

Examination of Diesel Aftertreatment Systems at NIOSH Lake Lynn Laboratory

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Abstract

A series of engine/dynamometer tests was conducted to assess the effects of three types of uncatalyzed diesel particulate filters (DPFs), a diesel oxidation catalytic converter (DOC) and three types of high temperature disposable filter elements (HT DFEs) on the concentrations and size distribution of diesel aerosols and concentration of nitric oxides in underground mine air. Tests were conducted in the NIOSH Diesel Laboratory at the Lake Lynn Laboratory experimental mine, a facility developed to allow evaluation of these and other control technologies directly in an underground environment. The aforementioned technologies are evaluated by comparing the aerosol and gas measurements in the mine air 60 m downstream of the exhaust from a naturally aspirated, mechanically controlled engine fitted with the tested systems or muffler and operated at four steady-state engine speed and power modes.

The tested DPF and HT DFE systems caused a 10-fold reduction in total mass concentrations of aerosols. The size distribution and number concentration measurements showed that all tested DPF systems and HT DFE elements effectively removed accumulation mode aerosols ($D_{50} > 30$ nm) for all test modes. An increase in peak number concentrations of nucleation mode ($D_{50} > 30$ nm) diesel aerosols is evident for some of tested DPF systems when engine was operated at high-load modes. The effects of uncatalyzed DPFs on nitric oxide (NO) and nitrogen dioxide (NO₂) concentrations are found to be minor. A four-fold increase in percentages of NO₂ in total nitrogen oxides (NO_x) over baseline case was observed for the DOC when the engine was operated at high-load modes.

The findings from this study should contribute to better understanding the potential for various control technologies to reduce exposure of underground miners to nano and ultrafine aerosols. In addition, detailed physical characterization of diesel aerosols made directly in occupational setting should foster a better understanding of the health risks associated with exposure to nano and ultrafine diesel aerosols.

Introduction

In recent years, health effects associated with exposure to diesel particulate matter and other primarily combustion-generated, nano and ultrafine aerosols have received substantial attention from public, government and academia. Pope and coauthors (2002) established that long-term exposure to combustion-related fine particulate pollution is an important risk factor for cardiopulmonary and lung cancer mortality. There is growing evidence suggesting that particle number, surface area, size, or perhaps some associated structural properties may affect nanoparticle toxicity, in comparison with larger respirable particles of the same composition (Donaldson and Stone, 2003), but in general, occupational health risks associated with exposure to nano and ultrafine aerosols are not yet clearly understood.

In January 2001 the U.S. Mine Safety and Health Administration (MSHA) promulgated regulations, 30 CFR 57.5060, limiting exposures of underground metal and nonmetal miners to diesel particulate matter (DPM). DPM exposures are currently being regulated solely on the basis of the total and elemental carbon mass per unit volume of air. No reference is made to either size or the number concentration of emitted particles. Mass-based exposure assessments are not always fully predictive of disease risk; in some cases respirable particle surface area and detailed surface compositional or morphological properties better correlate with toxicity or offer an explanation of seeming anomalies in epidemiological findings of disease risk (Wallace et al., 1990). Other studies have indicated the importance of complementing mass based exposure monitoring with measurements of size, number, and surface area of aerosols in attempt to assess adverse health impact of nano and ultrafine aerosols (Donaldson et al. 2000, 2002; Tran et al., 2000; Englert 2004, Oberdörster et al. 2000, 2004).

As a result of the new technology-forcing MSHA regulation, the U.S. underground mining community is currently working on identifying technically and economically feasible controls for the curtailment of DPM and toxic gaseous emissions from existing and new diesel powered equipment in underground mines. Various diesel emission control technologies, including diesel oxidation catalytic converters (DOCs), diesel particulate filters (DPFs) systems and high-temperature disposable filter elements (HT DFEs) are some of the tools available to the industry to control DPM emissions.

The majority of the work on size resolved characterization of diesel aerosols was done in laboratory environments (Bugarski 1999, Maricq et al. 1999, 2004, Vaaraslahti et al. 2004, Ntziachristos and Samas, 2006), on the road (Kittelson et al. 2005) and tunnels (Gautam et al. 2003, Jamriska et al 2004). Several researchers (McGinn et al. 2004, Bugarski et al. 2006a and 2006b) studied to a limited extent the effects of selected control technologies on concentrations of aerosols in underground mines.

Since the aerosol size and concentrations of semivolatile materials emitted by diesel engines in the work place are strongly influenced by a number of processes and ambient conditions, the best way to characterize them is to sample directly in an occupational setting. The facility developed at the NIOSH Lake Lynn Laboratory (LLL) enables the investigation of diesel emissions control technologies in underground environment with laboratory precision and accuracy.

Methodology

Three types of non-catalyzed DPF systems using Cordierite, silicon carbide (SiC), and sintered metal filter elements, two types of HT DFES, and a DOC are examined in this study. The sintered metal system was used with a fuel-born catalyst. The objective was to study the effects of these exhaust aftertreatment technologies on the physical properties of diesel aerosols and gases and compare those with the effects observed for a standard muffler. The testing was conducted using the NIOSH Diesel Laboratory at the NIOSH Lake Lynn Laboratory (LLL).

NIOSH Diesel Laboratory

The NIOSH Diesel Laboratory is situated in the D-drift of the LLL experimental mine (Figure 1). The LLL was developed from an underground limestone mine situated near Fairchance, Pennsylvania, about 97 km (60 miles) southeast of Pittsburgh, PA, and 16 km (10 miles) northeast of Morgantown, WV (Tribsch and Sapko 1990).

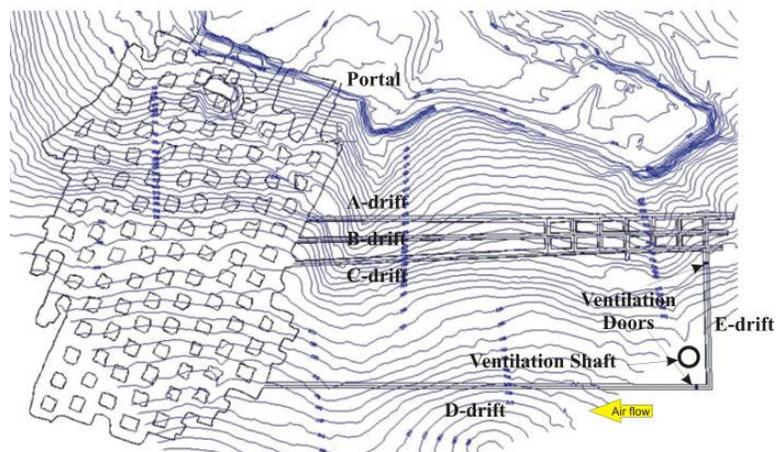


Figure 1. NIOSH Lake Lynn Laboratory Experimental Mine

The D-drift is approximately 530 m (1750 ft) long, 6 m (20 ft) wide, and 2 m (7 ft) high. A schematic of the laboratory layout is shown in Figure 2. The major components of the laboratory are an engine/dynamometer system, three sampling and measurement stations, and a ventilation measurement and control system.

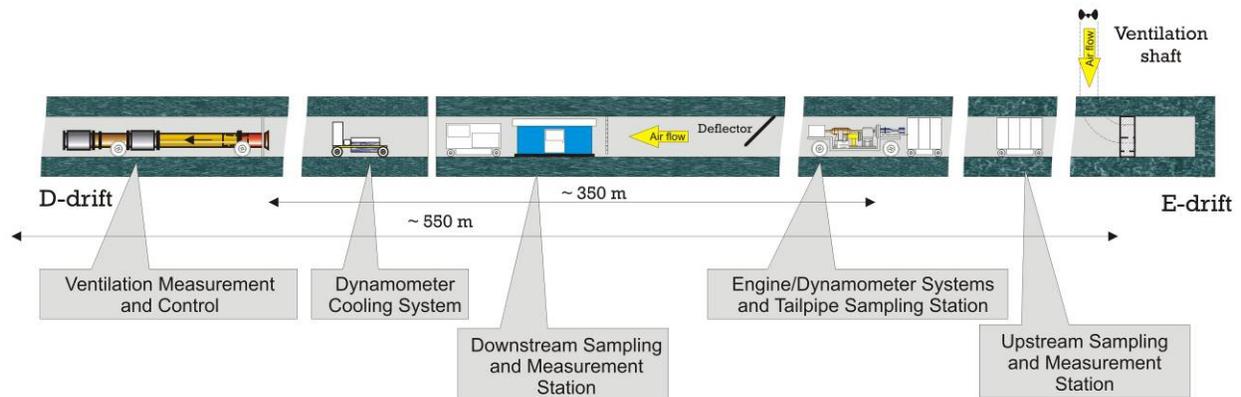


Figure 2. NIOSH Diesel Laboratory in D-drift of LLL

Dynamometer/Engine System

A water-cooled eddy-current dynamometer from SAJ (Pune, India, Model SE150) rated at 150 kW (201 bhp) is used to load and control a naturally aspirated, mechanically controlled Isuzu C240 diesel engine (Isuzu Motors Limited) (Figure 3). The Isuzu C240 is one of the most popular engines in U.S. underground coal mines and is primarily used to power light-duty vehicles.



Figure 3. Dynamometer/Isuzu C240 system

A Model Dyn-Loc IV dynamometer controller and a Model DTC-1 engine throttle controller (DyneSystems Co. Germantown, WI) provide control for the dynamometer and the engine, respectively. A DyneSystems “Companion” data acquisition system is used to acquire relevant dynamometer and engine operating parameters. Both controllers and data acquisition system are operated using CellAssistant for Windows software from DyneSystems.

The potential effects of the dynamometer cooling process on the test results are eliminated by placing the cooling system approximately 30 m downwind of the downstream sampling station.

Monitoring Stations

Ambient Stations

Ambient concentrations of aerosols and gases are measured in the mine air upstream and downstream of the dynamometer/engine system (Figure 2). The upstream ambient monitoring station is located approximately 60 m (197 ft) up wind of the dynamometer. This station is designed to measure background aerosol concentrations using following methods:

1. The Tapered Element Oscillating Microbalance (TEOM) Series 1400a (Thermo Electron Corp., East Greenbush, NY) ambient particulate monitor is used for real time measurements of total particulate matter under 0.8 μm ;
2. The Scanning Mobility Particle Sizer (SMPS) (TSI, St. Paul MN) is used to measure size distribution and count concentrations of aerosols between 10 and 408 nm.

The downstream ambient monitoring station is located about 60 m (197 ft) downwind of the dynamometer. This station is designed to measure concentrations of aerosols and gases using the following instrumentation:

1. The TEOM Series 1400a ambient particulate monitor was used for real time measurements of total particulate matter under 0.8 μm ;
2. The SMPS was used to measure size distribution and number concentrations of aerosols;
3. The Fast Mobility Particle Sizer (FMPS) (Model 3091, TSI) was used to measure size distribution and number concentrations of aerosols;
4. Electrical Low Pressure Impactor (ELPI), (Model DAS 3100, Dekati, Finland) was used to measure size distribution and number concentrations of aerosols.
5. Chemiluminescence NO/NO₂ analyzer Model CLD 700 AL, Eco Physics, Duernten, Switzerland;
6. CarbonCap hand-held recording CO₂ meter (Model GM70, Vaisala Oyj, Helsinki, Finland) to which a HM-70 probe is added to measure relative humidity and temperature.

Engine/Dynamometer and Tailpipe Station

Concentrations of CO and CO₂ in the raw exhaust of the test engine are measured upstream of emissions control system using a Model 602 Series non-dispersive infrared (NDIR) analyzer (California Analytical Instruments, Incorporated, Orange, CA).

Pertinent engine and ambient parameters are measured and recorded at this location as well. The details are given below.

Instrumentation

Total Aerosol Mass Concentration Measurements

At the upwind and downwind locations, ambient concentrations of total particulate matter are measured with the TEOM ambient monitor. The TEOM flow rate is set at 2.0 lpm. A 10-mm Dorr-Oliver cyclone followed by a diesel particulate matter cassette (SKC) with its filter element removed are used to pre-classify aerosols entering the TEOM, allowing only particles with an average aerodynamic diameter ($_{50d_{ae}}$) smaller than 0.82 μm to reach the collection filter. The

average concentrations for a test are obtained from the difference in filter masses recorded at the start and stop times.

Aerosol size Distribution and Total Number Concentration Measurements

Aerosol size distributions and concentrations at downstream station are measured using an SMPS. The second SMPS is used to measure size distributions and concentrations at the upstream station.

The SMPS at the downstream station is configured with an electrostatic classifier (EC) Model 3080L and a condensation particle counter (CPC) Model 3025A. The SMPS at the upstream sampling station consists of an EC Model 3080L and a CPC Model 3776. Both SMPSs are used to measure size distribution and number concentrations of particles in the range between 10 and 408 nm. The sample and sheath air flows in both ECs are maintained at 0.6 l/min and 6 l/min, respectively. The inlet impactor $_{50d_{ae}}$ for these conditions is 480 nm. The CPC is operated in high-flow mode to minimize diffusion losses. The instruments are operated using a dedicated laptop computer and Aerosol Instrument Manager Software Version 8.0.0.0 from TSI. Multiple charge and diffusion correction are applied on all data.

Concentrations of Nitric Oxide, Nitrogen Dioxide, Carbon Monoxide, Carbon Dioxide and Hydrocarbons

Concentrations of nitric oxide (NO) and nitrogen dioxide (NO₂) at the downstream station are measured with a Model CLD 700 AL chemiluminescence (CLD). The CarbonCap hand-held meter Model GM70 is used to measure carbon dioxide (CO₂) concentrations at the downstream station.

A Model 602 Series non-dispersive infrared (NDIR) analyzer is used to measure CO and CO₂ concentrations in the tailpipe. A portable gas conditioning system Model PSS-10 (M&C Products Analysentechnik GmbH, Ratingen, Germany) is used for conditioning samples prior to measurement.

Engine and Dynamometer Parameters

The exhaust mass flow rate (M_{ex}) was calculated from results of air intake and fuel flow rate measurements. The engine air intake volumetric flow rate is measured using laminar flow element (LFE) Model 50MC2-4 (Meriam Instruments, Cleveland, OH). The fuel mass flow rate is measured using Max 710 Fuel Measurement System with flow meter Model 213-310 (Max Machinery Inc., Healdsburg, CA). The system can measure diesel fuel flow rates between 0.12 and 175 lbs/hr with 0.5% accuracy. The density of the fuel obtained from the fuel analysis is used as input to the instrument. The flow rates are corrected for variations in temperature, pressure, and relative humidity.

The exhaust temperature was measured using a Model KMQSS-125G-6, K-type thermocouple (Omega, Inc). The engine backpressure was measured using a Model P356 differential pressure sensor (Kavlico Corp., Moorpark, CA). The output from the thermocouples and pressure sensors are collected using the “Companion” data acquisition system mentioned earlier.

Ventilation

Fresh air is supplied to the LLL underground facility via a ventilation shaft located in E-drift (Figure 1 and Figure 2). A Series 2000 Model 48-26-1770 XP Axivane fan (Joy Technologies Inc., New Philadelphia, OH) is used to push air into the mine. A portion of available air is diverted to the test zone via the E-drift that is situated immediately upwind and normal to the D-drift. A plywood wall near the downwind exit of D-drift completely blocks the drift except for sealed double doors (kept closed during testing) and a circular opening through which all of the D-drift air flows. A subsonic venturi meter (Primary Flow Signal, Inc., Tulsa OK) is sealed into the circular opening and measures total flow through the D-drift. The meter is connected to a 3-m section of duct followed by a Series 1000 Model 23-17-3450 Axivane fan (Joy Technologies) which maintains the ventilation flow rate through the D-drift. The flow rate measurements are compensated for variations in temperature, pressure, and humidity. Air quantities supplied to D-drift can be regulated by adjusting a bypass vent on the Venturi/auxiliary fan system.

The average ventilation flow rate in the D-drift throughout all tests was $5.69 \pm 0.06 \text{ m}^3/\text{s}$ ($12056.4 \pm 118.7 \text{ ft}^3/\text{min}$). The resulting exhaust dilution ratios at the downstream sampling station, calculated using results of exhaust gas and ventilation mass flow rate measurements, for R50, R100, I50, and I100 engine operating modes were 148, 149, 186, and 188, respectively.

Fuel

The engine was fueled with ultra-low sulfur diesel fuel procured from Guttman Oil (Belle Vernon, PA). The fuel was supplied to the engine from the 200-liter main fuel tank (Rohmac Inc., Mt. Storm, WV). The results of the analysis performed on that fuel by Core Laboratories, Houston, TX are given in Table 1.

Table 1. Fuel properties

Test	Method	Result	Units	
BTU, Net	ASTM D-240	43468	kJ/kg	
Cetane Number	ASTM D-613	61.8	-	
Density	ASTM D-4052	0.8038	gm/ml	
Flash Point, PMCC	ASTM D-93A	62.2	°C	
Hydrocarbon Type				
	Aromatics	ASTM D-1319	7.2	LV%
	Olefins	ASTM D-1319	1.1	LV%
	Saturates	ASTM D-1319	91.7	LV%
Oxygen Content		3.45	Wt. %	
Sulfur Content	ASTM D-5453	11	mg/kg	

The sintered metal DPF system was tested using the same fuel to which was added the fuel-borne catalyst from Innospec Limited, Cheshire, United Kingdom. The additive was premixed with diesel fuel at approximately 0.677 ml of additive per liter of fuel before it was added to auxiliary fuel tank on-board the dynamometer/engine system.

Test Protocol

The effects of aftertreatment devices were established by comparing results from a series of steady-state tests conducted both with the aftertreatment systems and with the muffler. The Isuzu C240 engine was operated at four steady-state engine operating modes. The description of the test modes is given in **Table 2**.

Table 2. Engine operating modes

Mode	Description	Engine Speed	Torque	Power
		Rpm	Nm	kW
R50	Rated speed 50% load	2950	55.6	17.2
R100	Rated speed 100% load	2950	111.2	34.3
I50	Intermediate speed 50% load	2100	69.1	14.9
I100	Intermediate speed 100% load	2100	136.9	30.6

In a typical test run, the engine was operated for approximately three hours at the selected engine mode. The initial hour of each test was dedicated to achieving system equilibrium. The measurements were initiated at the beginning of the second hour. The data shown in this report are results of averaging data obtained over the last hour of the test.

Aftertreatment Technologies

The aftertreatment devices tested in this study are listed in Table 3.

Table 3. Aftertreatment technologies

Technology	Supplier
Cordierite DOC	Engine Control Systems Ltd., Newmarket, Ontario, Canada, Purifier, PN#A16-0130
Cordierite DPF	Catalytic Exhaust Products, Toronto, Ontario, Canada, Model 912-SXT
SiC DPF	DCL International Inc., Concord, Ontario Canada, Model Minex Sootfilter, Model 5.66×10
Sintered Metal DPF	Mann+Hummel GMBH, Speyer, Germany, Model SMF-AR
DFE #1	Donaldson, Minneapolis, MN PN#604516
LD FE	Laundered Donaldson, Minneapolis, MN PN#604516
DFE #2	Filter Service & Testing, Huntington, UT, PN#11526

The Cordierite diesel particulate filter (DPF) system consisted of one 254×305 mm (10×12 in) filter element. The silicon carbide (SiC) DPF system was designed with two 144×254 mm (5.7×10 in) filter elements installed in parallel. The sintered metal (SM) DPF had a single filter unit with total surface area of 2.75 m². All DPF systems were designed to maintain engine backpressure below 10.21 kPa (41 in H₂O), the engine manufacturer-specified maximum allowable value.

Cordierite and SiC systems used uncatalyzed elements. The SM DPF system was tested in conjunction with the iron-based fuel borne catalyst. The testing of Cordierite and SiC elements was initiated after the systems were operated for more than 20 hours and subsequently

regenerated using a CombiClean regeneration station (Engine Control Systems Ltd.). The SM DPF system testing was started after the system accumulated approximately 4 hours of operation.

The HT DFEs were tested using a custom housing designed and built by Mac’s Mining Repair Service (Huntington, UT). Since the HT DFEs we tested are approved for use in applications where exhaust temperatures do not exceed 343 °C (650 °F), it was necessary to integrate an air-to-air heat exchanger (supplied by Mac’s Mining Repair) into the exhaust system between the engine and the HT DFE housing. Two DFE #1 were tested: one as new and a different one after laundering (LDFE) by Mac’s Mining Repair Service. The DFE #2 was tested only as new.

The average exhaust temperatures observed for four test modes are summarized in Table 4. It is important to note that exhaust temperatures were significantly lower for the HT DFE systems.

Table 4. Average exhaust gas temperatures

Mode	DPF,DOC, Muffler		HT DFE	
	Exhaust Temperature at Inlet of Device	Exhaust Temperature at Outlet from Device	Exhaust Temperature at Inlet of Device	Exhaust Temperature at Outlet from Device
	°C	°C	°C	°C
R50	306	258	200	154
R100	529	436	329	242
I50	254	216	160	125
I100	485	402	313	234

Results

Effects on Aerosol Size Distributions and Number Concentrations

The results of size distribution measurements at the downstream sampling station measured with the SMPSs are summarized in Figure 4, Figure 5, Figure 6, and Figure 7.

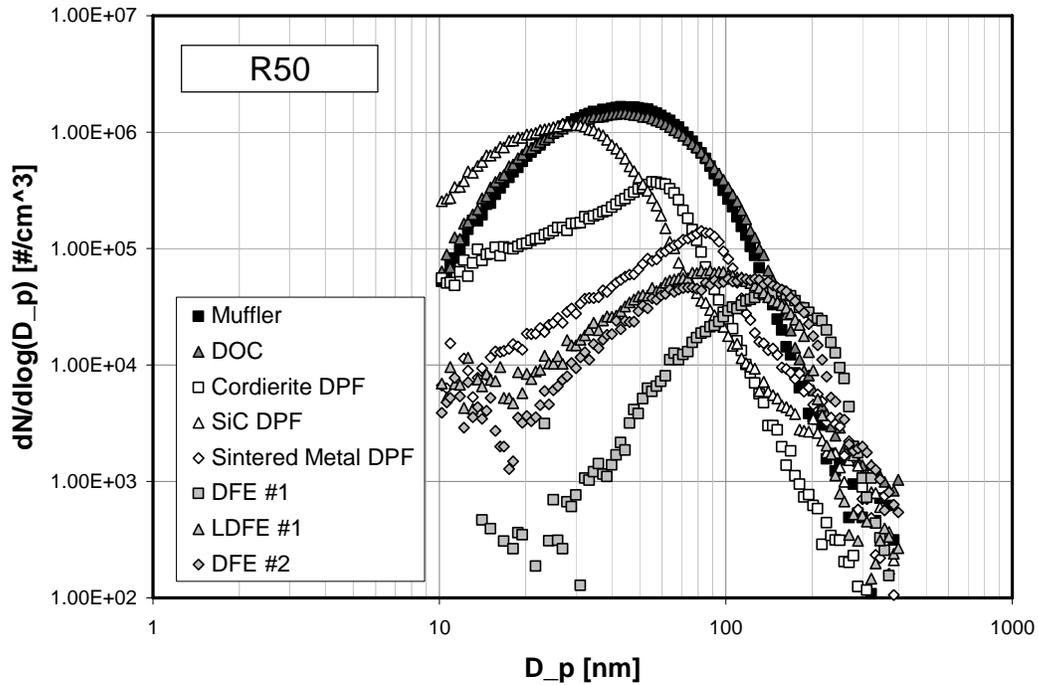


Figure 4. Aerosol size distribution measured during R50 tests

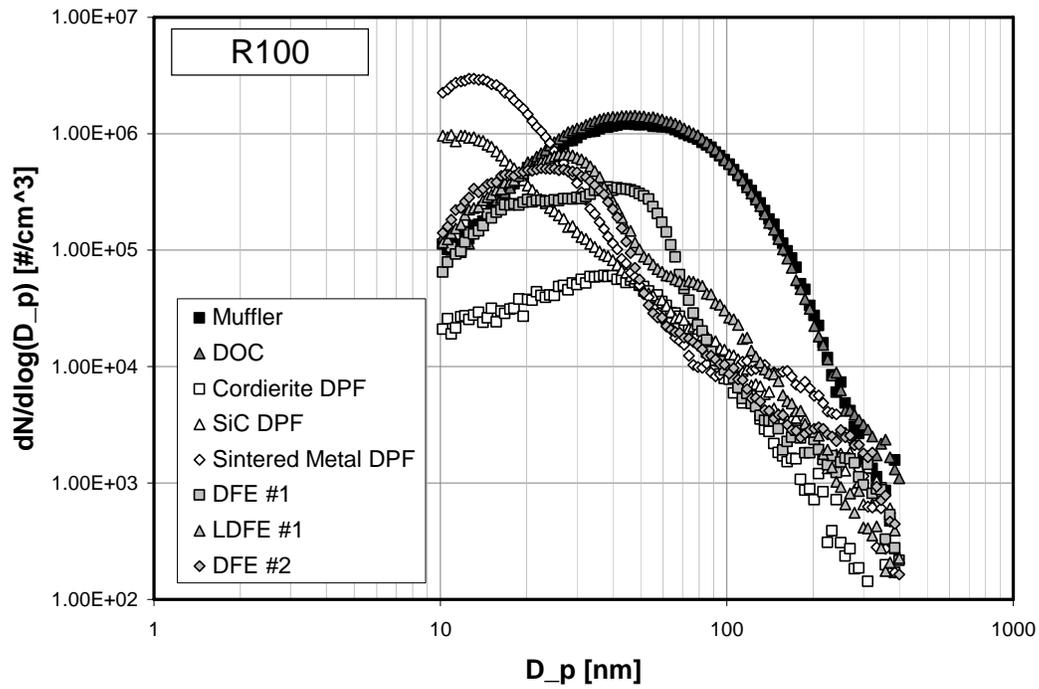


Figure 5. Aerosol size distribution measured during R100 tests

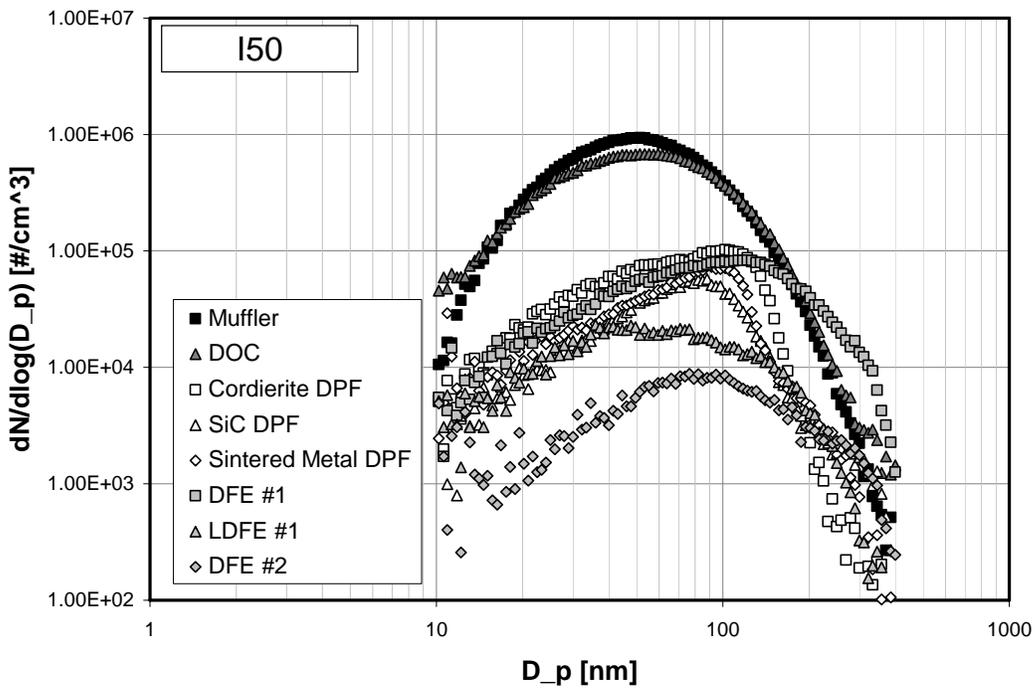


Figure 6. Aerosol size distribution measured during I50 tests

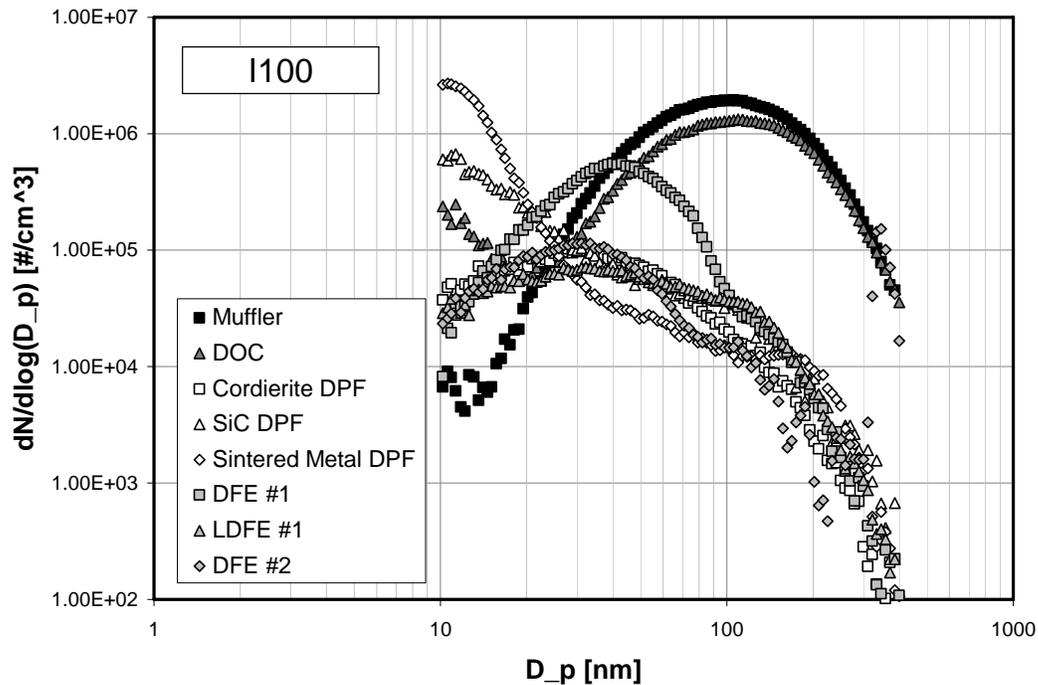


Figure 7. Aerosol size distribution measured during I100 tests

From the presented distributions one can conclude the following:

1. The DOC had relatively moderate effect on the size distribution of diesel aerosols in mine air.
2. All tested DPF systems and DFE elements effectively removed accumulation mode aerosols ($_{50}d_{ae} > 30$ nm) from mine air for all test modes.
3. Concentrations of nucleation mode aerosols ($_{50}d_{ae} < 30$ nm) were found to be substantially higher when the engine was operated at the higher load and higher exhaust temperature modes, R100 and I100, than at the lower load and lower temperature modes, R50 and I50 indicating positive correlation between concentrations of nucleation mode aerosols and exhaust temperatures (see Table 2).

Effects on Total Number and Mass Concentrations of Aerosols

The results of SMPS (downstream and upstream) and ELPI (downstream) measurements are used to calculate the effects of tested control technologies on changes in aerosol number concentration in mine air. The effects of the technologies on mass concentrations are calculated using TEOM data. The changes are summarized in Figure 8.

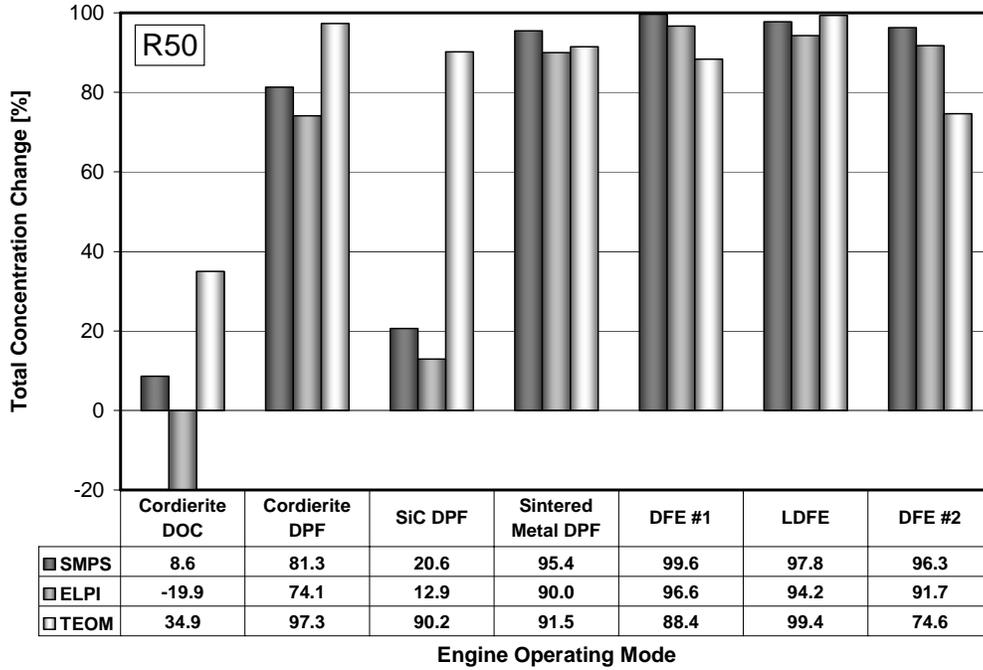


Figure 8. Percentage of total number and mass concentrations change for R50 test modes

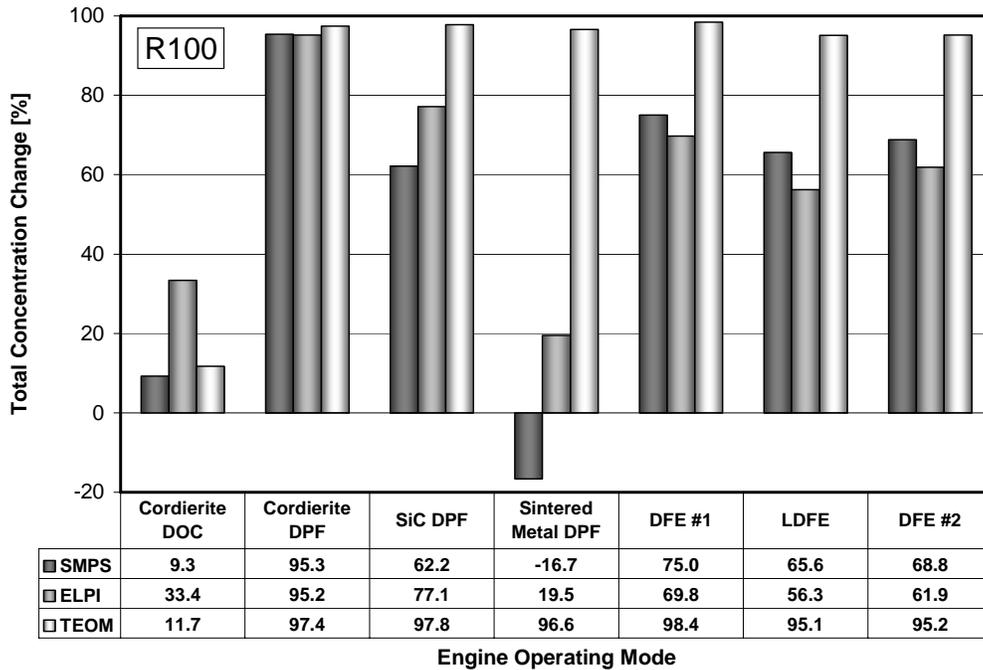


Figure 9. Percentage of total number and mass concentrations change for R100 test modes

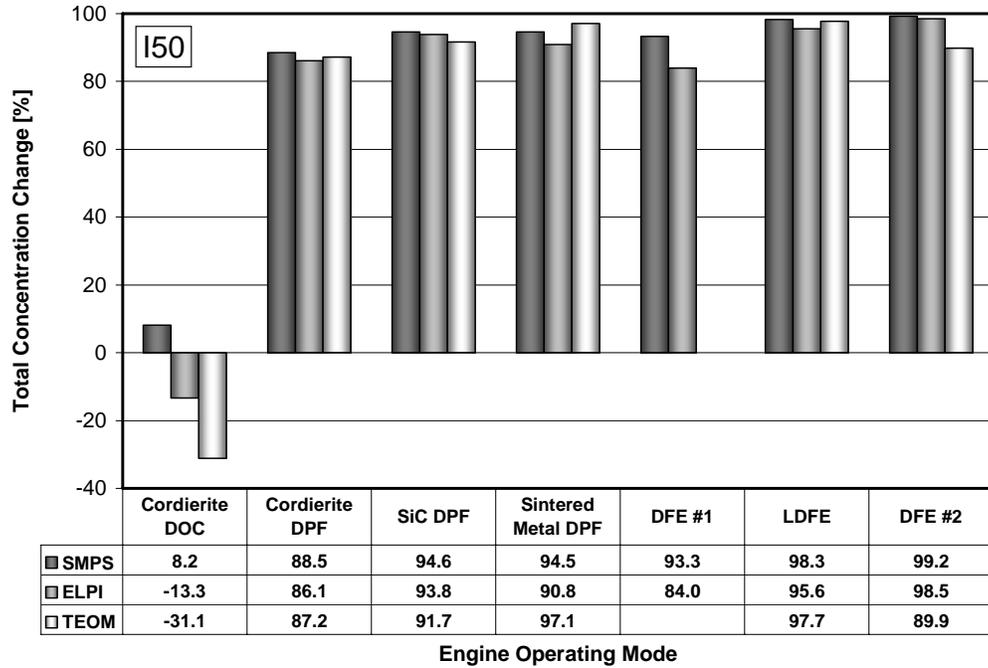


Figure 10. Percentage of total number and mass concentrations change for I50 test modes

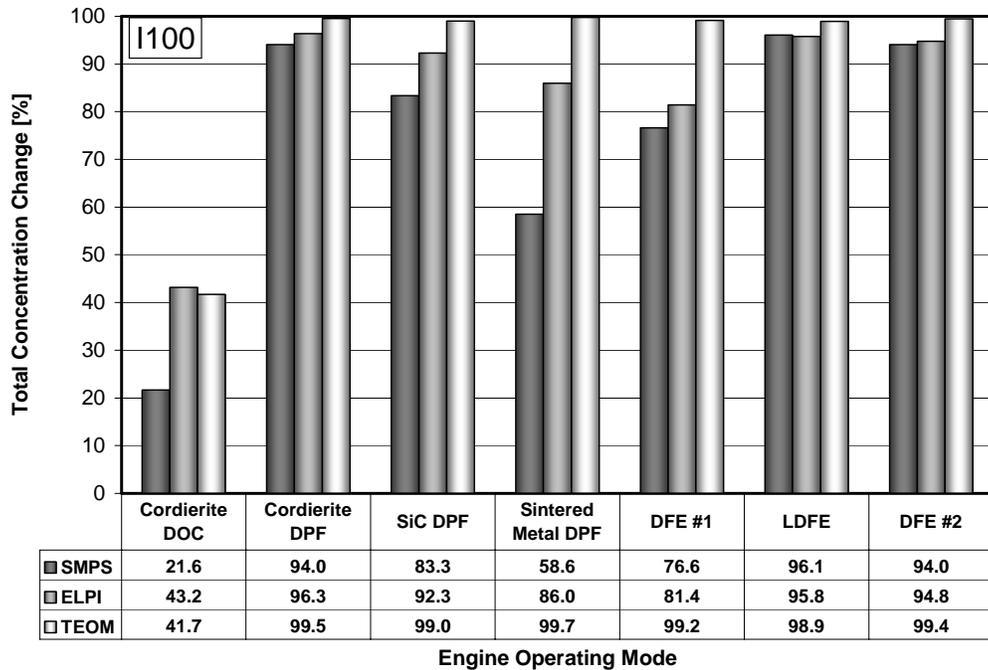


Figure 11. Percentage of total number and mass concentrations change for I100 test modes

The results indicate the following:

1. The effects of the DOC on number and mass concentrations were found to be engine operating mode dependent. The results indicate that the effects of DOC on number and mass concentrations were the most pronounced for high-load and high-temperature I100 engine operating modes.
2. The tested DPF and DFE systems in the majority of test cases caused a 10-fold reduction of the total mass concentrations measured by TEOM.
3. In the majority of the cases total mass reductions were accompanied with comparable reductions in total number concentrations. The exceptions were the cases (e.g. SiC DPF @ R50, SM DPF @ R100) when high concentrations of nucleation particles resulted in significantly lower reductions or even an increase in total particle number.

Effects on NO and NO₂ concentrations

The results of measurements of nitric oxide (NO) and nitrogen dioxide (NO₂) concentrations at the downstream station are used to calculate concentrations of total nitric oxides (NO_x = NO+ NO₂) and percentages of NO₂ in total NO_x. The NO_x concentrations are summarized in Figure 12, while the percentages of NO₂ in total NO_x are shown in Figure 13.

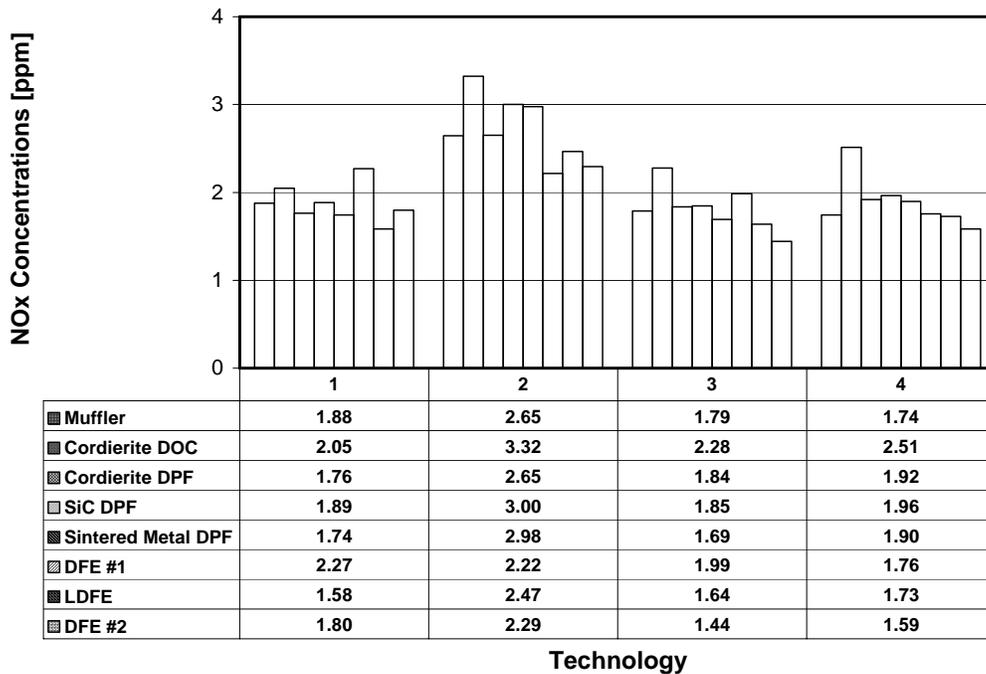


Figure 12. NO_x Concentrations [ppm]

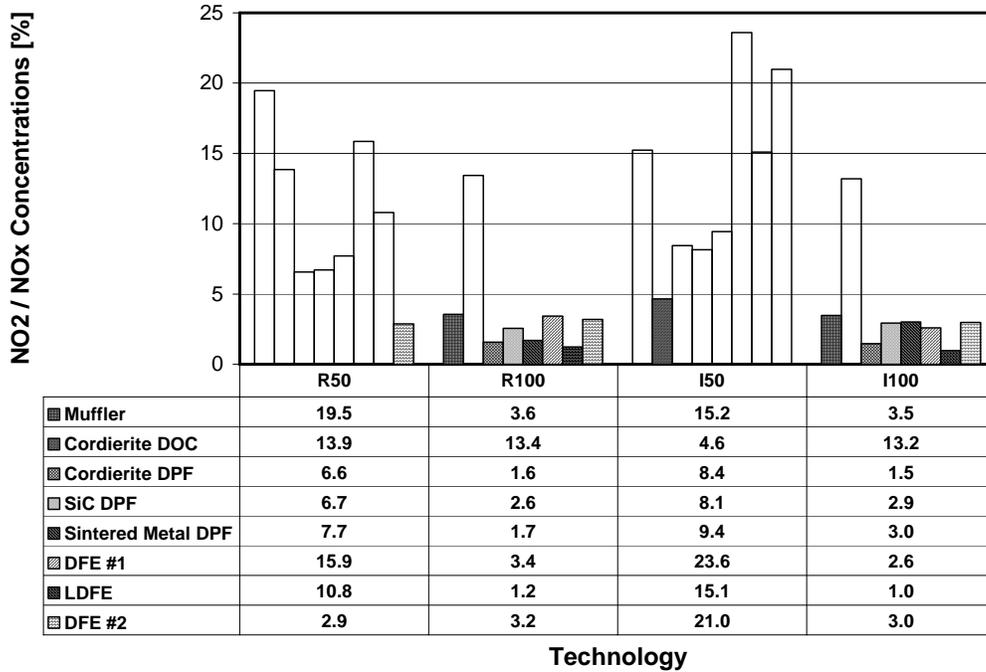


Figure 13. NO₂ percentages in total NO_x concentrations

The results showed the following:

1. The effects of the control technologies on NO_x concentrations are found to be minor. The average values and standard deviations for R50, R100, I50, and I100 modes are 1.87 ± 0.20 , 2.70 ± 0.36 , 1.81 ± 0.23 , and 1.89 ± 0.26 , respectively.
2. The percentages of NO₂ in total NO_x are found to be strongly dependent on engine operation mode / exhaust temperature.
3. The four fold increase in percentages of NO₂ in total NO_x over baseline case was observed for the DOC when the engine was operated at R100 and I100 (high exhaust temperature) modes. The same DOC did not promote oxidation of NO to NO₂ in the cases when engine was operated at the lower temperature R50 and I50 modes.
4. The substantial increase in NO₂ fraction in total NO_x was observed for DFE#1 and DFE#2 when the engine was operated at the I50 mode.

Conclusion

The series of the tests was conducted in the ventilated drift in the NIOSH Diesel Laboratory at the Lake Lynn Laboratory experimental mine with objective of studying the effects of selected aftertreatment technologies on the concentrations and size distribution of diesel aerosols and concentration of nitric oxides in underground mine air. The facility was developed to allow direct measurements in an underground mine occupational setting. The analysis was performed on the results of tests conducted at four steady state modes for the engine equipped with three different types of uncatalyzed DPFs, three different types of HT DFEs, a DOC, and a muffler. The results obtained with muffler were used to establish baseline case.

According to TEOM results, the tested DPF and DFE systems reduced the total aerosol mass concentrations by approximately 10 fold for majority of the test modes. That finding corroborated with findings from size distribution and number concentration measurements that showed that all tested DPF systems and DFE elements effectively removed accumulation mode aerosols ($_{50}d_{ae} > 30$ nm) from mine air. Substantial increase in peak number concentrations of nucleation mode ($_{50}d_{ae} > 30$ nm) aerosols was evident for SiC and SM DPF systems when engine was operated at R100 and I100 engine operating modes. The effects of DOC on number and mass concentrations were found to be engine operating mode i.e. exhaust temperature dependent. The 31 percent increase in aerosol mass was observed when DOC was tested at I50 mode. The effects of uncatalyzed DPFs on NO and NO₂ concentrations are found to be minor. The four fold increase in the NO₂ to NO_x fraction over the baseline case was observed for the DOC when the engine was operated at high-load engine operating modes.

The findings from this study should contribute to better understanding the potential for tested control technologies to reduce exposure of underground miners to nano and ultrafine aerosols without potential increase in exposures to nitrogen dioxide. In addition, better understanding of physical characteristics of diesel aerosols present in occupational setting should help better assessment of the health risks associated with exposure to nano and ultrafine diesel aerosols.

Disclaimer

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.

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