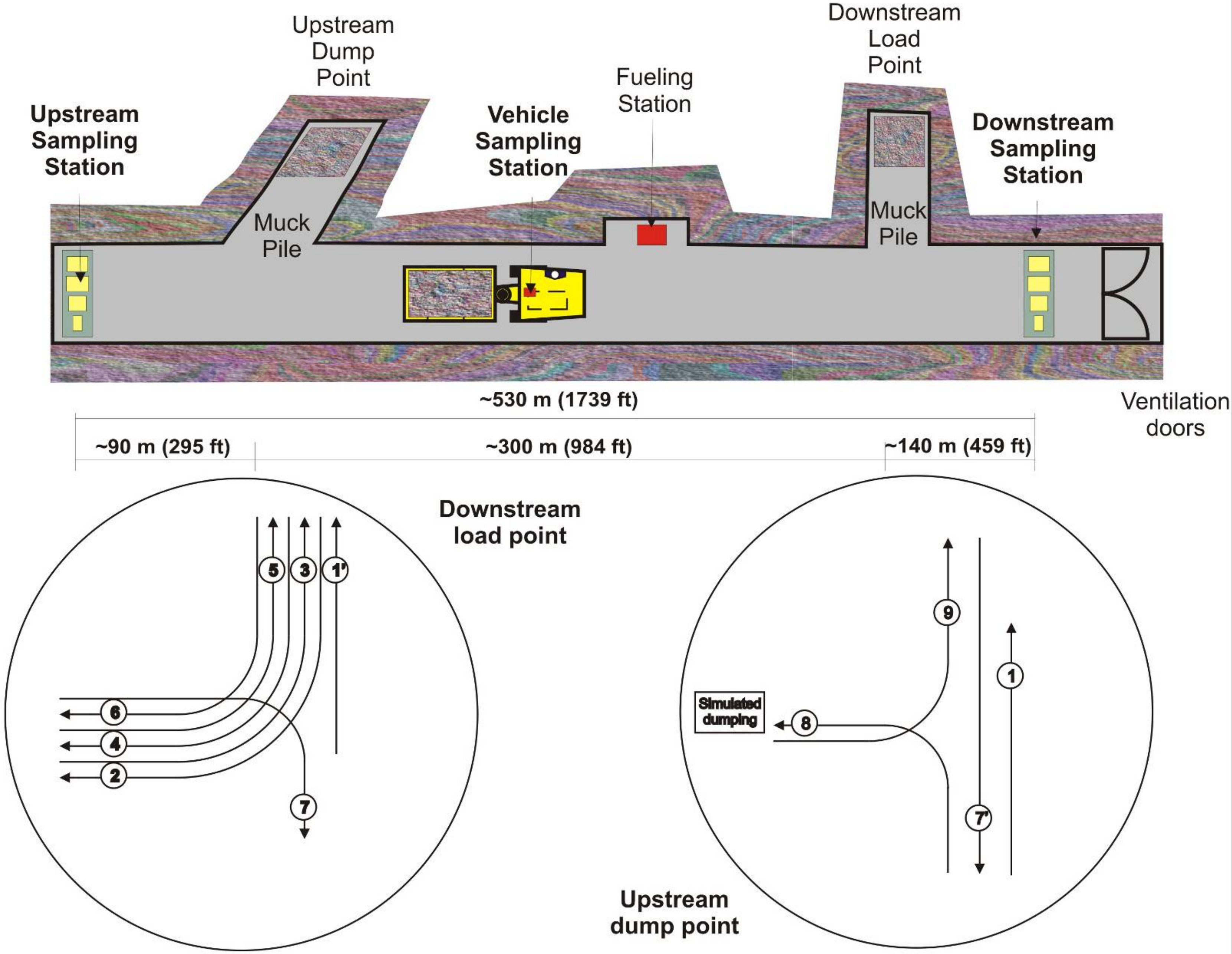
LHDs in Isolated Zone







Haulage Trucks in Isolated Zone

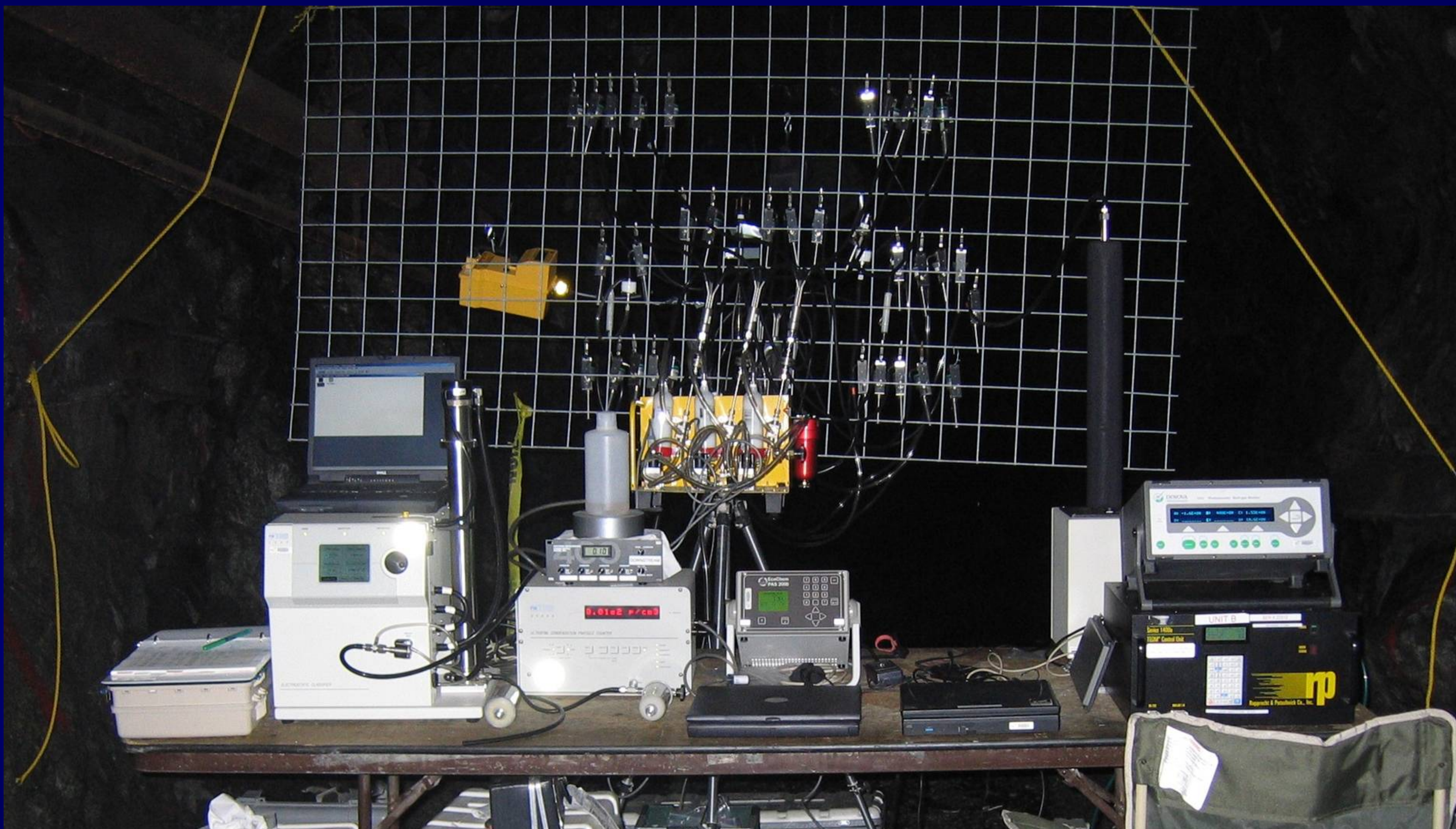


Sampling Strategy Used in IsoZone Tests

- 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.

Instrumentation at Downstream Sampling Station



Instrumentation at Upstream Sampling Station

NIOSH

Aftertretment Systems Tested in 2003

Aftertretment System	DPF Media	DPF Catalyst	DOC
Engelhard DPX DPF	Ceramic, Cordierite	platinum washcoat	N/A
DCL MineX 5C57 11 DPF	Ceramic, Cordierite	platinum washcoat	N/A
Engelhard PTX DOC	N/A	N/A	Ceramic substrate with platinum based catalyst

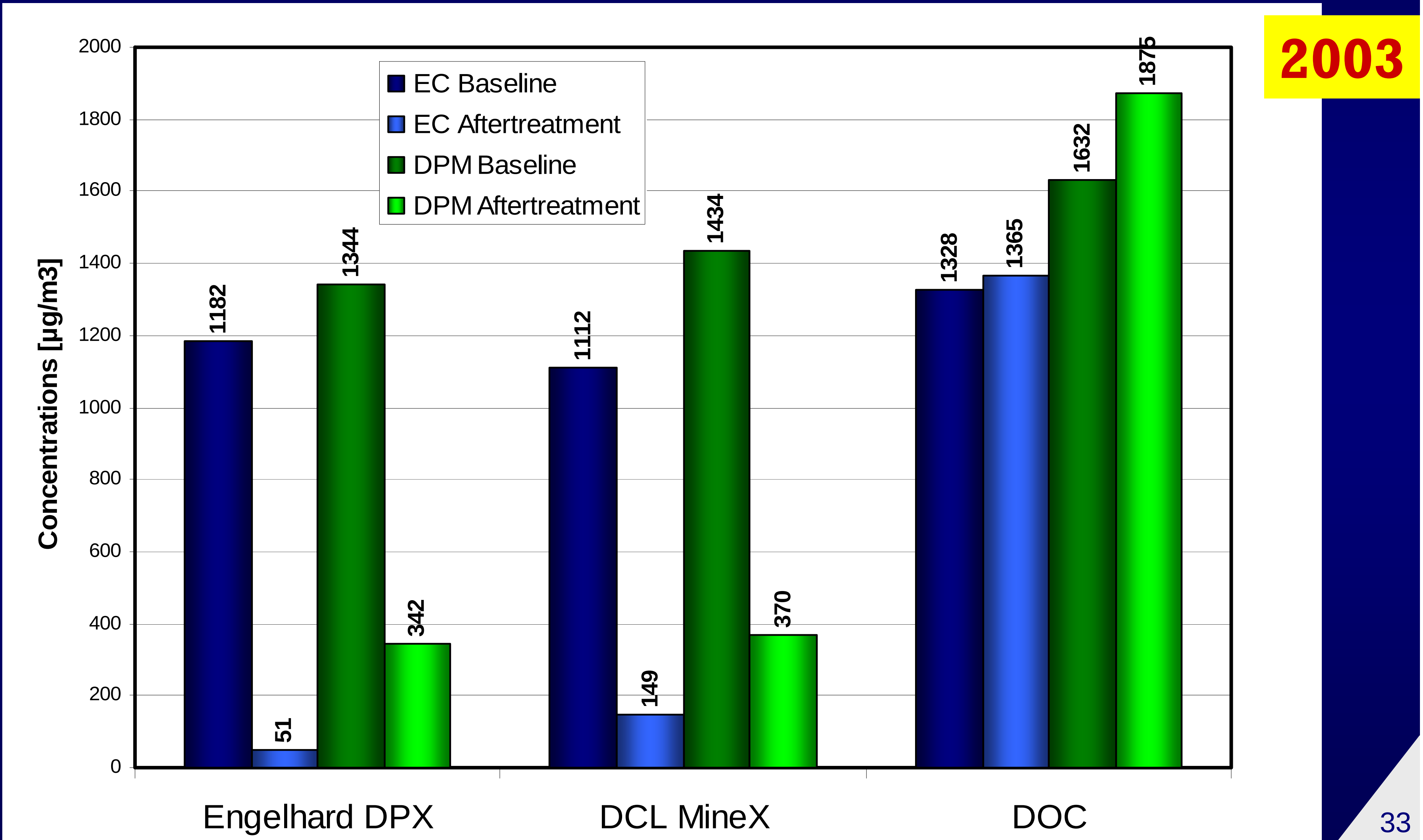
Aftertretment Systems Tested in 2004

Filtration System	DPF Media	DPF Catalyst	DOC Media and Catalyst
ArvinMeritor (AM) DPF with Pt DOC	Ceramic, Cordierite	N/A	Metal substrate with platinum based catalyst
ArvinMeritor (AM) DPF with Pd DOC	Ceramic, Cordierite	N/A	Metal substrate with palladium based catalyst
Donaldson P604516 DFE	High Temperature Disposable Filter Element	N/A	N/A
Filter Service DFE	High Temperature Disposable Filter Element	N/A	N/A

Selected Results of Isolated Zone Studies

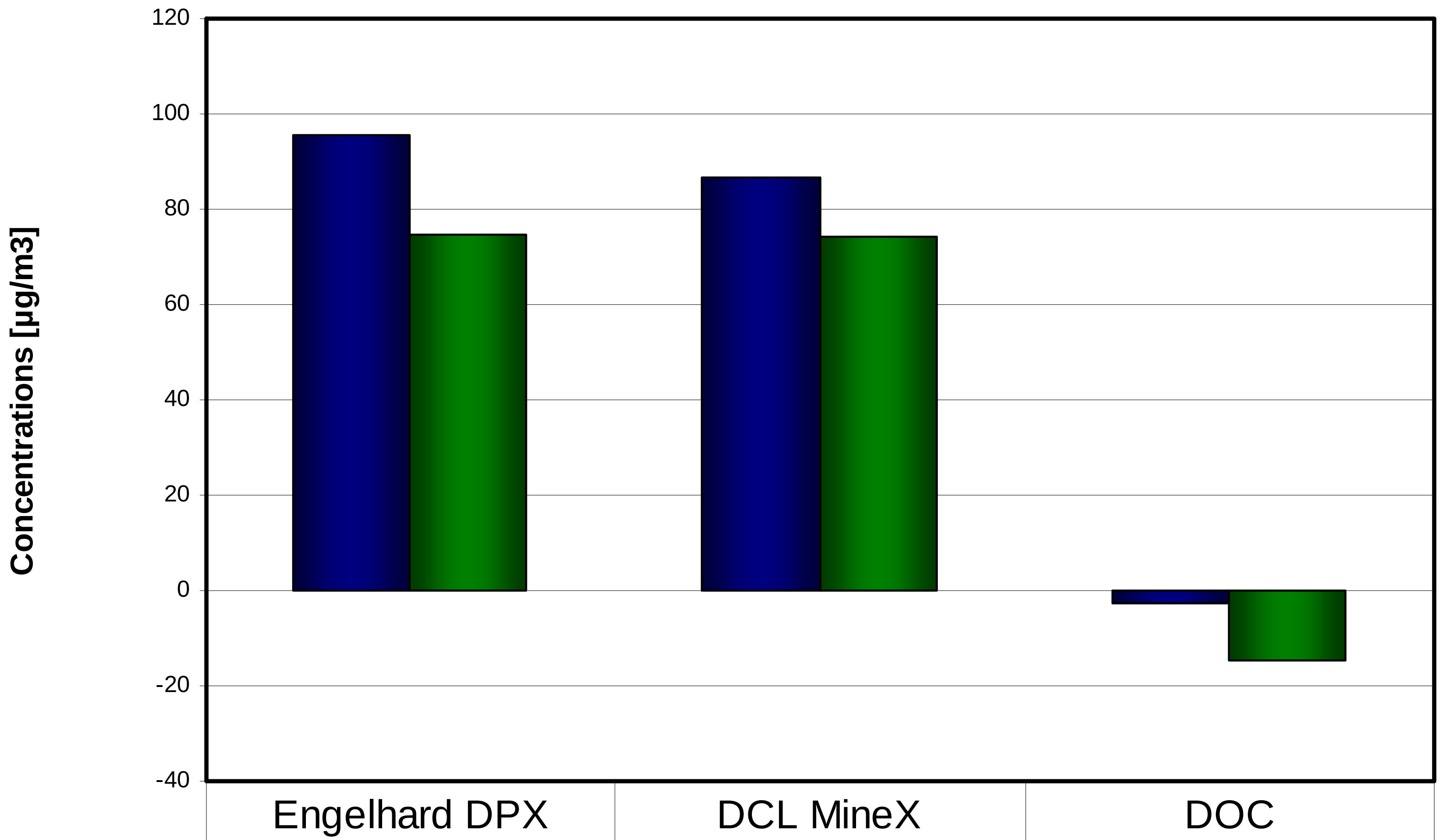
- Effects of selected DPF systems, FS with DFEs and DOC on:
  - mass concentrations of elemental carbon particles under 800 nm
  - number concentrations and size distribution of aerosols between 10 and 392 nm

The Effects of DPFs and DOC on Mass Concentrations of Elemental Carbon (EC)



The Effects of DPFs and DOC on Mass Concentrations of Elemental Carbon (EC)

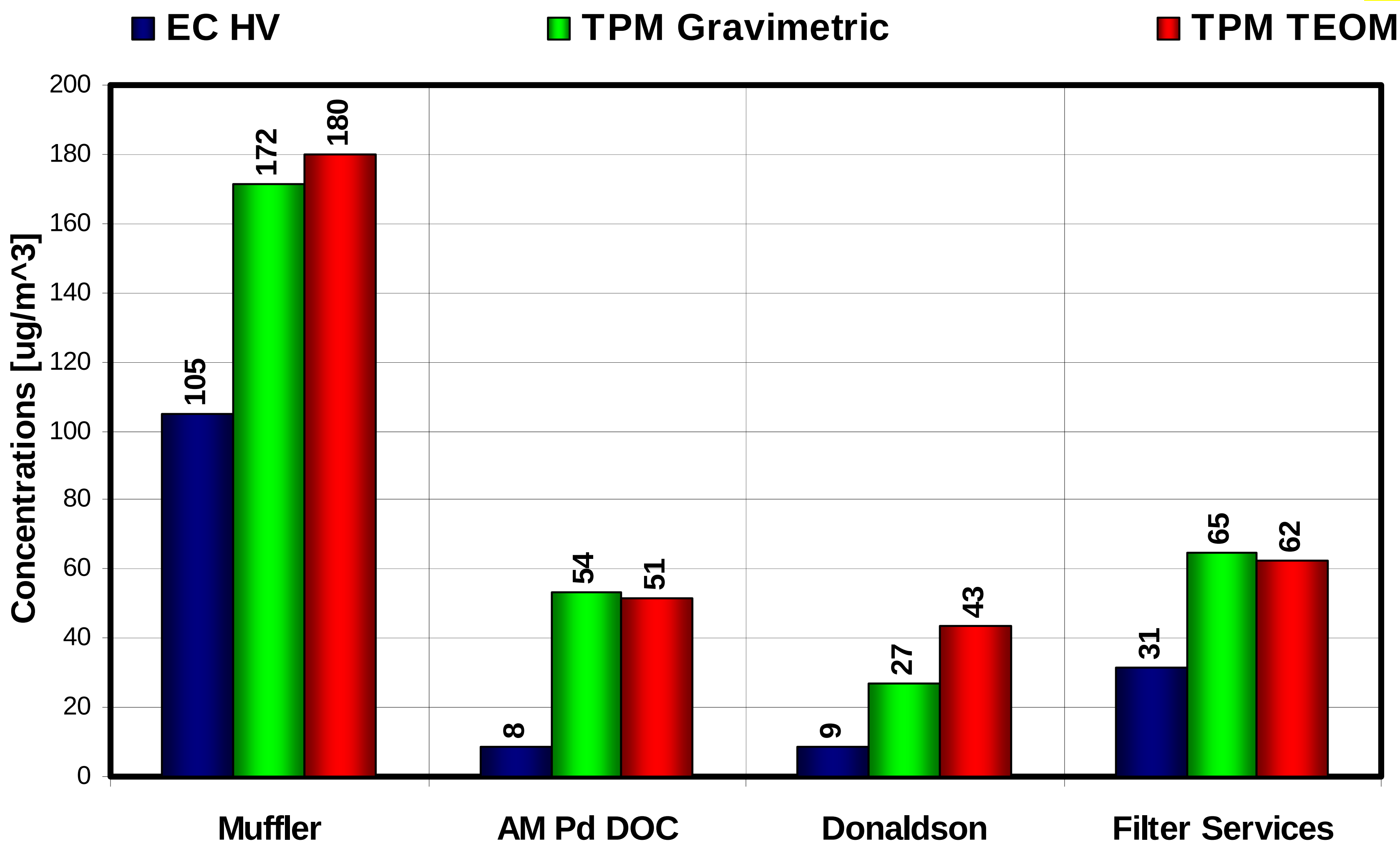
2003



	Engelhard DPX	DCL MineX	DOC
EC	96	87	-3
DPM	75	74	-15

The Effects of DPFs and DFEs on Mass Concentrations of Elemental Carbon (EC)

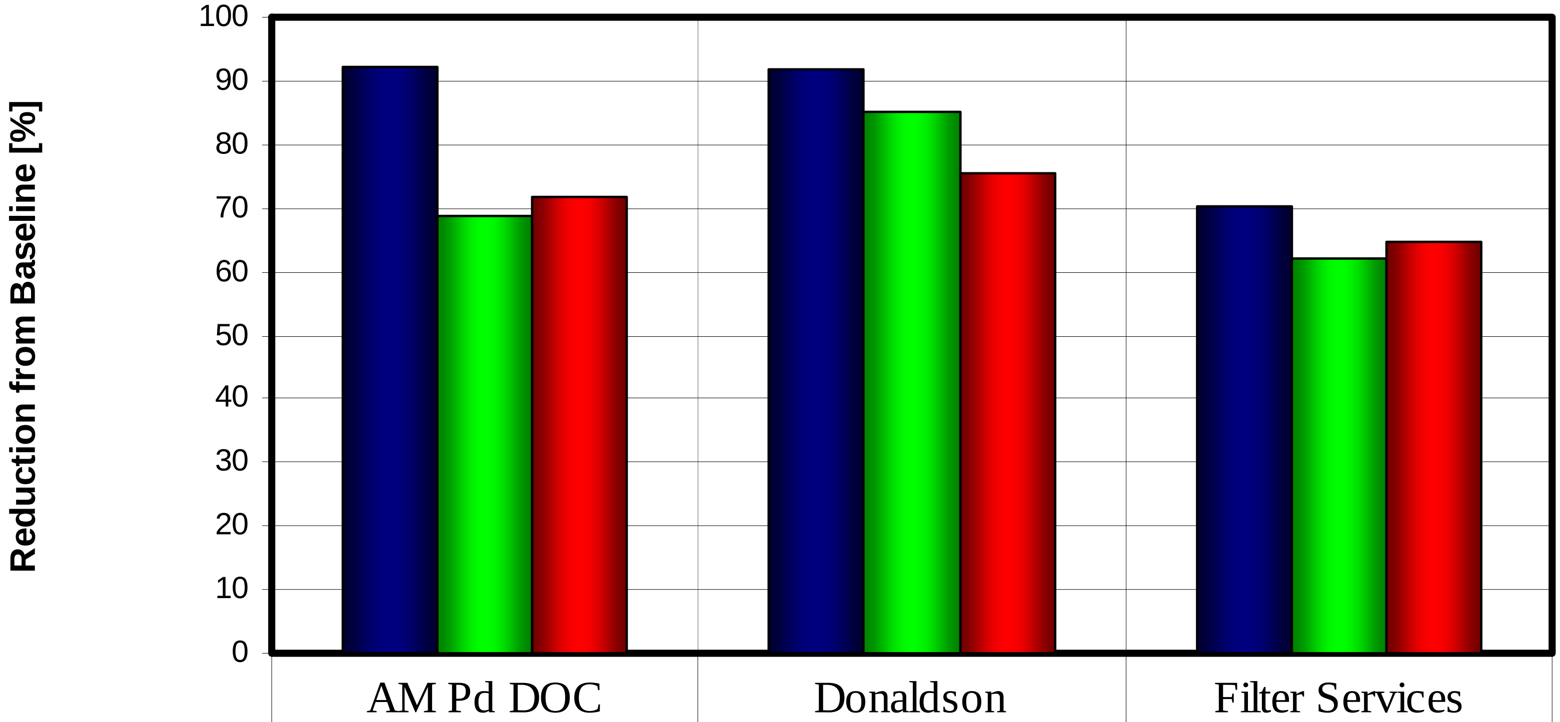
2004



NIOSH

The Effects of DPFs and DFEs on Mass Concentrations of Elemental Carbon (EC)

2004



	AM Pd DOC	Donaldson	Filter Services
EC HV	92	92	70
TPM GRAV	69	85	62
TPM TEOM	72	76	65

NIOSH

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

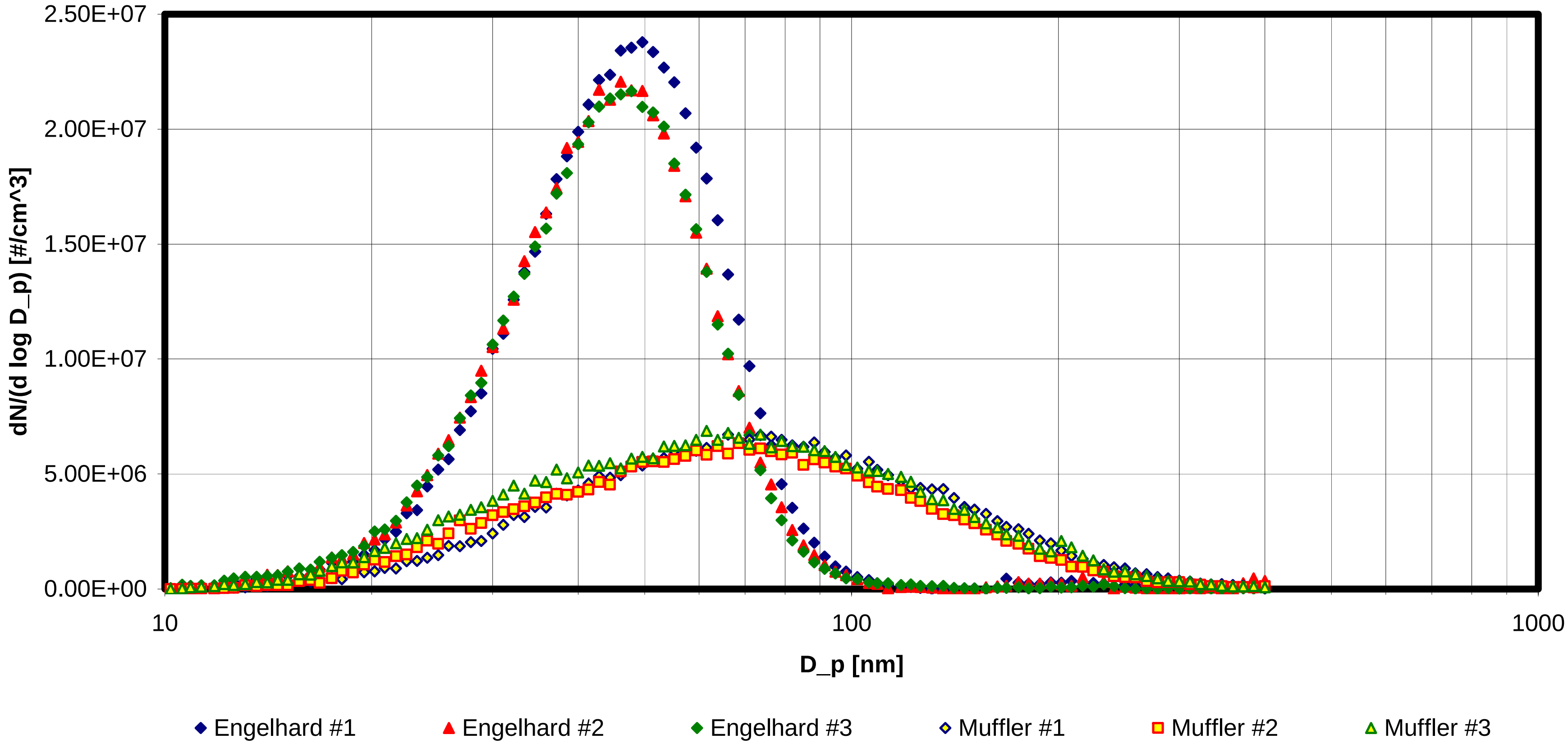
2003

Test Type	Average Geometric Mean [nm]	Average Total Particle Conc. @ MSHA VR [#/cm³]	Increase in Total Particle Conc. [%]
#92128 Haul Truck, MSHA VR = 5.66 m^3/s (12000 ft^3/min)			
Baseline	67.28	4.49E+06	--
Engelhard DPX DPF	43.74	8.07E+06	**79.6**
#99942 LHD, MSHA VR = 7.08 m^3/s (15000 ft^3/min)			
Baseline,	75.42	1.63E+07	--
DCL MineX DPF	38.06	2.61E+07	**60.6**
#92526 LHD, MSHA VR = 4.72 m^3/s (10000 ft^3/min)			
Baseline	85.74	8.56E+06	--
Engelhard PTX DOC	72.4	1.01E+07	**18.2**

- 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 with Engelhard DPX DPF vs. Muffler

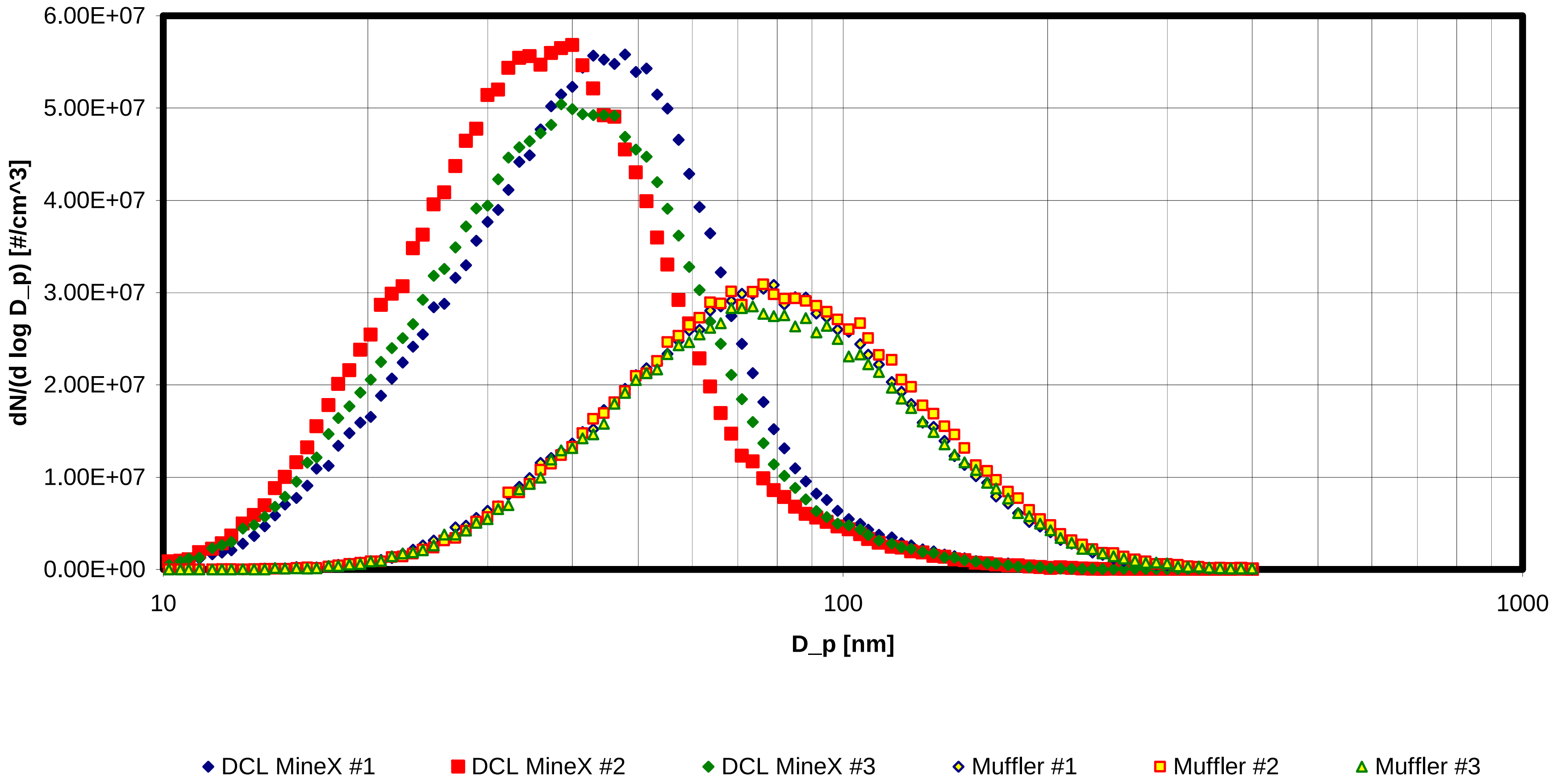
2003



NIOSH

Size distribution of aerosols in mine air
LHD with DCL MineX vs. Muffler

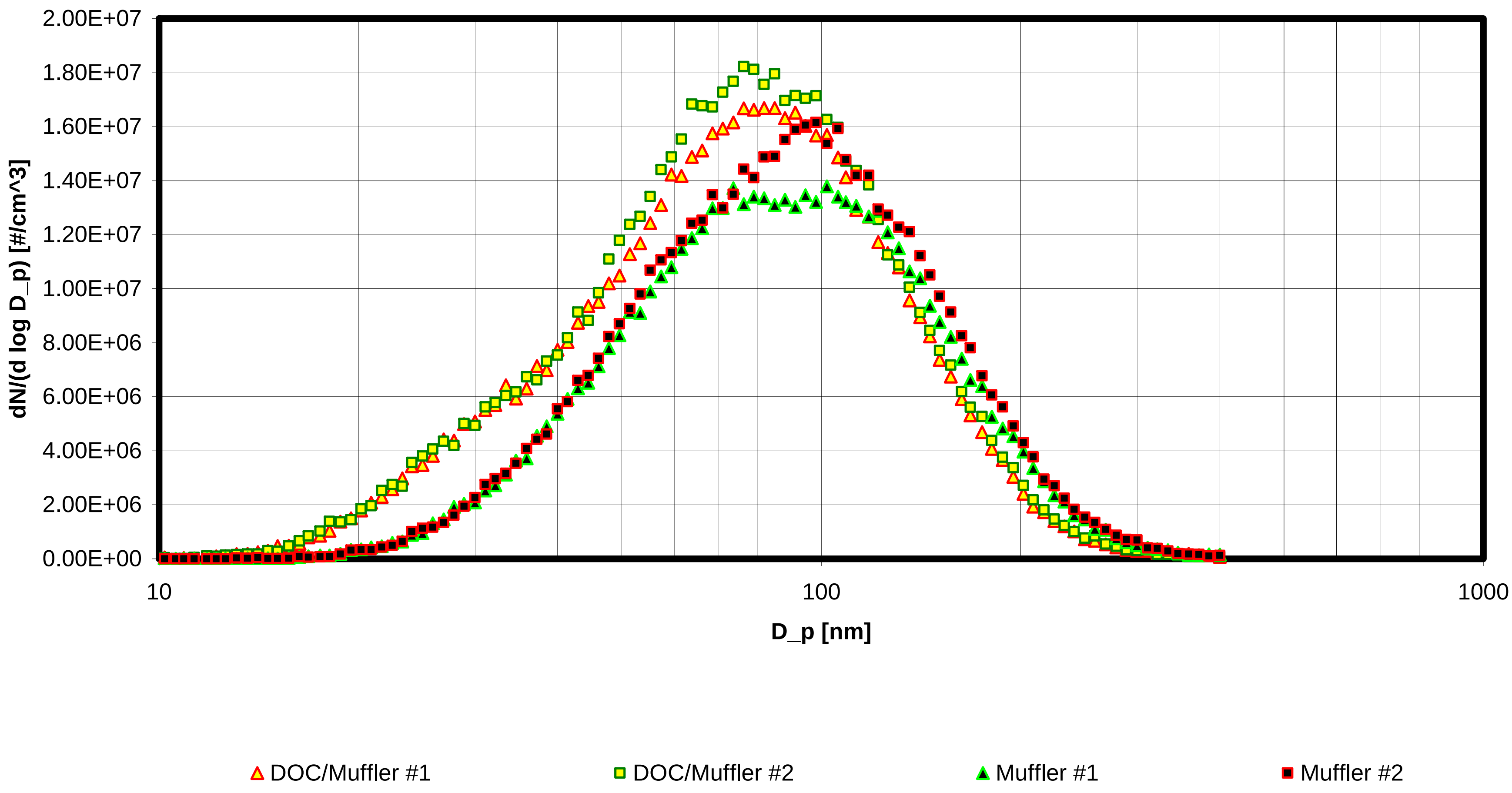
2003



NIOSH

Size distribution of aerosols in mine air
LHD with DOC/Muffler vs. Muffler

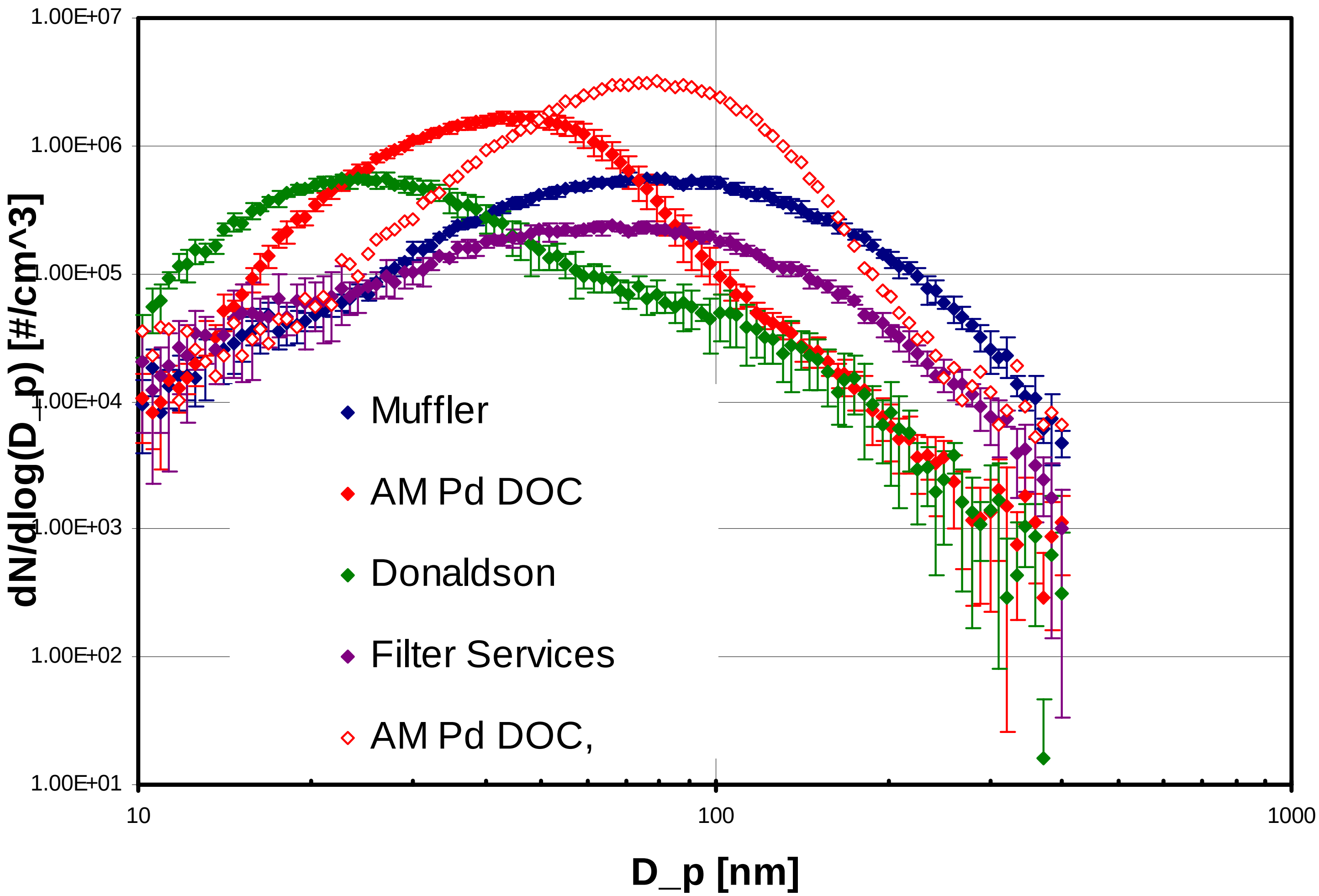
2003



NIOSH

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

2004



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

2004

Exhaust Configuration	Downstream			Upstream		Net Contribution	
	Average GMD 1	Average GMD 2	Norm. Average Number	Average GMD	Norm. Average Number	Norm. Average Number	Change
	nm	nm	10^7 #/cm^3	nm	10^7 #/cm^3	10^7 #/cm^3	%
Muffler	34.2	86.0	2.2098	63.2	0.0101	2.1997	
AM DPF with Pd DOC	42.5		4.5337	42.2	0.0208	4.5128	-105.2
Donaldson	24.2	68.3	1.6952	25.0	0.0692	1.6260	26.1
Filter Services	35.8	73.6	1.0360	40.8	0.0131	1.0229	53.5

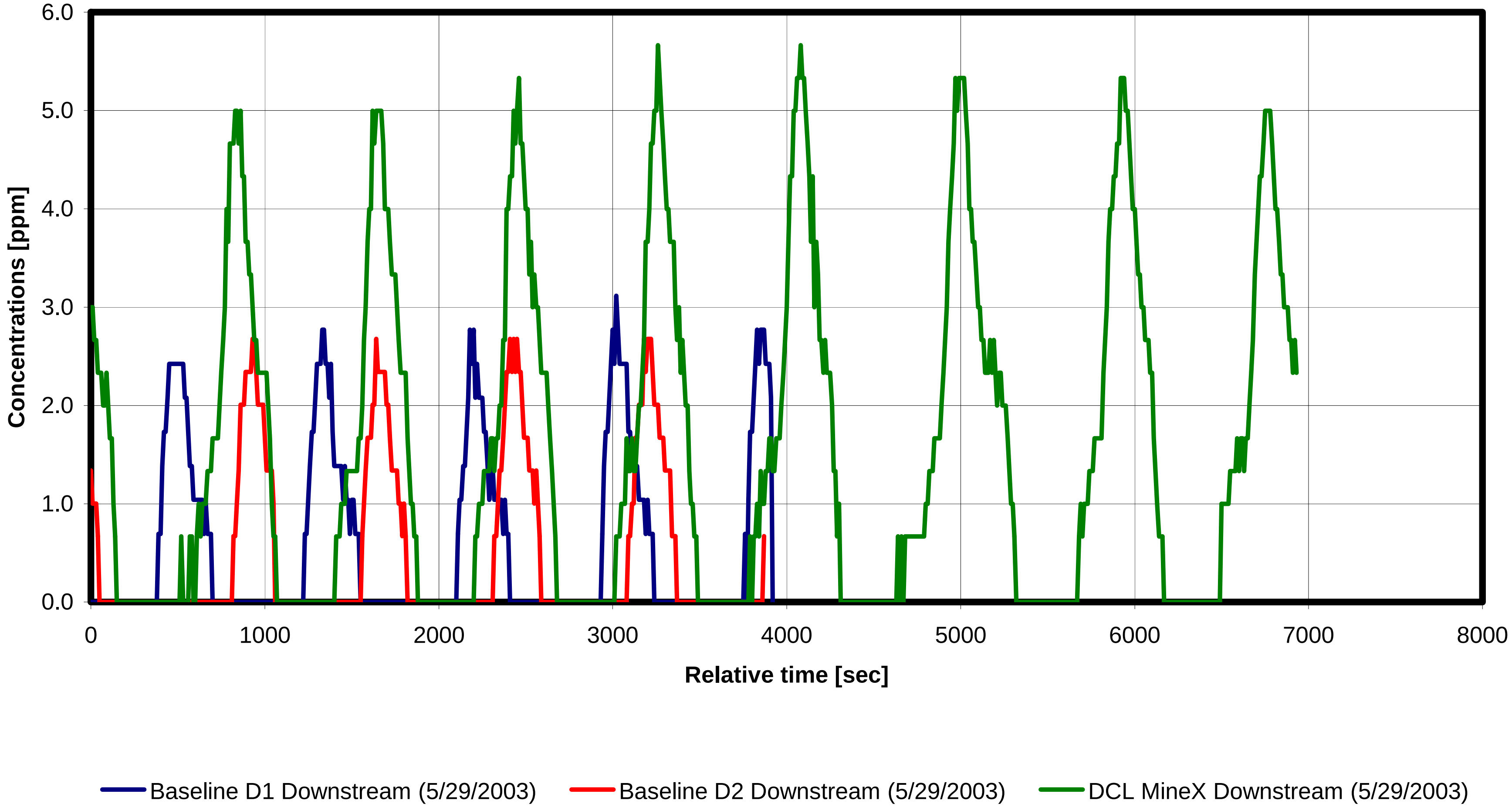
The Effects of DPFs and DOC on Concentrations of Nitrogen Dioxide (NO_2)

2003

Test Vehicle and Test Type	Average NO_2 concentration at MSHA Ventilation Rate	Increase in NO_2 concentrations by control technology
	ppm	%
#92128 Haul Truck, MSHA vent 5.66 m^3/min (12000 ft^3/min)		
Muffler	0.6	
Engelhard DPX DPF	2.1	269
#99942 LHD, MSHA vent rate 7.08 m^3/min (15000 ft^3/min)		
Muffler	0.5	
DCL MineX DPF	1.5	180
#92526 LHD, MSHA vent rate 4.96 m^3/min (10500 ft^3/min)		
Muffler	0.9	
Engelhard PTX DOC	1.1	26

- 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.

2003



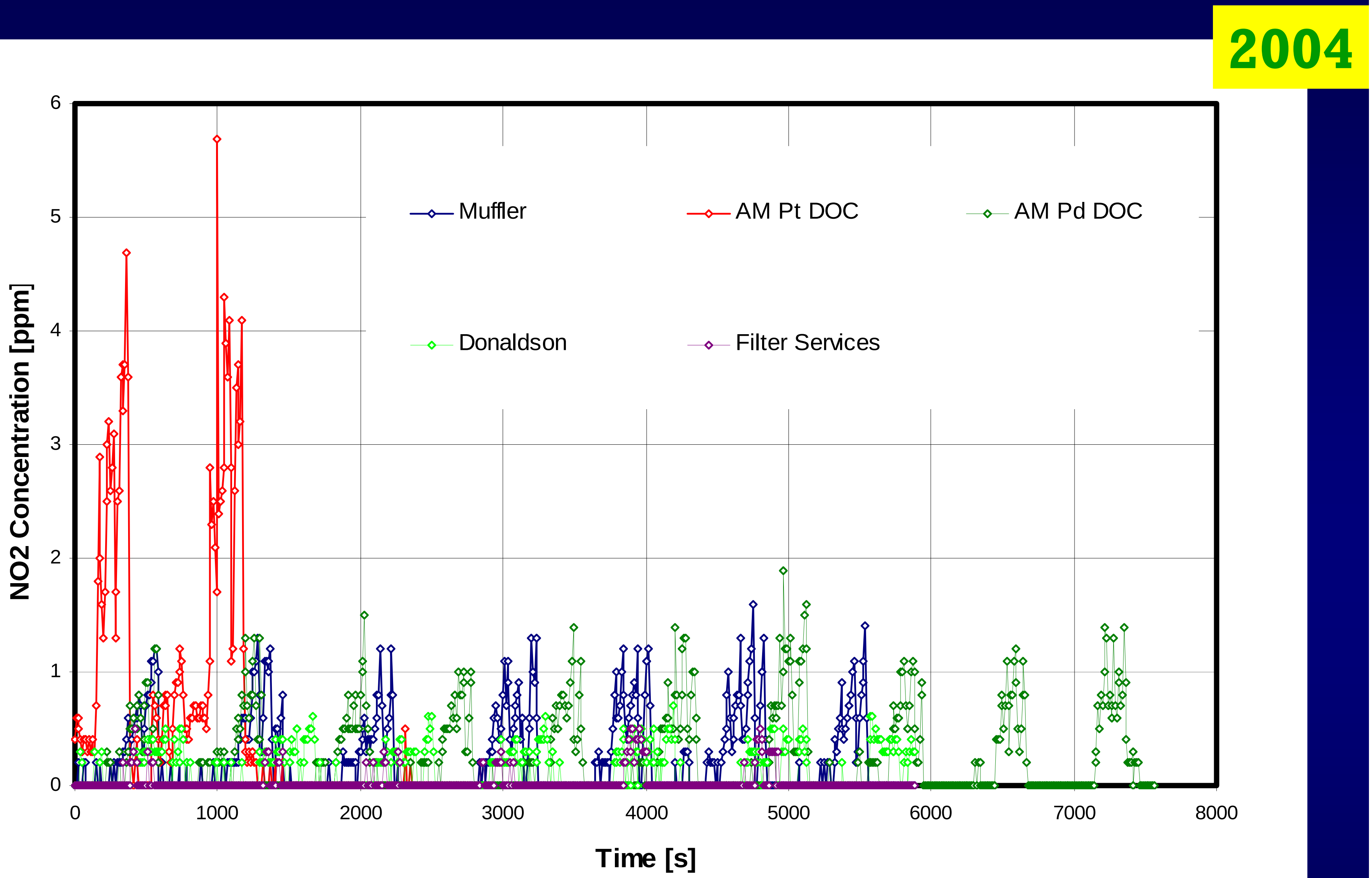
Ventilation-normalized NO_2 concentrations at downstream sampling station observed during the tests with LHD retrofitted with DCL MineX DPF

NIOSH

The Effects of DPFs with DOC and DFEs on Concentrations of Nitrogen Dioxide (NO_2)

Test Vehicle and Test Type	Average NO_2 concentration at MSHA Ventilation Rate	Increase in NO_2 by control technology
	ppm	%
Muffler	0.25	
AM Pt DOC	0.69	180
AM Pd DOC	0.24	-2
Donaldson	0.14	-44
Filter Services	0.03	-87

- The average ambient concentrations of NO_2 increased when vehicle with DPF and platinum coated DOC was tested.
- The average ambient concentrations of NO_2 did not increase when vehicle with DPF and palladium coated DOC was tested.
- Tested DFE reduced ambient concentrations of NO_2.



Ventilation-normalized NO_2 concentrations at downstream sampling station

NIOSH

References to Stillwater Reports

- Bugarski-AD, Schnakenberg-GH, Noll-JD, Mischler-SE, Patts-LD, Hummer-JA, Vanderslice-SE [2006]. Effectiveness of Selected Diesel Particulate Matter Control Technologies for Underground Mining Applications: Isolated Zone Study, 2003. U.S. Department of Health and Human Services, DHHS (NIOSH) Publication No. 2006-126, Report of Investigations 9667.

- Bugarski-AD, Schnakenberg-GH, Mischler-SE, Noll-JD, Patts-LD, Hummer-JA [2006]. Effectiveness of Selected Diesel Particulate Matter Control Technologies for Underground Mining Applications: Isolated Zone Study, 2004. U.S. Department of Health and Human Services, DHHS (NIOSH) Pub. No. 2006-138, Report of Investigations 9668.

- Available from http://www.cdc.gov/niosh/mining/pubs/programareapubs8.htm

Issues with Implementation of DPF Systems

- Selection
- Installation
- Secondary emissions
- Maintenance
- Engine backpressure monitoring
- Ash accumulation
- Education

Selection and Optimization of DPF System for Underground Mining Application

- Successes of DPF installations were found to be warranted only in the case of careful and educated DPF system selection for the particular application.
  - The objectives of DPF system installation should be clearly defined;
  - The technical limitations should be identified.

- Selection of DPF for the application is a delicate task and requires a relatively high level of expertise.

- Mine operators should coordinate efforts to upgrade new vehicles and retrofit existing vehicles with filtration systems with vehicle, engine, and aftertreatment technology manufacturers.

Selection and Optimization of a DPF System for Application

- The DPF is an integral part of the vehicle/engine/DPF system.
- Design of the system should be based on long-term exhaust temperature profiling
- The DPF system should be sized using realistic in-use emissions for the particular piece of equipment.
- DPF system should be installed and used only on the vehicles/engines application that it was designed for.

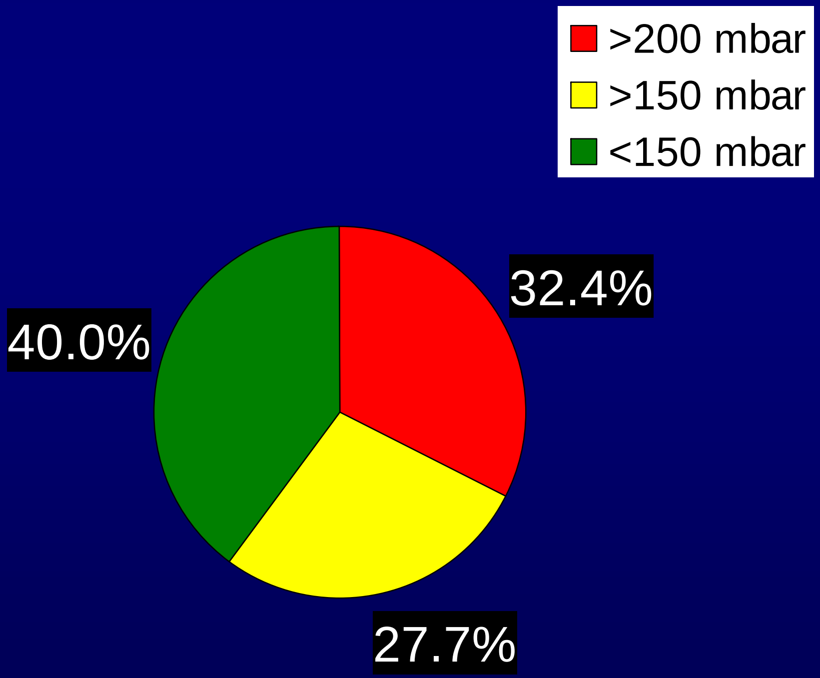
NIOSH

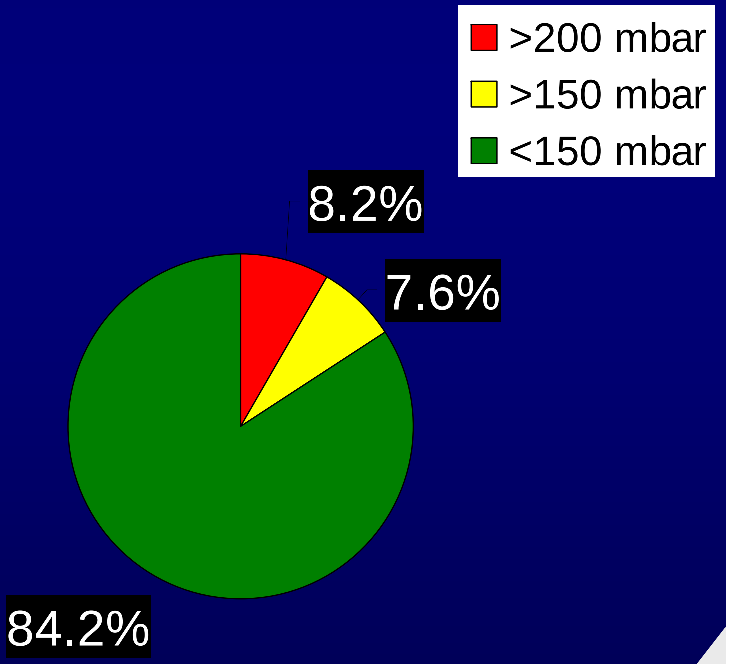
DPF System Maintenance

- The installation of DPF system should be proceeded and supported with thorough emissions-based maintenance:
  - In-use emissions should be measured at system inlet and outlet.
- DPF system can not replace engine maintenance
- Integrity of exhaust and DPF system should be maintained:
  - External leaks;
  - Internal leaks:
    - mechanical damage;
    - uncontrolled regeneration problems.

Engine Backpressure

- Engine backpressure limitations
  - Engine manufacture vs. DPF system manufacturer recommendations.





Courtesy Josef Stachulak, Inco Ltd.

Engine Backpressure Monitoring

- Sizing of the system is critical:
  - Engine backpressure – engine limitations:
    - Caterpillar 3306 PCNA - 34 in H_20;
    - DDEC Series 60 – 42 in H_20.
- Reliable backpressure monitoring and logging capabilities are essential for filtration system performance.
- Pressure gage and alarm should be included in the filtration system.
- Operator training and education.

Ash Accumulation

- Ash originates from fuel, lubricating oil, engine wear and/or fuel additives:
  - up to 1% of DPM.
- Ash cannot be regenerated as carbon. Accumulation of ash in the filter results in a continuous increase in base backpressure.
- Periodic cleaning of the filter is required.

Conclusion

- The strategies and technologies to achieve targeted mine air quality standards should be carefully planned and selected.
- In significant number of cases achieving substantial reductions in the miners exposure to DPM strongly depends on the ability of the operators to widely implement advanced diesel emissions control technologies.
- DPF systems and FS with DFEs offer dramatic reductions in DPM/EC emissions,
- but careful planning, selection and optimization is needed to overcome potential implementation issues.
- The introduction of those systems should be supported with emissions assisted maintenance and filtration system support program.
- The maintenance and production crews should be adequately trained to support operation of the systems.

Thank you for your attention!

The findings and conclusion of this publication have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be constituted to represent any agency determination or policy. Mention of any company or product does not constitute endorsement by NIOSH.

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