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DIESEL EXHAUST AEROSOL, REVIEW OF OCCUPATIONAL EXPOSURE

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ABSTRACT

The U.S. Bureau of Mines and others have conducted a number of occupational exposure surveys since the publication of the International Agency for Research on Cancer report of 1989, which labeled diesel exhaust as a probable human carcinogen. These surveys have assessed diesel exhaust exposure using measurement of diesel aerosol and/or specific polycyclic aromatic hydrocarbons as indicators of exposure. This paper reviews present diesel emission standards, available diesel exhaust aerosol measurement techniques, and the results of the occupational exposure surveys. In the surveys, diesel aerosol was emphasized because it is a major component of diesel exhaust, is suspected to contribute to the health hazard, and is readily measurable. Three primary aerosol measurement techniques were used: respirable combustible dust, size-selective sampling, and measurement of the elemental carbon fraction. Occupations surveyed included mine workers, railroad workers, forklift operators, fire fighters and truck drivers. The studies found mean diesel aerosol concentration levels in the range of 0.004 to 1.74 mg/m³. Highest aerosol exposures were in confined spaces such as mines where heavy diesel equipment is used. Polycyclic aromatic hydrocarbons typically are found at very low concentration levels and are not unique to diesel exhaust.

INTRODUCTION

Measurement of human exposure to toxic agents is the first step in determining the exposure-dose-response relationship. It is a fundamental step in risk assessment. Measuring exposure to diesel exhaust pollutants is particularly challenging due to the complexity and variability of exhaust components. This paper is a condensed version of a paper prepared for the Health Effects Institute's Special Report on Diesel Exhaust.⁽¹⁾ It reviews current occupational health standards for diesel emissions, available diesel exhaust aerosol measurement techniques, and the results of occupational exposure surveys completed after the publication of the International Agency for Research on Cancer (IARC) report of 1989.⁽²⁾ These surveys have assessed diesel exhaust exposure using diesel particulate matter (DPM) and/or measurements of specific polycyclic aromatic hydrocarbons (PAHs) as indicators of exposure. DPM is emphasized because it is a major component of diesel exhaust, is suspected to contribute to the health hazard, and is measurable. PAHs are closely associated with DPM and are suspected to have a role in cancer initiation.

Occupational Health Standards

Occupational exposure surveys of diesel exhaust frequently measure regulated pollutants, or pollutants that are suspected carcinogens, even if no permissible

exposure limits (PELs) have been established. In the United States, various organizations recommend a range of allowable values for diesel exhaust gaseous constituents, including carbon monoxide (CO), carbon dioxide (CO₂), sulfur dioxide (SO₂), nitrogen dioxide (NO₂), nitric oxide (NO), and formaldehyde (HCHO). Table I summarizes these recommended levels, showing 8-hour or 10-hour time-weighted-average values where available; where these are not available, 15-minute short-term exposure values are included. The Mine Safety and Health Administration (MSHA) has proposed revised air quality regulations, but these are not shown.⁽³⁾

Table I: Range* of Allowable Gaseous Exposure Limits for 8-hr-Time-Weighted-Average Occupational Exposures[†].

Pollutant	Range, ppm
CH ₄ O ^a	0.016-2.0
CO	25-50
CO ₂	5,000-10,000
NO	25
NO ₂ ^d	1.0-5.0
SO ₂	2.0-5.0

*ACGIH, MSHA, NIOSH, OSHA

[†]NIOSH has a 10-hr-time-weighted average value

^aSuspect carcinogen. MSHA has only a 15-min short-term value

^dNIOSH and OSHA have 15-min short-term values

There is no specific U.S. permissible exposure limit (PEL) for DPM at this time. Diesel aerosol is of respirable size and thus is limited under a variety of PELs for respirable dust, including MSHA's 2.0 mg/m³ respirable coal mine dust standard. MSHA has announced that it will consider regulating DPM.⁽⁴⁾ Recently, the American Conference of Governmental Industrial Hygienists (ACGIH) added diesel exhaust to the list of Notice of Intended Changes for 1995-1996 with a recommended threshold limit value (TLV) of 0.15 mg/m³ and a designation of suspected human carcinogen.⁽⁵⁾

1. Respirable Combustible Dust

Respirable combustible dust (RCD) is used to estimate DPM concentrations in Canadian non-coal mines. This is determined from the amount of combustible dust in a respirable dust sample by determining the mass that is removed from the sample by combustion at 500 °C.^(6,7) An estimate of the DPM concentration is made by multiplying the respirable combustible dust measurement by an empirical correction factor of 0.67. This adjusts for the contribution of unburnt fuel, evaporated lube oil, and other carbonaceous material to the DPM estimate. For aerosol samples collected in a coal mine or other environments where nondiesel carbonaceous aerosol is present, respirable combustible dust analysis is not appropriate to estimate DPM levels.

Based on RCD measurements, British Columbia has established a respirable combustible dust standard of 1.5 mg/m^3 for underground non-coal mines.⁽⁸⁾ The Canada Centre for Mineral and Energy Technology recommends that this standard be reduced eventually to 0.75 mg/m^3 .⁽⁹⁾

In the Federal Republic of Germany, DPM is defined by the coulometric determination of total carbon content in fine dust particulate.⁽¹⁰⁾ Based on this analytical procedure, the following technical exposure limits were established: 0.6 mg/m^3 for DPM in underground non-coal mines and construction sites; and 0.2 mg/m^3 for other occupational environments. Coal mines are not regulated. The technical exposure limit of a hazardous material is the minimum concentration possible with current technology and serves as a guidance mechanism for implementing necessary protective measures and monitoring policies in the workplace.⁽¹¹⁾ As with RCD, this method of measurement is also not appropriate for coal mines or other areas where substantial amounts of carbonaceous

phenanthrene, acridine, chrysene, and pyrene. No PELs are established for other gas-phase or particle-bound PAHs. The ACGIH designates diesel exhaust components benz[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, and chrysene as "suspected human carcinogens"; but recommends no TLVs. The benzene-extractable portion of coal tar pitch volatiles is designated as a "confirmed human carcinogen" by the ACGIH, with a TLV of 0.2 mg/m^3 .⁽¹²⁾

Diesel Exhaust Aerosol Measurement

DPM, depicted in Figure 1, is small in size and is composed of organic and elemental carbon, adsorbed and condensed hydrocarbons, and sulfate. The proportion of organic to inorganic carbon varies depending upon a number of factors, which include fuel, engine type, duty cycle, engine maintenance, operator habits, use of emission control devices, and lube oil consumption. In general, nonextractable elemental carbon accounts for a greater fraction of DPM mass than extractable organics.⁽¹⁴⁾

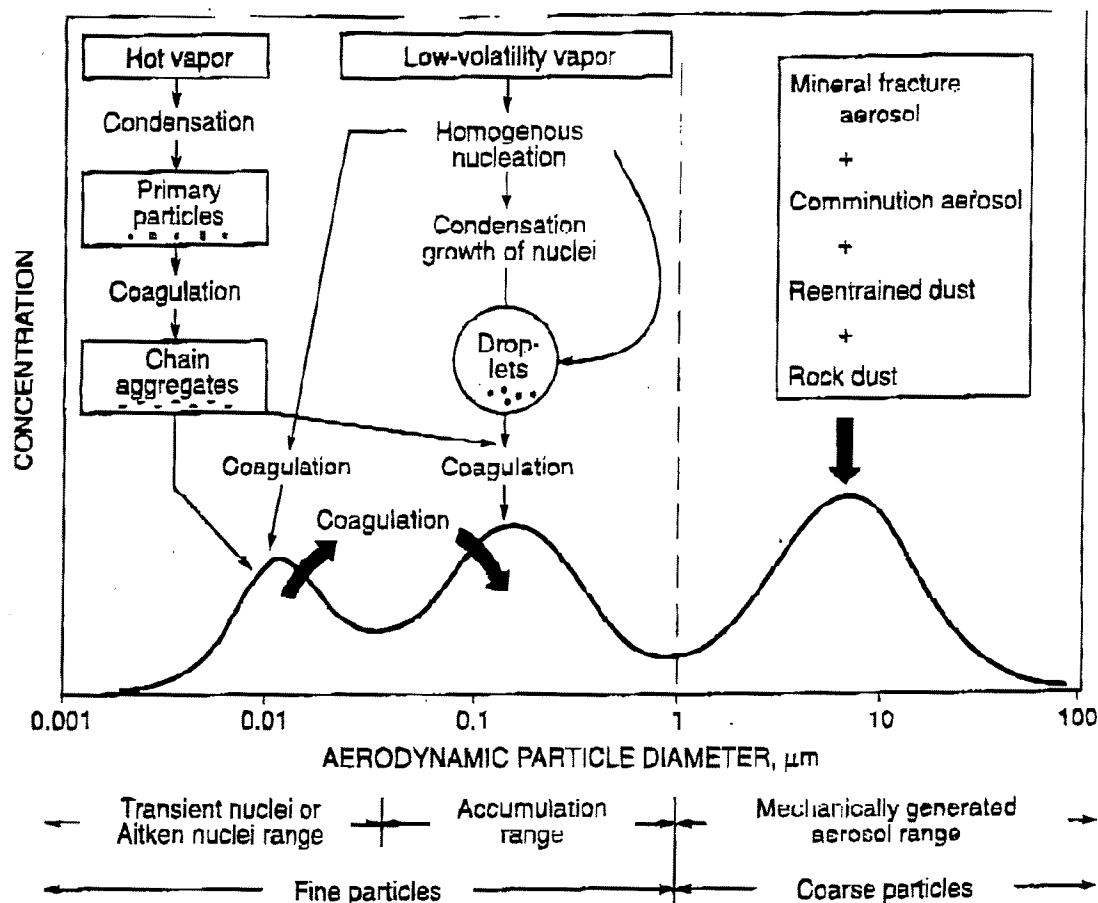


Figure 1. Trimodal aerosol size distribution arising from different mechanisms of aerosol generation.

Of the diesel associated PAHs, only chrysene (0.2 mg/m^3) and those connected with coal tar pitch volatiles, 0.2 mg/m^3 as benzene solubles, have Occupational Safety and Health Administration (OSHA) PELs.⁽¹²⁾ The OSHA PEL for coal tar pitch volatiles specifically includes anthracene, benzo[a]pyrene,

In addition to RCD measurements, two other techniques have been used in the subject surveys to measure exposure to diesel aerosol in the workplace. These are size-selective sampling with gravimetric analysis and elemental carbon analysis.

2. Size-selective Sampling

Figure 2 depicts the trimodal size distribution that arises from different mechanisms of aerosol generation.⁽¹⁵⁾ Primary combustion aerosols, including diesel exhaust aerosol, are formed as very small particles in the 0.001 to 0.08 μm range, but physical mechanisms such as condensation and coagulation quickly transfer the aerosol mass from the nuclei mode to the accumulation mode. These processes result in an approximately 0.2 μm mass median diameter for diesel aerosol, with 90% of the particles less than 1.0 μm in size. Mechanically generated aerosols, on the other hand, typically contain particles greater than a micron in diameter, with only a small portion of the mass under a micron in size.

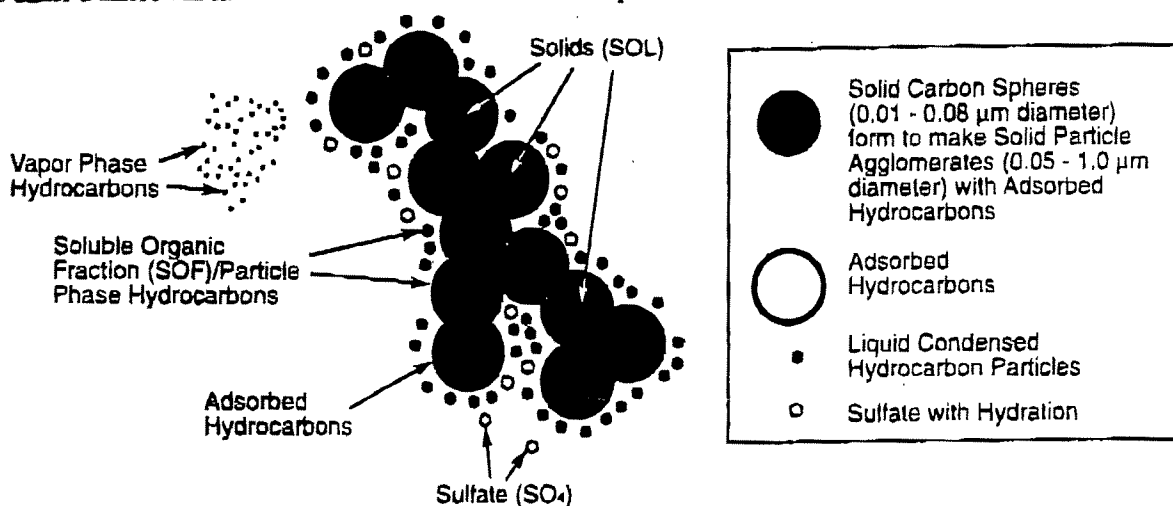


Figure 2. Schematic drawing of diesel exhaust aerosol and associated gas- and condensed-phase compounds. (Adapted with permission from SAE Paper No. 940233, 1994, Society of Automotive Engineers, Inc.)

The difference in the aerodynamic diameter particle size between combustion and mechanically generated aerosols can be used to separate diesel aerosol from noncombustion aerosols in the collecting process. This is done using inertial impaction, which removes large nondiesel particles and a small percentage of large diesel particles. The submicrometer aerosol, predominantly diesel in origin, is collected on a filter downstream of the impaction substrate. Gravimetric analysis is used to determine the mass concentration in each of these size fractions. The respirable dust mass concentration can be calculated from the concentrations of the two measured fractions.

Size-selective sampling has been used extensively in mining to evaluate the performance of emission control devices and to determine the concentrations of respirable dust and DPM in the mine atmosphere.⁽¹⁶⁻²¹⁾ One such sampler, a personal diesel exhaust aerosol sampler (PDEAS), pictured in Figure 3, is based upon the principles of size-selective sampling and has been used extensively by the Bureau.⁽²²⁾ The sampler operates at a flow rate of 2 L/min, which is compatible with commercial personal sampler pumps. The final sample

contains most of the DPM present in the mine air plus a small amount of mineral dust contamination, usually less than 10%.

This technique, coupled with gravimetric analysis, has limitations. In environments where submicrometer aerosol sources are well-defined and have relatively high concentration, this method is effective. If a sample flow rate of 2 L/min is used and gravimetric analysis is to within 0.1 mg, the aerosol concentration for the fraction of aerosol less than 0.8 μm should have a theoretical limit of detection of 0.3 $\text{mg}/\text{m}^3 \pm 50\%$ with a confidence level of 95%.⁽²¹⁾ This lower limit of detection is a worst-case estimate based on MSHA's current gravimetric analysis practice, mine aerosol interferences, and tolerances in

sampler manufacture. With gravimetric analysis to within 0.005 mg, the lower limit of detection would be 0.2 mg/m^3 . Measurements have shown that the PDEAS is capable of a precision of 0.015 mg/m^3 . When other forms of submicrometer aerosol are present or concentrations are low, other analysis methods with greater specificity and sensitivity are required to quantify the diesel aerosol fraction.

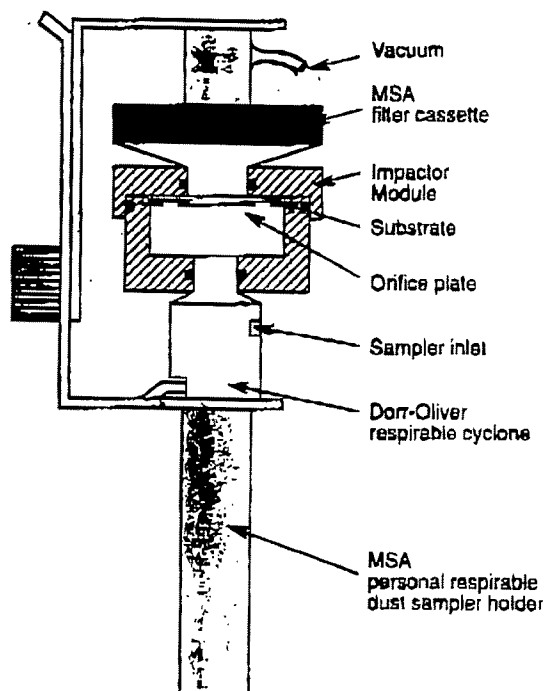


Figure 3. Size-selective exhaust aerosol sampler developed by the U.S. Bureau of Mines

3. Elemental Carbon Analysis

Size-selective sampling can collect a sample of submicron particulate matter that can be analyzed gravimetrically and by other analytical methods. These methods are frequently more specific and sensitive than the gravimetric method. Recent research has focused on analyzing the submicron or respirable fraction for elemental carbon. Elemental carbon accounts for a significant fraction of DPM emissions, acts as a carrier of suspected mutagens and carcinogens, and is readily detectable by thermal-optical analysis. The association between particle exposure and health effects, discussed elsewhere, further strengthens the use of elemental carbon as a surrogate for DPM exposure. Elemental carbon has an analytical definition which is operationally defined by the method of analysis.⁽²³⁾

It has been claimed that elemental carbon is the most reliable overall measure of exposure to diesel exhaust because selecting an extractable organic compound or class of compounds as a reliable surrogate of exposure is difficult.⁽²⁴⁾ The soluble organic fraction (SOF) associated with diesel exhaust aerosol is highly variable in composition, is chemically complex, and uncertainty exists about the compounds responsible for mutagenic and carcinogenic activity. Also, low concentrations and the presence of interfering chemical compounds make analysis difficult. These factors make SOF an unreliable measure of diesel exposure.

The use of a temperature-based thermal-optical method for speciation of organic (volatile and nonvolatile) and inorganic (carbonate) compounds, and elemental carbon is being investigated.⁽²⁵⁾ Aerosol samples are collected by inertial impaction to classify

particles by size. As noted previously, particles less than $1.0 \mu\text{m}$ in size are predominately from combustion sources. Thermal-optical analysis is used to detect and quantify different types of carbon. Volatilized carbon is oxidized to CO_2 and subsequently reduced to methane, which is quantified by flame-ionization detection. The second stage of analysis begins by reducing the combustion chamber temperature, introducing oxygen, and reheating to 750°C . During this stage, elemental carbon and char content are determined. The estimated limit of detection in the laboratory is $2 \mu\text{g}$ of either elemental or organic carbon per filter, which translates to a concentration of about $1 \mu\text{g}/\text{m}^3$, assuming 2 m^3 of sample air volume.⁽²⁶⁾

An experiment to investigate possible environmental tobacco smoke interference with elemental carbon measurements was conducted.⁽²⁷⁾ Tobacco aerosol was generated in a controlled environment by three men smoking a total of eight cigarettes per hour. Respirable particulate was on the order of $1,100 \mu\text{g}/\text{m}^3$. The total carbon from tobacco smoke was found to average 1.8% elemental carbon and 98.2% organic carbon.

As part of the same study, an experiment was conducted to investigate the precision and reproducibility of the thermal-optical method to determine elemental carbon in diesel exhaust. Diesel aerosol was generated under four load-and-speed conditions and diluted in a dilution tube at Ford Motor Company's Research and Engineering Facility in Dearborn, Michigan. Elemental carbon constituted an average of 62% of the total particulate mass on the filters and 64% of the total carbon loading. Total carbon constituted 91% of the total mass on the filters. The mean coefficient of variation of the method for elemental carbon determination was 7.3%.

As a consequence of these results, a proposal for the use of elemental carbon as a surrogate measure of diesel exhaust exposure determined with the thermal-optical method of analysis has been advanced.⁽²⁷⁾ The arguments for this are: (1) most diesel exhaust aerosol mutagenicity appears associated with the particulate phase, and lung tumor induction in laboratory rats is primarily associated with the particulate phase; (2) clearance in animals is adversely affected by particulate deposition, and "inert" substances deposited in the lung may also induce lung cancer; (3) submicrometer elemental carbon detection by thermal-optical analysis has sensitivity 100-fold greater than the gravimetric method, and the diesel particulate fraction is mostly carbon; and (4) nearly all the elemental carbon from vehicular traffic is attributable to diesel exhaust.

As pointed out earlier, the percentage of elemental carbon in total DPM fluctuates. Major factors which

contribute to this fluctuation include engine type, duty cycle, fuel, lube oil consumption, state of engine maintenance, and the presence or absence of an emission control device. The fluctuation in the ratio of elemental to organic carbon can cause an inaccurate estimate of the total DPM present. The estimate will improve if both organic and elemental carbon are measured and an adjustment is made for the presence of nondiesel carbon sources.

More detailed information on the analyses of carbonaceous compounds resulted from the Carbonaceous Species Methods Comparison Study, which was conducted at Citrus College in Glendora, California, between August 11 and 21, 1986.⁽²⁸⁾

The aerosol sampling techniques described above, and used in the occupational exposure surveys described below, collect all particulate matter meeting specific aerosol sampling penetration criteria. These are not predictive of deposited dose.⁽²⁹⁾ Dose is a function of the fraction of particulate matter that is deposited in the lung or other area and not necessarily a function of the particulate matter that penetrates the airways. Reliance on measurements of total DPM as the indicator of exposure may overestimate the actual deposited dose of DPM in lung tissue, because the mass median diameter of diesel aerosol is 0.2 μm , which is near the point of minimum deposition for the alveolar portion of the lung. Health effects assessments based solely upon measurements of total DPM exposure may lead to inaccurate conclusions. If detailed size distribution data are available, then a correction can be applied to total DPM measurements to estimate the deposited dose. Unfortunately, industrial hygiene surveys rarely collect these data because most often the objective is to determine compliance with an existing PEL or to determine the efficiency of a control strategy. Further details on size-selective sampling criteria for thoracic and respirable mass fractions are given by Rabbe.⁽³⁰⁾

Diesel Pollutant Exposure in the Workplace

IARC reviewed occupational and environmental exposures to pollutants in diesel exhaust.⁽²⁾ In general, the personal exposure pollutant concentrations that the IARC report summarized were well below current occupational health standards. Since the publication of the IARC report, several studies have been published on diesel exhaust exposures of coal and non-coal miners, railroad workers, forklift operators, fire fighters, and truck drivers. These studies are of interest because they report pollutant levels, attempt to account for background contaminants, and use new sampling and analytical techniques that are more specific for assessing exposure to diesel pollutants, especially DPM exposure. None of the studies provide information on the dose of DPM deposited in the lung. All the studies attempt to quantify either total DPM or total elemental carbon and other pollutants.

Occupational Exposures

1. Miners

Concentrations of RCD have been reported for 21 Canadian non-coal mines.⁽⁷⁾ A total of 223 personal and area samples were collected at these mines. Mean RCD concentrations ranged from 0.17 to 1.30 mg/m^3 with maximum concentrations ranging from 1.02 to 3.10 mg/m^3 . Estimates of DPM concentration were obtained by multiplying these values by 0.67, the correction factor used in Canada. The range of mean DPM exposure was 0.1 to 0.9 mg/m^3 , and the range of maximum concentrations was 0.7 to 2.1 mg/m^3 . These measurements suggest that average exposure to DPM in Canadian non-coal mines is less than the 1.5 mg/m^3 recommended level.

In the U.S., coal mine air quality data have been reported by the Bureau for five underground coal mines with diesel-powered haulage equipment.⁽³¹⁻³⁴⁾ Diesel coal haulage vehicles typically use Caterpillar or Motorenwerke Mannheim indirect injection engines in the 56- to 112-kW range (6- to 11-L displacements). The vehicles are equipped with water scrubbers to remove flames and sparks and to cool the exhaust.

In each mine, daily area samples were collected on a continuous miner section in the clean air intake, in the haulageway where diesel activity was taking place, on shuttle cars, and in the return airway where contaminated air exits the section. Both full- and partial-shift samples were collected using the PDEAS and the micro-orifice uniform-deposit impactor (MOUDI). Two of the mines were also monitored for the major gaseous pollutants found in diesel exhaust: CO, CO₂, NO, NO₂, and SO₂, either by collecting bag samples for subsequent gas analysis or by using Palmes dosimeters.

The PDEAS-determined mine-average DPM concentrations for all five mines are summarized in Table II. Section intake air concentrations were below 0.2 mg/m^3 . The mean concentration in the haulageway was 0.89 mg/m^3 , with a standard deviation of 0.44 mg/m^3 . DPM contributed 52 % of the respirable aerosol at this location. These results were very close to the mean DPM concentrations calculated from size distribution measurements obtained using the MOUDI; 0.95 mg/m^3 , with a standard deviation of 0.5 mg/m^3 . The relatively high standard deviations reflect the differences in aerosol concentrations between mines and, to a lesser extent, the day-to-day differences within the same mine. Concentrations of CO, CO₂, NO, NO₂, and SO₂ were all well below regulated levels.

Table II: Mean Concentrations of Diesel Exhaust Aerosol in Mines as Measured in PDEAS Samples.⁽³²⁾

Location	N	Concentration, mg/m ³		
		Mean	SD	Median
Haulage	42	0.89	0.44	0.75
Shuttle car	51	0.67	0.23	0.65
Return	100	1.43	0.97	1.06

N = Number of samples

SD = Standard deviation

Other investigators have used size-selective sampling methods to quantify submicrometer aerosol concentrations in diesel-equipped coal mines. Concentrations of aerosol of size less than 1 μm aerodynamic diameter were measured in two underground coal mines using diesel shuttle cars; samples were collected using the Anderson Model 298 cascade impactor.⁽¹⁶⁾ Mean submicrometer aerosol concentrations for the two mines ranged from 0.1 mg/m³ at the section intake to 0.8 mg/m³ at the continuous mining machine operator's position. Mean NO and NO₂ concentrations were also reported for the two mines, and the concentrations were well below regulated levels.

A single-jet impactor was tested by MSHA at five underground coal mines using diesel equipment.⁽³⁵⁾ Mine worker exposure to DPM ranged from 0.18 to 1.00 mg/m³, and area samples collected in haulage ways agreed within 0.12 mg/m³ of section worker exposure. At three mines, the single-jet impactor and PDEAS were used together at a sampling location. More than 60 paired data points were obtained. Respirable aerosol measurements agreed within 25 %, and DPM measurements agreed within 0.06 mg/m³.

During the Bureau's in-mine studies, samples collected in four of the mines were also analyzed for PAHs and mutagenic activity.⁽³⁶⁻³⁷⁾ High-volume samplers equipped with inertial impactors to collect size-differentiated particles were operated at a flow rate of 1.13 m³/min, with mean sample times ranging from 19 to 42 minutes. The diesel fraction was less than 1 μm in size. Samples were collected only during periods of mining activity and are not necessarily representative of personal exposure. Filter samples were kept cold until Soxhlet extracted with dichloromethane. The SOF was tested for Ames activity and the concentrations of fluoranthene, pyrene, and benzo[a]pyrene were determined using high performance liquid chromatography. Detailed chemical and mutagenic results for diesel-aerosol associated parameters are summarized in Table III. Because they are not shift averages, these values represent the highest potential DPM-related pollutant levels. Additional detailed data on PAH and mutagenicity levels in coal and non-coal mines is also available from evaluations of various types of emission control systems used in underground mines.⁽³⁸⁻⁴⁰⁾

Table III: Mean In-Mine Extractable Organics, Mutagenicity, and PAH Levels Associated With Diesel Exhaust Aerosol.^(36, 37)

Parameter		Mine			
		I	K	L	O
SOF	mg/m ³	0.40 (33) ^a	0.17 (12)	0.08 (24)	0.18 (20)
SOF	pct	24 (31)	19 (5.2)	5.7 (13)	13 (22)
Activity ^b	Rev/m ³	970 (60)	440 (24)	NT	690 (44)
Fluoranthene	ng/m ³	390 (38)	140 (16)	48 (30)	160 (16)
Pyrene	ng/m ³	270 (34)	70 (14)	32 (55)	180 (20)
Benzo[a]pyrene	ng/m ³	61 (39)	16 (6.7)	<0.046 ^c	18 (22)

^aMean concentration (coefficient of variation, percent)

^bAmes activity reported without S9 activation using strain TA98, Rev = revertants

^cAll values < minimum detectable levels

NT = Not tested due to insufficient extractable mass

SOF = Soluble organic fraction

PAH levels in Canadian salt and nickel mines were compared to levels found in the city of Sudbury.^(41, 42) Area samples were collected using high-volume samplers operated from 10 minutes to 24 hours. The samplers were not equipped with inertial impactors to selectively collect the submicron fraction. Filter deposits were extracted with benzene and methanol using a combination of sonication and Soxhlet extraction. The extract was purified and separated into individual PAHs using thin-layer chromatography; PAHs were then quantified using spectro-fluorometric analysis. The results reported in Table IV are not necessarily representative of exposure, nor are they specific for diesel exhaust. The results show that the total underground concentration of PAHs is higher than the comparable concentration in the city of Sudbury by a factor of five.

Two surveys were conducted to evaluate the effectiveness of high-temperature exhaust filtration units, propane fueled engines, and ceiling exhaust fans to reduce diesel pollutant concentrations. Only data from full-shift personal samples, collected on diesel forklift operators, are reported here. Data from Dock 1 represent forklifts equipped with and without filters, and data from Dock 2 represent forklifts without filters.

During each survey, NIOSH collected personal and area samples for submicrometer organic and elemental carbon, NO₂, CO, benzene solubles, 17 specific PAHs, Ames activity, and other pollutants. Of the pollutants measured during the surveys, only elemental carbon provided a clear basis for differentiation between the diesel- and propane-fueled

Table IV: PAH Concentrations Found in Canadian Diesel equipped Underground Mines and in the City of Sudbury.⁽⁴¹⁾

PAH	Mine mean, ng/m ³		City mean, ng/m ³
	Nickel	Salt	
Pyrene	80.2	256.0	14.6
Flouranthene	5.6	19.7	1.1
Benzo[a]anthracene	8.9	18.5	1.6
Benzo[e]pyrene	18.2	62.2	5.3
Perylene	0.5	0.3	0.1
Benzo[k]fluoranthene	2.6	5.4	0.6
Benzo[a]pyrene	1.9	1.2	0.3
Benzo[ghi]perylene	6.9	9.3	0.9
Dibenzo[def,mno]chrysene	0.5	0.6	0.1
Dibenzo[ah]anthracene	1.9	3.5	0.3
Naphtho[1234,def]chrysene	4.6	8.4	1.1
Benzo[ghi]perylene	0.9	1.9	0.1
Total PAHs	132.7	387.0	26.1

PAH = Polynuclear aromatic hydrocarbon
Concentrations rounded to 0.1 ng/m³

2. Forklift, Truck, and Fire Engine Operators

The National Institute for Occupational Safety and Health (NIOSH) evaluated the effectiveness of several techniques for controlling exposure of dock workers to forklift diesel emissions.⁽⁴³⁾ During the course of the investigation, NIOSH collected personal and area samples for diesel pollutants, including submicrometer elemental carbon. NIOSH used thermal-optical analysis to determine the elemental and organic carbon fractions of samples collected using inertial impaction as previously discussed.

engines. The filters reduced elemental carbon by 92 % at Dock 1 but had little effect on organic carbon, as shown in Table V. Use of the filters resulted in geometric mean concentrations not significantly different from background elemental carbon concentrations (1.6 µg/m³) measured one mile from the dock.

Table V: Personal Elemental and Organic Carbon Concentrations from a NIOSH Survey of Dockworkers Using Diesel Forklift Trucks.⁽⁴³⁾

Dock	Form of Carbon	Geometric Mean	95 pct Confidence Interval
Unfiltered exhaust, $\mu\text{g}/\text{m}^3$			
1	elemental	23.2	18.6 - 29.1
1	organic	49.4	37.9 - 64.3
2	elemental	54.6	46.1 - 64.7
2	organic	138	95.6 - 200
Filtered exhaust, $\mu\text{g}/\text{m}^3$			
1	elemental	1.9 ^a	1.5 - 2.3
1	organic	47.9	36.8 - 62.3

^a92 percent reduction

GM = Geometric mean concentration

CI = Confidence interval

NIOSH concluded that the presence of environmental tobacco smoke substantially influenced the organic carbon concentration. Measurements for other pollutants were frequently below the level of detection and did not provide any evidence to differentiate between the propane- or diesel-fueled engines, or to conclude that any one motor type was more or less hazardous in terms of health effects.

NIOSH conducted a health hazard evaluation of diesel exhaust exposure inside three fire stations.⁽⁴⁴⁾ Diesel exhaust emissions contaminated fire station crew living quarters when equipment was operated inside the fire stations. Personal and area samples were collected only while the fire fighters were within the fire stations. Personal and area samples were collected to determine elemental carbon concentrations and general area samples were collected for other diesel pollutants including CO and benzene solubles.

The arithmetic mean elemental carbon concentration for 18 personal exposure samples collected inside the three fire stations was $30 \mu\text{g}/\text{m}^3$. This mean was corrected for the average ambient elemental carbon concentration of $10 \mu\text{g}/\text{m}^3$ measured outside the fire stations. The corrected range of elemental carbon concentrations was 6 to $70 \mu\text{g}/\text{m}^3$. In general, area samples evidenced higher concentrations. These ranged from less than background levels to over $680 \mu\text{g}/\text{m}^3$ in the apparatus bays. Area samples for CO found concentrations less than applicable standards. The benzene soluble data are difficult to interpret because of the possible presence of non-diesel sources of organic carbonaceous aerosols, such as cigarette smoke.

3. Truck Drivers

An industrial hygiene survey of the trucking industry found that gas-phase surrogates of diesel exhaust exposure; such as CO, CO₂, SO₂, NO₂, sulfuric acid (H₂SO₄), NO_x, HCHO, and volatile hydrocarbons; were all below established occupational exposure criteria.⁽⁴⁵⁾ Levels of elemental carbon were found to constitute approximately 60 % of the carbonaceous particulate fraction with concentrations ranging between 33 and $94 \mu\text{g}/\text{m}^3$.

As part of a case-control mortality study of trucking industry workers, exposures to DPM were measured among four exposed job groups: highway drivers, local drivers, mechanics, and dock workers using forklift trucks.⁽²⁷⁾ The main purpose of the study was to estimate occupational exposures using submicrometer elemental carbon as a surrogate measure of DPM. During the course of the field study, background aerosol samples were also collected in a residential area and near the highway and analyzed for submicrometer elemental carbon. Background levels ranged from 1 to $3 \mu\text{g}/\text{m}^3$ and included elemental carbon emitted from all sources.

Results of the field study are summarized in Table VI. Highest exposures were for dock workers and drivers who were operating diesel vehicles, and the mechanics who were exposed to diesel exhaust in the maintenance area. It is interesting to note that drivers of diesel trucks are exposed to levels of elemental carbon that are similar to background levels, suggesting that drivers' exposure comes from the highway environment rather than from their vehicles'

Table VI: Elemental Carbon Concentrations from a Survey of Truckers.⁽²⁷⁾

Job	Elemental carbon, $\mu\text{g}/\text{m}^3$	
	GM	95 pct CI
Dockworker	27.2	23.8 - 31.0
Mechanic	12.1	10.0 - 14.7
Local Driver	4.0	3.2 - 5.0
Road Drivers	3.8	3.1 - 4.7
Highway-R	2.5	1.7 - 3.6
Residential-B	1.1	0.7 - 1.5

B = Background

GM = Geometric mean

CI = Confidence interval

exhaust. This finding has interesting implications, should the epidemiological study show higher relative risks for exposed teamsters compared with nonexposed teamsters. The authors also provided add data on exposure broken down by cold and hot weather.

4. Railroad Workers

As part of a series of epidemiological studies, railroad workers' exposure to diesel exhaust was examined.^(46, 47) Respirable particulate matter, adjusted to remove the contribution of cigarette smoke, was used as a surrogate measure of DPM. Respirable dust samples were collected at the facilities of four small railroads in the northern United States. Filters were preextracted with dichloromethane and preweighed. After sampling, filters were reweighed, pooled, and extracted to measure the contribution of cigarette smoke as determined by nicotine content. Based on these findings, an adjusted respirable particulate exposure was determined and used as a measure of DPM. Table VII summarizes the personal exposure results. Although the adjusted respirable particulate concentrations in Table 7

adjust for the presence of tobacco smoke, they do not take into account the possible presence of other respirable dusts such as sand, dirt, and fibers.

Another part of this study used high volume samplers at fixed locations within four locomotive repair shops to determine the concentrations of total dust, respirable dust, soluble organics, and vapor phase components.⁽⁴⁸⁾ The geometric mean respirable dust concentration was $96 \mu\text{g}/\text{m}^3$ with a geometric standard deviation of 2.14 $\mu\text{g}/\text{m}^3$ for 23 samples. The geometric mean total dust concentration was $164 \mu\text{g}/\text{m}^3$ with a geometric standard deviation of 1.86 $\mu\text{g}/\text{m}^3$ for 26 samples. The geometric mean for vapor phase components was $432 \mu\text{g}/\text{m}^3$ for nine samples. Approximately 30 to 40 pct of the particle mass was extractable in dichloromethane and the extracts were mutagenic, mostly in the polar fraction. The mutagenic activity was about one order of magnitude greater than the mutagenic activity in urban air. None of the vapor phase material contained mutagenic activity. This study further characterized the air quality in railroad shops, but provides no direct information on DPM exposure. Other sources of

Table VII: Personal Exposures of Railroad Employees to Respirable Particulate Matter Other Than Cigarette Smoke.⁽⁴⁶⁾

Job group	Respirable particles, $\mu\text{g}/\text{m}^3$		Exposure group ^a
	Geometric Mean	Geometric SD	
Clerks	17	2.2	U
Signal maintainers	49	1.9	L
Engineer/firer			
Freight	73	2.3	M
Yard	49	2.4	M
Passenger	39	2.2	M
Braker/conductor			
Freight conductor	52	2.2	M
Freight braker	88	1.8	M
Passenger	85	2.1	M
Yard	92	2.0	M
Hostler	191	1.9	M
Electrician	134	2.2	H
Mechanist	114	2.3	H
Supervisor, other	130	1.9	H

^aA priori exposure category. U = unexposed, M = medium, H = high

GM = Geometric mean

GSD = Geometric standard deviation

pollution may have contributed to the measured values. Like the previous studies, this study did not determine the concentration of elemental carbon, the submicron portion of the respirable particulate matter, or the respirable combustible dust fraction, which are more direct measures of DPM exposure.

SUMMARY

Diesel exhaust is chemically complex, containing literally hundreds of different substances. This complexity makes it impossible to monitor all exhaust pollutants to determine exposure. Exposure assessments generally monitor regulated pollutants or select a surrogate measure(s) of exposure. The surrogate measure should be representative of diesel exhaust as a whole, have some relationship to adverse health effects, and, if possible, be unique to diesel exhaust. Unfortunately, many of the compounds found in diesel exhaust are also emitted from other combustion sources and are thus not unique to diesel exhaust.

A limited number of exhaust constituents have PELs. These include the gases CO, CO₂, NO, NO₂, SO₂, HCHO, and some PAHs. Canada has recommended a limit for respirable combustible dust of 1.5 mg/m³ in non-coal mines. Germany has established technical exposure limits of 0.6 mg/m³ for the total carbon content in fine dust particulate in underground non-coal mines and construction sites; and a 0.2 mg/m³ limit for other occupational environments. The U.S. has no PEL for DPM at this time.

DPM is formed during combustion and as a result the aerosol is small in size with a mass median aerodynamic diameter of 0.2 μ m. DPM is composed of organic and elemental carbon, adsorbed and condensed hydrocarbons, and sulfate. The proportion of organic to inorganic carbon varies, depending upon a number of factors: fuel, engine type, duty cycle, engine maintenance, operator habits, use of emission control devices, and lube oil consumption. In general, nonextractable elemental carbon accounts for a greater fraction of DPM mass than extractable organics.

The aerodynamic diameter particle size difference between combustion and mechanically generated aerosols is used to separate diesel aerosol from non-combustion aerosols by inertial impaction. Submicrometer DPM is collected on a filter downstream of the impaction substrate. Gravimetric analysis determines the mass fraction in each size range. Also, the filter containing the submicrometer material can be analyzed by other methods to increase the sensitivity and specificity for DPM. This is an advantage over other aerosol measurement techniques, which either do not collect a sample or destroy the sample during analyses. However, size-selective sampling collects all DPM meeting specific aerosol sampling criteria but may not be representative of the amount of DPM deposited

in human lung airways. Hence, reliance on measurements of total DPM as the indicator of exposure may overestimate the actual deposited dose of DPM in lung tissue and lead to inaccurate health effects assessments.

Recent occupational exposure studies have measured DPM concentrations in the workplace. Methods most frequently used to assess DPM exposure include respirable dust sampling followed by gravimetric analysis of the combustible and noncombustible fractions, size selective sampling for particulate matter less than 0.8 μ m in size followed by gravimetric analysis, and size-selective sampling followed by elemental carbon analysis. These studies have found mean DPM concentration levels to range from 0.004 to 1.74 mg/m³. Occupational exposures are highest in confined spaces such as mines where heavy diesel equipment is used and fresh air is supplied by forced ventilation. In general, workplace exposure to DPM is several orders of magnitude higher than the outdoor ambient exposures reported in other sections of this report.

At the present time, the best surrogate measure of DPM in the occupational environment appears to be elemental carbon. Elemental carbon generally accounts for about 40 to 60 % of DPM mass, and is detectable at relatively low levels using size-selective sampling and thermal-optical analysis. Elemental carbon is detectable apart from the organic carbon found in cigarette smoke and diesel exhaust. Additionally, data summarized in other sections of this report suggest that carbon particles can cause cancer in laboratory rats. As pointed out earlier, the percentage of elemental carbon in total DPM fluctuates. The fluctuation in the ratio of elemental to organic carbon can cause an inaccurate estimate of the total DPM present. The estimate will improve if both organic and elemental carbon are measured and an adjustment is made for the presence of nondiesel carbon sources. Consideration should also be given to the measurement of a few specific PAHs which are known carcinogens. Unfortunately, these compounds are typically found at very low levels and are not unique to diesel exhaust.

REFERENCES

1. Watts, W.F.: Assessment of Occupational Exposure to Diesel Emissions. In: Diesel Exhaust: A Critical Analysis of Emissions, Exposure, and Health Effects, pp 109-123. Health Effects Institute, Cambridge, MA (1995).
2. IARC Monographs on the Evaluation of Carcinogenic Risks To Humans - Diesel and Gasoline Engine Exhausts and Some Nitroarenes, vol. 46, 458 pp. International Agency for Research on Cancer, Lyon, France (1989).

3. Mine Safety and Health Administration, U.S. Department of Labor: Air Quality, Chemical Substances, and Respiratory Protection Standards; Proposed Rule, 30 CFR Part 56 et al. Fed. Reg. 54 (166):35769-35852 (Aug. 29, 1989).
4. Mine Safety and Health Administration, U.S. Department of Labor: Permissible Exposure Limit for Diesel Particulate. Fed. Reg. 57(3):500-503 (Jan. 6, 1992).
5. American Conference of Governmental Industrial Hygienists: Annual Reports of the Committees on Threshold Limit Values and Biological Exposure Indices. Notice of Intended Changes for 1995-1996. ACGIH Today 3(2):1 (1995).
6. Gangal, M.; Ebersole, J.; Vallieres, J.; et al.: Laboratory Study of Current (1990/91) SOOT/RCD Sampling Methodology for the Mine Environment. Mining Research Laboratory, Canada Centre for Mineral and Energy Technology (CANMET), Ottawa, Canada (1990).
7. Gangal, M.K.; Dainty E.D.: Ambient Measurement of Diesel Particulate Matter and Respirable Combustible Dust in Canadian Mines. In: Proceedings of the 6th US Mine Ventilation Symposium, Salt Lake City, UT, 1993, pp. 83-89. R. Bhaskar, Ed., Society for Mining, Metallurgy, and Exploration, Inc. (SME), Littleton, CO (1993).
8. Ministry of Energy, Mines and Petroleum Resources, Resource Management Branch: Health, Safety and Reclamation Code for Mines in British Columbia: Part 6, Mine Design and Procedures, Victoria, British Columbia, Canada, pg. 6-21 (1992).
9. I.W. French and Associates, Ltd.: Addendum to Health Implications of Exposure of Underground Mine Workers to Diesel Exhaust Emissions. Energy, Mines & Resources, Canada, Contract No. 09SQ.23440-7-9042, 152 pp (1990).
10. Bauer, H.; Dahmann, D.; Fricke, H.: Coulometric Determination of Diesel-engine-emissions in Non-coal Mines. Staub-Reinhaltung der Luft, 51:319-325 (1991).
11. Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area: MAK-and BAT-Values 1993: Maximum Concentrations at the Workplace and Biological Tolerance Values for Working Materials, Report No. 29, pp. 98-102, VCH Verlagsgesellschaft, Weinheim (Federal Republic of Germany) (1993).
12. American Conference of Governmental Industrial Hygienists: Guide to Occupational Exposure Values-1992. Amer. Conf. Gov. Ind. Hyg. Cincinnati, OH, 137 pp (1992).
13. American Conference of Governmental Industrial Hygienists: 1994-1995 Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices. Amer. Conf. Gov. Ind. Hyg. Cincinnati, OH, 119 pp (1994).
14. Perez, J.M.; Williams, R.L.: A Study of Particulate Extracts from 1980s Heavy Duty Diesel Soc. Auto. Eng. Tech. Paper 892491, 11 pp (1989).
15. Cantrell, B.K.; Rubow, K.L.: Measurement of Diesel Exhaust Aerosol in Underground Coal Mines. Bureau of Mines IC 9324, pp. 11-17 (1992).
16. McCawley, M.; Cocalis, J.: Diesel Particulate Measurement Techniques for Use With Ventilation Control Strategies in Underground Coal Mines. Ann. Amer. Conf. Gov. Ind. Hyg., v. 14:271-279 (1986).
17. Marple, V.A.; Kittelson, D.B.; Rubow, K.L.; et al.: Methods for the Selective Sampling of Diesel Particulates in Mine Dust Aerosols. Bureau of Mines OFR 44-87, NITS PB 88-130810, 94 pp (1986).
18. Rubow, K.L.; Cantrell, B.K.; Marple, V.A.: Measurement of Coal Dust and Diesel Exhaust Aerosols in Underground Mines. In: Proceedings of the 7th International Conference on the Pneumoconiosis, Pittsburgh, PA, August 23-26, 1988. NIOSH Publication No. 90-108, pp. 645-650. U.S. Department of Health and Human Services, Atlanta, GA (1990).
19. Cantrell, B.K.; Zeller, H.W.; Williams, K.L.; et al.: Monitoring and Measurement of In-Mine Aerosol: Diesel Emissions, Bureau of Mines IC 9141, pp 41-51 (1987).
20. Cantrell, B.K.; Rubow, K.L.: Mineral Dust and Diesel Aerosol Measurements in Underground Metal and Nonmetal Mines. In: Proceedings of the 7th International Conference on the Pneumoconiosis. Pittsburgh, PA, August 23-26, 1988. NIOSH Publication No. 90-108, pp. 651-655. U.S. Department of Health and Human Services, Atlanta, GA (1990).
21. Cantrell, B.K.; Rubow, K.L.: Development of Personal Diesel Aerosol Sampler Design and Performance Criteria. SME Preprint No. 90-74, 5 pp. Society for Mining, Metallurgy, and Exploration, Inc. (SME), Littleton, CO (1990).
22. Rubow, K.L.; Marple, V.A.; Tao, Y.; et al.: Design and Evaluation of a Personal Diesel Aerosol Sampler for Underground Coal Mines. SME Preprint No. 90-132, 5 pp. Society for Mining, Metallurgy, and Exploration, Inc. (SME), Littleton, CO (1990).
23. Cadle, S.H.; Groblicki, P.J.: An Evaluation of Methods for Determination of Organic and Elemental Carbon in Particulate Samples. In: Particulate Carbon: Atmospheric Life, pp. 89-109. GT Wolff and RL Klimisch, Ed's, Plenum Press, NY, NY (1982).
24. Fowler, D.P.: Industrial Hygiene/Environmental Sampling Program to Develop Qualitative and Quantitative Data on Diesel Exhaust Emission Exposure. Final Report on CRC-APRAC Project No. CAPM-24-78. SRI International, Menlo Park, CA (1985).
25. Birch, M.E.; Cary, R.A.: An Elemental Carbon Based Method for Monitoring Occupational Exposures to Particulate Diesel Exhaust. Aerosol Sci. and Tech., In-Press (1996).

26. Johnson, R.L.; Shaw, J.J.; Cary, R.A.; et al.: An Automated Thermal-Optical Method for the Analysis of Carbonaceous Aerosols, Atmospheric Aerosol: Source/Air Quality Relationships. In: Amer. Chem. Soc. Symp. Ser. No. 167, pp. 223-233. Macias ES, Hopke PK eds., Amer. Chem. Soc., Washington, DC (1981).
27. Zaebs, D.D.; Clapp, D.E.; Bader, L.M.; et al.: Quantitative Determination of Trucking Industry Workers' Exposure to Diesel Exhaust Particles. Am. Ind. Hyg. Assoc. J., 52(12):529-541 (1991).
28. Hering, S.V.; Appel, B.R.; Cheng, W.; et al.: Comparison of Sampling Methods for Carbonaceous Aerosols in Ambient Air. Aerosol Sci. Tech. 12(1):200-213 (1990).
29. McCawley, M.A.: Should Dust Samples Mimic Human Lung Deposition? Counterpoint. Appl. Occup. Environ. Hyg. 5(12):829-835 (1990).
30. Raabe, O.G.: Size-Selective Sampling Criteria for Thoracic and Respirable Mass Fractions. Ann. Am. Conf. Ind. Hyg. 11:53-65 (1984).
31. Watts, W.F.; Baumgard, K.J.; Cantrell, B.K.; et al.: Control of Diesel Particulate Matter in Underground Coal Mines. Bureau of Mines RI 9276, 11 pp (1989).
32. Watts, W.F.; Cantrell, B.K.; Ambs, J.L.; et al.: Diesel Exhaust Aerosol Levels in Underground Coal Mines. Bureau of Mines IC 9324, pp. 31-39 (1992).
33. Cantrell, B.K.; Rubow, K.L.; Watts, W.F.; et al.: Pollutant Levels in Underground Mines Using Diesel Equipment. Soc. Min. Eng. Trans. 290:1901-1907 (1992).
34. Cantrell, B.K.; Rubow, K.L.; Watts, W.F.; et al.: Pollutant Levels in Underground Mines Using Diesel Equipment. In: Proceedings of the 6th US Mine Ventilation Symposium, Salt Lake City, 1993, pp. 59-64. R. Bhaskar, Ed., Society for Mining, Metallurgy, and Exploration, Inc. (SME), Littleton, CO (1993).
35. Haney, R.A.: Diesel Particulate Exposures in Underground Mines. SME Preprint No. 90-40, 7 pp. Society for Mining, Metallurgy, and Exploration, Inc. (SME), Littleton, CO (1990).
36. Bagley, S.T.; Baumgard, K.J.; Gratz, L.D.: Comparison of In-Mine and Laboratory-Generated Diesel Particulate Matter, Biological Activity, and Polynuclear Aromatic Hydrocarbon Levels. In: Proceedings of the Third Symposium of Respirable Dust in the Mineral Industries, University Park, PA, 1987, pp. 61-70. RL Frantz and RV Ramini, Eds., Society for Mining, Metallurgy, and Exploration, Inc. (SME), Littleton, CO (1991).
37. Bagley, S.T.; Baumgard, K.J.; Gratz, L.D.: Polynuclear Aromatic Hydrocarbons and biological Activity Associated with Diesel Particulate Matter Collected in Underground Coal Mines. Bureau of Mines IC 9324, pp. 40-48 (1992).
38. Bagley, S.T.; Gratz, L.D.; Johnson, J.H.: Relative Health Risks of Diesel Emission Control Systems. Contract Final Report, Grant No. R01 OH02611. U.S. Department of Health and Human Services, NIOSH, Cincinnati, OH (1994).
39. Ambs, J.L.; Cantrell, B.K.; Klein, A.D.: Evaluation of a Disposable Diesel Exhaust Filter. In: Advances in Filtration and Separation Technology, Vol. 4, Fine Particle Filtration and Separation, pp. 287-291. KL Rubow, Ed., American Filtration Society, Houston, TX (1991).
40. Ambs, J.L.; Cantrell, B.K.; Watts, W.F.; et al.: Evaluation of a Disposable Diesel Exhaust Filter for Permissible Mining Machines. Bureau of Mines RI 9508, 8 pp (1994).
41. Westaway, K.C.; Faulds, A.J.: Diesel PAH Levels in Underground Mines. In: Health Issues Related to Metal and Nonmetallic Mining, pp. 355-378. W.L. Wagner, W.N. Rom, J.R. Merchant, Ed's, Butterworth, Co., Boston, MA (1983).
42. Westaway, K.C.: Polynuclear Aromatic Hydrocarbons and Mutagens in the Mine Environment. In: Workshop on Research Needs in Toxicology, Pub. No. AECL-9718, pp. 160-199. Atomic Energy Canada Ltd., Mississauga, Ontario, Canada (1988).
43. National Institute of Occupational Safety and Health: Health Hazard Evaluation Report: Yellow Freight Systems, Inc., Columbus, OH, Maybrook, NY. NIOSH Report No. HHE HETA 90-088-2110. U.S. Department of Health and Human Services (NIOSH), Cincinnati, OH (1990).
44. National Institute of Occupational Safety and Health: Health Hazard Evaluation Report: City of Lancaster, Division of Fire Lancaster, Ohio. NIOSH Report No. HHE HETA 92-0160-2360. NTIS No. PB-94140142. U.S. Department of Health and Human Services (NIOSH), Cincinnati, OH (1992).
45. National Institute of Occupational Safety and Health: Health Hazard Evaluation Report: Consolidated Freightways, Peru Illinois. NIOSH Report No. HHE HETA 88-077-1969. U.S. Department of Health and Human Services (NIOSH), Cincinnati, OH (1989).
46. Woskie, S.R.; Smith, T.J.; Hammond, S.K.; et al.: Estimation of the Diesel Exhaust Exposures of Railroad Workers I. Current Exposures. Am. J. Ind. Med. 13:381-394 (1988).
47. Schenker, M.B.; Samuels, S.J.; Kado, N.Y.; et al.: Markers of Exposure to Diesel Exhaust in Railroad Workers. Research Report No. 33, 64 pp. Health Effects Institute, Cambridge, MA (1990).
48. Hammond, S.K.; Smith, T.J.; Woskie, S.R.; et al.: Railroad Diesel Exhaust: Concentration and Mutagenicity. Appl. Occup. Environ. Hyg. 8(11):955-963 (1993).