IC 9324

INFORMATION CIRCULAR/1992

Diesels in Underground Mines: Measurement and Control of Particulate Emissions

Proceedings: Bureau of Mines Information and Technology Transfer Seminar, Minneapolis, MN, September 29-30, 1992

Compiled by Staff, Twin Cities Research Center,
Bureau of Mines

DIESEL RESEARCH

U.S. BUREAU OF MINES

United States Department of the Interior

Bureau of Mines

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UNITED STATES DEPARTMENT OF THE INTERIOR
Manuel Lujan, Jr., Secretary

BUREAU OF MINES
T S Ary, Director

PREFACE

This Information Circular summarizes U.S. Bureau of Mines research to measure and control diesel exhaust particulate emissions in underground mines. The 15 papers in this publication cover a broad spectrum of topics on diesel aerosol measurement and emission controls. These papers were presented at an Information and Technology Transfer Seminar held in Minneapolis, MN, on September 29-30, 1992.

The Bureau sponsors several meetings on various subjects each year. They direct the mineral industry's attention to beneficial research results. Those desiring more information about the Bureau's research programs and future technology transfer activities should contact the U.S. Bureau of Mines, Office of Technology Transfer, 810 7th Street, NW, Washington, DC 20241.

CONTENTS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	in H_2O	inch of water (pressure)
atm	atmosphere	kg	kilogram
°C	degree Celsius	kg/shift	kilogram per shift
cfm	cubic foot per minute	km	kilometer
cm	centimeter	kPa	kilopascal
cm^2	square centimeter	krev/MJ	kilorevertant per megajoule
°C/s	degree Celsius per second	kW	kilowatt
°F	degree Fahrenheit	lb	pound
°F/s	degree Fahrenheit per second	lb·ft/min	pound foot (moment of mass) per minute
ft	foot	L/min	liter per minute
ft^2	square foot	m	meter
ft·lbf	foot pound (force)	m^2	square meter
ft·lbf/min	foot pound (force) per minute	m^3	cubic meter
g	gram	mg	milligram
gal	gallon	mg/m^3	milligram per cubic meter
g/bhp·h	gram per brake horsepower hour	$\mu g/m^3$	microgram per cubic meter
g/h	gram per hour	mg/MJ	milligram per megajoule
g/MJ	gram per megajoule	mg/sm^3	milligram per standard cubic meter
h	hour	min	minute
hp	horsepower	mm	millimeter
Hz	hertz	μm	micrometer
in	inch	m^3/min	cubic meter per minute
in^2	square inch	m^3/s	cubic meter per second

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT—Continued

ng/m^3	nanogram per cubic meter	r/min	revolution per minute
ng/MJ	manogram per megajoule	s	second
N·m	newton meter	std ft^3/h	standard cubic foot per hour
N·m/min	newton meter per minute	V	volt
N·m/s	newton meter per second	vol pct	volume percent
pct	percent	w/cm^2	watt per square centimeter
ppb	part per billion	wt pct	weight percent
ppm	part per million	yd	yard
rev/m^3	revertant per cubic meter	yd^3	cubic yard

DIESELS IN UNDERGROUND MINES: MEASUREMENT AND CONTROL OF PARTICULATE EMISSIONS

Proceedings: Bureau of Mines Information and Technology Transfer Seminar, Minneapolis, MN, September 29-30, 1992

Compiled by Staff, Twin Cities Research Center, Bureau of Mines

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ABSTRACT

The goal of the U.S. Bureau of Mines diesel engine research program is to reduce exhaust emissions from diesel-powered equipment used in underground mines. This research has led to significant advances in aerosol measurement and to the development of more effective emission controls.

This Information Circular contains reports of some of the presentations made at the Bureau's Information and Technology Transfer Seminar on Diesels in Underground Mines given in Minneapolis, MN, on September 29-30, 1992. The seminar emphasized the measurement and control of diesel particulate matter emissions. Topics covered include a discussion of the health issues associated with the use of diesel equipment underground, an overview of regulations, measurement techniques for diesel exhaust aerosol, levels of diesel exhaust pollutants found in mines, and modern emission controls.

An appendix is included that contains a report describing the capabilities of the Bureau's diesel emissions research laboratory, two papers describing the effects of engine maintenance on emissions, a paper describing the monitoring of carbon dioxide in mine air as an indicator of air quality, a glossary, and a list of abbreviations and acronyms.

INTRODUCTION

Diesel engine research is conducted at the U.S. Bureau of Mines, Twin Cities Research Center (TCRC). This research is frequently cosponsored by industry, and collaborative research ventures between industry, academia, other government agencies, and the Bureau are common. The last Bureau Technology Transfer Seminar on Diesels in Underground Mines[1] was held in 1987, and over the last 5 years, a great deal of new knowledge has been gained.

The National Institute for Occupational Safety and Health (NIOSH) has clarified the health issue by recommending that whole diesel exhaust be regarded as "a potential occupational carcinogen" and by stating that "reductions in exposure to diesel exhaust in the workplace would reduce the risk".[2] The U.S. Mine Safety and Health Administration (MSHA) convened an Advisory Committee on Standards and Regulations for Diesel-Powered Equipment in Underground Mines and is beginning to implement its recommendations[3] that cover health, safety, and certification and approval issues surrounding the use of diesels underground. In January 1992, MSHA published an Advanced Notice of Proposed Rulemaking to regulate diesel particulate matter (DPM) in underground mines.[4] The Bureau has collaborated with MSHA, NIOSH, academia, and industry to significantly advance diesel exhaust aerosol (DEA) measurement and emission control technology. This Information Circular (IC) summarizes the research performed by the Bureau and others. A brief discussion of the contents is given below.

The intent of this IC is to convey recent information to mine operators, who can use this information to improve working conditions at their operations. This IC does not cover all diesel-related research that is being performed by the Bureau and others. Further technical information on DEA measurement can be obtained by contacting Bruce K. Cantrell, supervisor of the dust-aerosol technology research group at TCRC, (612) 725-4607. Technical information concerning DPM control can be obtained from Robert W. Waytulonis, supervisor of the diesel research group at TCRC, (612) 725-4760. Information concerning the Bureau's health, safety, and mining technology research programs can be obtained by contacting J. Harrison Daniel, staff engineer, Washington, DC, (202) 501-9309.

[1]U.S. Bureau of Mines. Diesels in Underground Mines. IC 9141, 1987, 165 pp.

[2]National Institute for Occupational Safety and Health. Carcinogenic Effects of Exposure to Diesel Exhaust. Current Intelligence Bull. 50, Dep. Health and Hum. Serv. (NIOSH) Publ. 88-116, 1988, 30 pp.

[3]U.S. Department of Labor. Report of the Mine Safety and Health Administration Advisory Committee on Standards and Regulations for Diesel-Powered Equipment in Underground Coal Mines, 1988, 70 pp.

[4]Federal Register. U.S. Mine Safety and Health Administration (Dep. Labor). Permissible Exposure Limit for Diesel Particulate. V. 57, No. 3, Jan. 6, 1992, pp. 500-503.

HEALTH ISSUES

The first paper in this IC focuses attention on the health issues surrounding the use of diesel equipment underground. Although the Bureau does not conduct health research, awareness of these issues helps to focus and establish the scope of the Bureau's diesel research program. Specific diesel exhaust pollutants are targeted for measurement and control.

DIESEL EXHAUST AEROSOL MEASUREMENT

The next five papers cover DEA measurement, which is critical to maintaining a healthful working environment. The Bureau and the University of Minnesota's Particle Technology Laboratory, under sponsorship of the Generic Mineral Technology Centers, have collaborated to develop diesel aerosol sampling methods.

The papers in this series cover instrumentation development, DEA measurement, and levels of aerosols measured in coal and metal-nonmetal mines. The first two papers describe techniques of DEA measurement for coal mines and metal-nonmetal mines. The third paper describes a new, inexpensive aerosol sampler that can be used to monitor DEA levels in coal mines. The fourth paper summarizes DEA data obtained from five underground coal mines, one of which was revisited to determine the effects of a disposable diesel exhaust filter on air quality. The last paper in this series describes results obtained from the chemical and biological analyses of diesel particulate samples collected underground. This is a collaborative research project involving the Bureau and Michigan Technological University and funded in part by NIOSH.

This discussion of aerosol measurement in the mine environment includes the terms "dust," "aerosol," "diesel particulate matter," "diesel exhaust aerosol," and "diesel aerosol." The terms "dust" or "particulate" refer to finely divided material usually associated with a discussion of physical and chemical properties. The term "aerosol" refers to finely divided material (particulate) suspended in air. When referring to air suspension of particulates, the proper terminology is "aerosol." Sources of aerosol include drilling, blasting, loading, hauling, conveying, continuous mining, rock dusting, and exhaust from diesel-powered equipment. When DEA has been deposited on a filter, it is properly termed "diesel particulate matter". These same distinctions pertain to the papers on diesel exhaust particulate control.

DIESEL EXHAUST PARTICULATE CONTROL

Particulate control is the subject of the next series of papers. The first paper discusses the impacts of pending regulations and technological developments on mines using diesel-powered equipment. The next four papers cover the development and evaluation of diesel emission control devices, including oxidation catalytic converters, disposable and reusable filters, ceramic diesel particulate filters, and a ceramic, regenerable fiber-coil filter. Each of these devices can be used in underground mines to decrease a miner's exposure to diesel pollutants. The oxidation catalytic converter effectively removes gas-phase hydrocarbons and carbon monoxide and reduces the soluble organic fraction of DPM. The filtration devices remove DPM from the exhaust and are in various stages of development.

HEALTH RISKS ASSOCIATED WITH THE USE OF DIESEL EQUIPMENT UNDERGROUND

By Winthrop F. Watts, Jr.[1]

ABSTRACT

A miner working underground where diesel equipment is used is exposed to a wide variety of exhaust pollutants. These include carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, sulfur dioxide, hundreds of different hydrocarbons (HC's) and diesel particulate matter (DPM). The National Institute for Occupational Safety and Health (NIOSH) and the International Agency for Research on Cancer (IARC) have respectively declared diesel exhaust to be "potentially" or "probably" carcinogenic.

The U.S. Bureau of Mines does not conduct health studies. However, the results of health studies reported by others define the health issues associated with the use of diesel equipment. This information helps to shape the direction and scope of the Bureau's diesel research program. These studies also target specific pollutants or groups of pollutants for the emission control research conducted by the Bureau.

This paper summarizes the health literature published since the Bureau's last Technology Transfer Seminar on Diesels in 1987. The areas covered include diesel exhaust composition, permissible exposure limits (PEL's) for exhaust constituents, and the health issues associated with diesel exhaust exposure.

INTRODUCTION

Evidence obtained primarily from animal inhalation studies and limited epidemiological investigations has led NIOSH (*1*)[2] to recommend that "... whole diesel exhaust be regarded as a potential occupational carcinogen." NIOSH further stated that "the excess cancer risk for workers exposed to diesel exhaust has not yet been quantified, but the probability of developing cancer should be decreased by minimizing exposure." IARC (*2*) reached a similar conclusion, stating that "diesel engine exhaust *is probably carcinogenic to humans.*" Prior to these declarations, there was insufficient evidence to make statements concerning the carcinogenicity of diesel exhaust, but it was well known that diesel exhaust caused less severe problems, such as headache, eye irritation, and unpleasant odors (*3*).

In response to the NIOSH and IARC statements regarding potential carcinogenicity, the U.S. Mine Safety and Health Administration (MSHA) began the administrative process to promulgate rules covering the use of diesel equipment underground. This process began in 1988 with an MSHA advisory committee, which recommended a three-tier approach, including approval of diesel equipment, safety, and health (*4*). Since then, MSHA has published an Advanced Notice of Proposed Rulemaking to regulate DPM in underground mines (*5*).

The goal of the U.S. Bureau of Mines diesel research program is to minimize the health and safety problems arising from the use of diesel equipment underground. The Bureau does not conduct health research, but studies reported by others define the health issues surrounding the use of diesel equipment. These studies act as a major force in shaping the direction and scope of the Bureau's diesel research program. Since the last Bureau Technology Transfer Seminar on Diesels in Underground Mines

[1]Industrial hygienist, Twin Cities Research Center, U.S. Bureau of Mines, Minneapolis, MN.

[2]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

was held in 1987, NIOSH and IARC have issued statements regarding potential health effects resulting from exposure to diesel exhaust. These statements and the issues and rationale behind them are reviewed in this paper. The objective of this paper is to provide an up-to-date and concise literature summary of the health issues that pertain to the use of diesel equipment underground and to show how this information impacts the Bureau's diesel research, which is described in this Information Circular (IC).

DIESEL EXHAUST COMPOSITION

Diesel exhaust contains literally thousands of gaseous and particulate substances, some of which are known mutagens and/or carcinogens. Typically, the major gaseous components found in air (argon, carbon dioxide, water, nitrogen, and oxygen) comprise 99 pct of the mass of diesel exhaust. Much smaller quantities of the pollutant gases carbon monoxide, nitric oxide, nitrogen dioxide, sulfur dioxide, and HC's are also present. The quantity and com-position of the specific gaseous HC's are sometimes dif-ficult to measure because of low concentrations and the large number of species present. These pollutants are toxic, asphyxiating, or strongly irritating at concentrations above those shown in table 1, which is discussed in the next section.

DPM is a complex mixture of chemical compounds, composed of nonvolatile carbon, hundreds or thousands of different adsorbed or condensed HC's, sulfates, and trace quantities of metallic compounds. DPM is of special concern because it is almost entirely respirable, with 90 pct of the particles, by mass, having an equivalent aerodynamic diameter of less than 1.0 µm. This means that the particles can penetrate to the deepest regions of the lungs and, if retained, cause or contribute to the development of lung disease. Of greater concern is the ability of DPM to adsorb other chemical substances, such as (1) potentially mutagenic or carcinogenic polynuclear aromatic hydrocarbons (PAH's); (2) gases, such as sulfur dioxide and nitrogen dioxide; and (3) sulfuric and nitric acids. DPM carries these substances into the lungs, where they may be removed and transported by body fluids to other organs, where they may cause damage (*6*).

The quantity, chemical composition, and physical properties of exhaust emissions change during normal engine operating conditions. Emissions are affected by the type of engine, duty cycle, fuel quality, maintenance, intake ambient air conditions, operator habits, and emission controls. Since emissions vary for so many reasons, it is difficult to define a typical diesel exhaust. Two different consequences of this variation in exhaust composition are that (1) animal inhalation studies, which use light-duty diesel engines (*7-9*) as a source of exhaust, may produce results different from those produced by heavy-duty diesel engines (*10*); and (2) emission controls may have positive or negative effects on emissions, depending on operating conditions. For example, the performance of emission controls that use catalysts, such as oxidation catalytic converters (OCC's) is dependent upon exhaust temperature and fuel sulfur content (*11-12*). The benefits derived from a decrease in carbon monoxide and HC's caused by the OCC might be offset by an increase in sulfate particulates produced by the OCC if a high-sulfur diesel fuel is used. It is possible to define the range of emissions for the more common pollutants for a specific engine. These data are shown in figure 1 for a heavy-duty, indirect-injection diesel engine tested at the Bureau's diesel engine research laboratory (*13*).

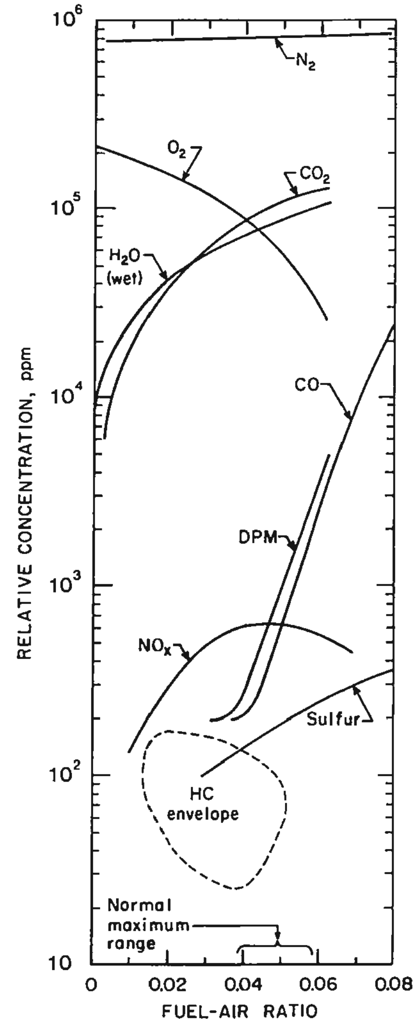

Figure 1.—Relationship between fuel-air ratio and relative concentration of exhaust emissions for a heavy-duty, direct-injection diesel engine. Adapted from Waytulonis (*13*).

PERMISSIBLE EXPOSURE LIMITS

Many of the pollutants found in diesel exhaust have PEL's. In the United States, the American Conference of Governmental Industrial Hygienists (ACGIH) recommends threshold limit values (TLV's) and NIOSH suggests recommended exposure limits (REL's). The U.S. Occupational Safety and Health Administration (OSHA) and MSHA establish and enforce PEL's based upon all available information. As shown in table 1, there is a range of values recommended by these organizations for diesel exhaust gaseous constituents. A TLV is defined as the time-weighted average concentration for a normal 8-h workday and a 40-h workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effects (*14*). As noted in table 1, NIOSH and OSHA do not have an 8-h, time-weighted average exposure for nitrogen dioxide; rather, they have a 1-ppm, 15-min, short-term exposure limit. MSHA is considering this recommendation (*15*).

There is no specific U.S. PEL for DPM at this time. DPM is of respirable size and thus it is limited under a variety of PEL's for respirable dust, including MSHA's 2.0-mg/m³ respirable coal mine dust standard. MSHA has published an advance notice of proposed rulemaking for DPM (*5*). Respirable combustible dust is a surrogate measure for DPM used in Canadian mines, and Canada recently lowered the recommended limit for respirable combustible dust in noncoal mines from 1.5 to 0.5 mg/m³ (*16*).

Table 1.—Range of gaseous exposure limits recommended by ACGIH, NIOSH, and OSHA for 8-h, time-weighted average exposure and MSHA PEL's

Pollutant	Range of limits, ppm	MSHA PEL's, ppm	
		Coal	Noncoal
Formaldehyde[1]	[2]0.016 - 1	1	2
CO	35 - 50	50	50
CO_2	5,000 - [2]10,000	5,000	5,000
NO	25	25	25
NO_2	[3]1 - 3	3	5
SO_2	[2]0.5 - 5	2	5

[1]Suspected carcinogen.

[2]NIOSH recommendation based on a 10-h, time-weighted average.

[3]OSHA and NIOSH have only a 1-ppm, 15-min, short-term exposure limit.

Of the PAH's, only chrysene (0.2 mg/m³) and coal-tar pitch volatiles (0.2 mg/m³ as benzene solubles) have established OSHA PEL's. The OSHA PEL for coal-tar pitch volatiles specifically includes anthracene, benzo[a]pyrene, phenanthrene, acridine, chrysene, and pyrene. ACGIH designates benzo[a]pyrene, chrysene, and coal-tar pitch volatiles as "suspected human carcinogen" or "human carcinogen" (*14*). The OSHA PEL for coal-tar pitch volatiles is mentioned because these PAH's are also present in diesel exhaust. There are no PEL's established for other gas-phase or particle-bound PAH's.

HEALTH ISSUES

Two recent reports have defined the qualitative risk resulting from exposure. NIOSH summarized their findings in Current Intelligence Bulletin 50 (*1*). In the "Conclusions" section of that document, NIOSH stated the following:

"Recent animal studies in rats and mice confirm an association between the induction of cancer and exposure to whole diesel exhaust. The lung is the primary site identified with carcinogenic or tumorigenic responses following inhalation exposures. Limited epidemiological evidence suggests an association between occupational exposure to diesel engine emissions and lung cancer. The consistency of these toxicological and epidemiological findings suggests that a potential occupational carcinogenic hazard exists in human exposure to diesel exhaust.

Tumor induction is associated with the diesel exhaust particulates. Limited evidence indicates that the gaseous fraction of diesel exhaust may be carcinogenic, as well."

In the "Recommendations" section of the same document, NIOSH stated the following:

"The excess cancer risk for workers exposed to diesel exhaust has not yet been quantified, but the probability of developing cancer should be decreased by minimizing exposure. As a prudent public health policy, employers should assess the conditions under which workers may be exposed to diesel exhaust and reduce exposures to the lowest feasible limits. Although a substantial amount of information suggests that some component (or combination of components) of the particulate fraction of diesel exhaust is associated with tumor initiation, the relative roles of the particulate and gaseous phases of emissions need further characterization."

IARC (*2*) prepared a monograph evaluating the cancer risks to humans from gasoline and diesel engine exhausts. IARC echoed the statements made in the NIOSH document and concluded that "diesel engine exhaust *is probably carcinogenic to humans.*" Like NIOSH, IARC did not quantify the excess cancer risk for workers exposed to diesel exhaust.

The findings of NIOSH and IARC raise issues that are at the center of the diesel debate: (1) Most data relating diesel exhaust exposure to lung cancer are derived from animal inhalation studies and extrapolating these results to humans is controversial; (2) the mechanism of tumor formation is unknown and the role of the gaseous fraction in tumor formation is unclear, although tumor induction is associated with DPM; (3) the quantitative risk for excess cancer has not been defined; (4) the probability of developing an occupational disease is lessened by minimizing exposure, but no safe level of exposure has been established; and (5) aerosol instruments to monitor workplace exposure and engineering controls to reduce exposures to the lowest feasible level are new technologies in the research stage of development. Each of these issues is briefly discussed in the following sections.

ANIMAL INHALATION STUDIES

Interpretation of results from rodent bioassays is frequently controversial. Interpretation is affected by the test methods, the physiological differences between rodents and humans, and the assumptions and models used in the interpretation. Carcinogenicity is usually determined by administering large doses of a substance(s), on a daily basis, for the lifetime of the rodent. Models are developed and the results are extrapolated to estimate the health effects in humans. The extrapolations frequently include the incorporation of additional safety factors, which result in even lower exposure recommendations. In most cases, the mechanisms of tumor formation are not well understood and the differences in physiology between rodents and humans are not taken into account. The specific case of diesel exhaust inhalation studies is confounded by the chemical complexity of the exhaust mixture, the fact that only rats and possibly mice show a significant tumor response, and the prolonged duration of exposure required to cause tumors. Despite these limitations, animal inhalation data are frequently the only data upon which to base a decision and are often accepted as sufficient.

ROLE OF POLLUTANTS IN TUMOR INITIATION

Understanding the fundamental mechanisms of tumor formation and the role each pollutant plays in that process is extremely important. NIOSH statements (*1*) make it clear that some component (or combination of components) of the diesel particulate fraction has a role in tumor formation, but the relative contribution of DPM and the gas-phase components is less clear. This position is reinforced by investigators at Lovelace Inhalation Toxicology Research Institute (*17*). They concluded from a rat inhalation study that "... repeated inhalation of carbonaceous particles causes lung inflammation regardless of organic content, but that the level of DNA damage is primarily related to the organic content." The investigators further concluded that "... large accumulations of diesel-exhaust soot in the lung might have caused tumors independently from chemical carcinogens." As a result of these findings, the Bureau emphasizes the evaluation of control technology capable of reducing DPM and/or gas-phase pollutants. Special emphasis is placed on reducing the organic fraction of DPM and gas-phase HC's. These evaluations are discussed in other papers in this IC.

RISK ASSESSMENT

Risk assessment is a part of the risk management process, as illustrated in figure 2, which was adapted from a paper by McClellan (*18*). The process combines classic industrial hygiene practices, such as field measurements and hazard identification, with health effects studies, risk characterization, and public decisionmaking. This process provides an orderly framework for considering data and developing public policy.

Defining the health risk from exposure to diesel exhaust is particularly difficult because of the chemical complexity of the exhaust. It is also controversial because different assumptions and models are used to interpret data that are frequently inadequate or not available.

Exposure, Dose, and Response

Figure 3, also adapted from McClellan (*18*), shows the relationship between exposure, dose, and response. Some of the factors that are considered in determining exposure include the intensity, or ambient pollutant concentration, sometimes expressed in milligrams per cubic meter; and population factors, such as age, sex, and occupation, that

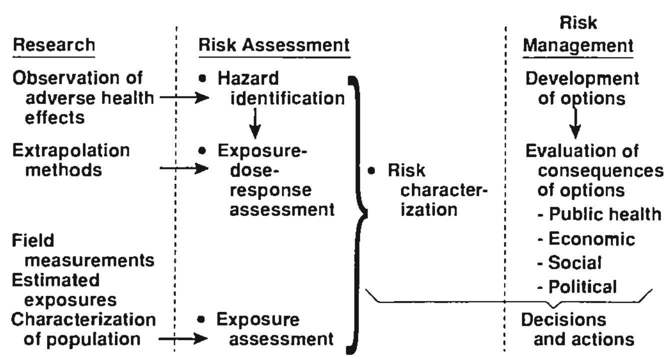

Figure 2.—Risk management process. Adapted from McClellan (*18*).

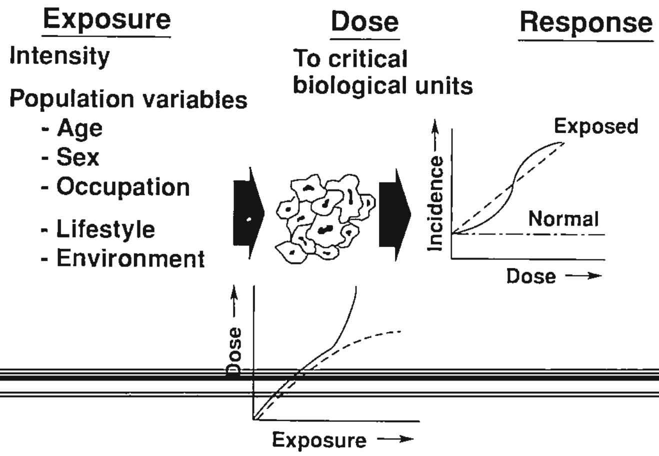

Figure 3.—Relationship between exposure, dose, and response. Adapted from McClellan (*18*).

may affect the extent of exposure. Dose is frequently expressed as the mass of pollutant per mass of body tissue and defined as the amount of pollutant that is absorbed or deposited in the body over a period of time. Dose is a fraction of the measured exposure, and to obtain quantitative risk estimates, better estimates of exposure and target-tissue dose are required.

Figure 3 shows a dose-versus-exposure graph. The dashed line represents a situation where increasing exposure past a certain level does not significantly affect the target-tissue dose. In this case, an equilibrium is established between deposition and removal. The solid line represents another situation where increasing the exposure past a certain level causes the physiological defense mechanisms to be overwhelmed, resulting in a tremendous increase in dose to the target tissue.

Dose is a critical factor in disease causation, as illustrated by the second graph, incidence versus dose, in figure 3. The normal response is indicated by the dashed-dotted line, which shows no increase in the incidence of disease (cancer), regardless of pollutant dose. The other two curves compare the threshold response to the nonthreshold response. The threshold curve, depicted by the solid line, shows that, at low doses, disease incidence rises slowly, but beyond a certain dose, there is a rapid rise. The nonthreshold response depicted by the dashed line shows a linear increase of disease incidence with increasing dose.

Risk assessment is further complicated by the fact that particle deposition in the pulmonary or gas-exchange region of the lung is strongly dependent upon particle size (*19*). Determination of the dose of mutagenic PAH's requires that both the gas-phase and particle-bound PAH's be measured. The particle size distribution of diesel exhaust and the effect that emission control technology has on PAH's are discussed in other papers in this IC.

Epidemiology

Better quantitative risk estimates also require better epidemiological data. Epidemiological studies designed to determine the risk associated with diesel exhaust exposure have generally yielded negative or inconclusive results. These studies are plagued by faulty design, resulting in inadequate data. Critical design flaws in many of the studies are reviewed by Steenland (*20*). Flaws include the inability to account for the smoking status of the population and the lack of exposure data for the time period under study. Occupational exposure for many of the gas-phase mutagenic substances is frequently not known because the pollutant concentration in the diluted exhaust is often below the level of detection. When exposure information is available, it frequently does not overlap the time period of the health studies. For instance, a study of miners working from 1940 to 1970 would typically rely on exposure information collected in the 1980's, after the problem was observed. Current exposure levels most likely are lower because of the imposition of occupational health standards and improvements in technology, which may result in inaccurate estimates of past exposure.

Another problem occurs because the occupational workforce is comprised of predominately healthy individuals between the ages of 20 and 50 and studies that use the general population as a control group tend to show the occupational group to be healthier (*21*). The general population includes the aged and disabled, while occupational groups such as miners are selected prior to employment, in part, because of good health. This phenomenon is referred to as the healthy worker effect.

The population of miners exposed to diesel exhaust is small in number; thus, when the level of risk is low, relatively few cases of a disease are observed. Epidemiological studies are difficult to conduct and lack statistical power when few cases of a disease are observed in the study population. Miners also have other occupational exposures, such as quartz and radon, which may confound interpretation of the epidemiological study. The duration of exposure to onset of illness is typically 15 to 30 years for a carcinogen. Few miners work continuously for 30 years because of the cyclical nature, competitiveness, and increasing mechanization of the industry. Additionally, if the lung cancer risk posed by diesel exhaust exposure is low, relatively few miners will actually develop the disease; therefore, these miners will be missed by the relatively insensitive epidemiological investigations.

Most epidemiological studies have not confirmed the results from animal inhalation studies (*2*); thus, risk assessments are forced to rely upon extrapolation of animal inhalation data.

Exploratory Risk Assessment

NIOSH (*22*) completed an exploratory risk assessment at the request of MSHA to estimate the health risk from diesel exhaust exposure. The risk assessment was based upon a rat inhalation study conducted at Lovelace Inhalation Toxicology Research Institute (*9*), and the authors emphasized that their findings were based upon a series of assumptions and involved considerable uncertainty. They estimated that the excess lifetime risk of lung cancer to coal miners exposed to 0.5 mg/m^3 DPM is between 1 in 100 and 5 in 1,000. The 0.5 mg/m^3 used in the NIOSH risk assessment is not unrealistic. The Bureau has measured DPM aerosol concentrations at specific coal mine locations, including the section intake, haulageway, production equipment, and return (*23-24*). Mean concentrations at these locations ranged between 0.2 and 1.0 mg/m^3. Other investigators at MSHA (*25*) and NIOSH (*26*) have reported similar concentrations.

REDUCING EXPOSURE

In Current Intelligence Bulletin 50, NIOSH alludes to the removal of diesels and the substitution of other power sources: "A preferred engineering control technique is substitution (replacing a hazardous material or process with an alternative that has a lower health risk). However, the health and safety implication of any proposed alternatives to diesel power requires careful evaluation before implementation." Eliminating exposure to pollutants is the best way to avoid health problems, but frequently this is impractical. For instance, almost all noncoal mines and some coal mines use diesel equipment. Requiring these mines to switch from diesel to entirely electric-powered haulage would be very costly and possibly impossible, depending upon the method of mining used. More often, PEL's are established (table 1) that allow a threshold level of exposure. A more stringent standard may be applied to carcinogens because they pose a more severe health threat. The Bureau is developing emission control technology, described in detail in this IC, in anticipation of these more stringent standards.

EXPOSURE MONITORING AND EMISSION CONTROL

Field measurements, exposure estimation, development of options, and evaluation of consequences have prominent roles in the risk management process (fig. 2). Although the Bureau does not conduct health research, it plays an active role in the risk management process by developing aerosol instrumentation to measure diesel exhaust aerosol and evaluate emission control options to reduce exposure to exhaust constituents. The Bureau, NIOSH, and MSHA are cooperating to develop and test instrumentation to measure diesel aerosol in the workplace. During the performance evaluation of these instruments, aerosol data are collected to determine the efficiency of emission control devices in the underground mine environment. These data are also useful in estimating exposure to diesel exhaust aerosol. The Bureau is also cooperating with Michigan Technological University in a study funded by NIOSH[3] to determine the effects of control technology on the chemical composition and mutagenic character of diesel exhaust aerosol collected in the underground mine environment. These instruments, exposure estimates, emission control devices, and evaluations are described in detail in other papers in this IC.

SUMMARY

Evidence obtained primarily from animal inhalation studies and epidemiological investigations has led NIOSH (*1*) to recommend that "... whole diesel exhaust be regarded as a potential occupational carcinogen." NIOSH further recommended that "the excess cancer risk for workers exposed to diesel exhaust has not yet been quantified, but the probability of developing cancer should be decreased by minimizing exposure." IARC (*2*) echoed the statements made in the NIOSH document and concluded that "diesel engine exhaust *is probably carcinogenic to humans.*" Even though the excess risk for workers exposed to diesel exhaust is not quantitatively defined, there is sufficient evidence to begin the risk management process, as illustrated by MSHA's advance notice of proposed rulemaking, to regulate DPM in underground mines (*5*). Although the Bureau does not conduct health studies or establish regulations, it does participate in the risk management process by conducting research to develop aerosol instrumentation that measures diesel exhaust aerosol and by evaluating diesel emission control options for the mine environment.

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[3]NIOSH grant OH 02611-03 awarded to S. T. Bagley, Michigan Technological University, Houghton, MI, Jan. 1, 1989.

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MEASUREMENT OF DIESEL EXHAUST AEROSOL IN UNDERGROUND COAL MINES

By Bruce K. Cantrell[1] and Kenneth L. Rubow[2]

ABSTRACT

Quantifying exposure to diesel exhaust aerosol in an underground coal mine depends on the ability to measure this component of respirable mine aerosol separately from coal dust. Such measurement is complicated by the carbonaceous nature of both the diesel and coal dust particulate that make up the respirable aerosol. Hence, special sampling and analytical techniques must be used to distinguish between these two aerosol components.

As part of a continuing study of diesel exhaust aerosol characteristics, the U.S. Bureau of Mines has applied size-selective sampling together with gravimetric analysis to separate and measure respirable diesel exhaust and coal dust aerosol concentrations in diesel-equipped underground coal mines. This technique is based on the premise that the diesel portion of the aerosol is predominantly submicrometer and the mineral dust portion is mostly greater than 1 μm in size. In the study, chemical mass balance (CMB) modeling, based on the distribution of chemical elements in aerosol and aerosol source material samples, is used to referee the analysis of diesel exhaust and mineral dust aerosol concentrations from the size-selective sampling results.

Based on the results of the study, the Bureau, in cooperation with the University of Minnesota and the U.S. Mine Safety and Health Administration (MSHA), have developed a prototype personal diesel exhaust aerosol sampler for underground coal mines. The sampler has three stages: a preclassifier stage to select for respirable aerosol, an inertial impaction stage with an aerodynamic diameter (d_p) size cut at 0.8 μm to separate diesel aerosol from mineral dust and collect the mineral dust, and a final filtration stage to collect the diesel fraction of the sample. The sampler has been evaluated in both laboratory and field experiments conducted by the Bureau, MSHA, and the Generic Minerals Technology Center for Respirable Dust (GMTC-RD).

INTRODUCTION

In an ongoing research program, the U.S. Bureau of Mines (*1-2*)[3] and the University of Minnesota's Particle Technology Laboratory (*3*), operating under a grant from GMTC-RD (*4*), have studied the use of size-selective sampling techniques to measure the mass concentration (c_m) of diesel aerosol in underground coal mines. The study was based on the premise that size-selective sampling techniques can be used to separate diesel exhaust aerosol, which is predominantly submicrometer in size, from coal dust aerosol, which is mostly greater than 1 μm in size. Results from the study have confirmed this premise and have been used to design a personal diesel exhaust aerosol sampler for use in underground coal mines (*5*). This paper reviews general mine aerosol characteristics, data used in development of the personal sampler, design of the sampler, and evaluation of the sampler in both laboratory and field tests (*6*).

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[3]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

ACKNOWLEDGMENTS

The authors would like to acknowledge the participation of Kenneth Rahn, professor, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI, who offered his staff to perform the instrumental neutron activation analysis (INAA) used in this work.

This research was partially supported the U.S. Department of Interior's Mineral Institute program administered by the Bureau through the Generic Mineral Technology Center for Respirable Dust under grant number G-1135142 to the University of Minnesota.

MINE AEROSOL CHARACTERISTICS

Mine aerosols arise from a variety of sources and, as illustrated in figure 1, the aerosol mass size distribution is influenced by these sources (7). The physical mechanisms such as condensation and coagulation that transfer aerosol mass from one size to another is displayed in figure 1. There are three distinct size ranges that can be identified from features in measured size distributions. The smallest of these, 0.001 to 0.08 μm, is the Aitken nuclei range, which contains primary aerosol from combustion sources such as diesel engines and secondary aerosol formed from coagulation of primary aerosols to form chain aggregates. The next size range, 0.08 to approximately 1.0 μm, termed the accumulation range, contains emissions in this size range plus aerosol accumulated by mass transfer through coagulation and condensation processes from the nuclei range. The last range, 1.0 to approximately 40 μm, is termed the coarse aerosol size range. Aerosols within this range generally originate from mechanical processes such

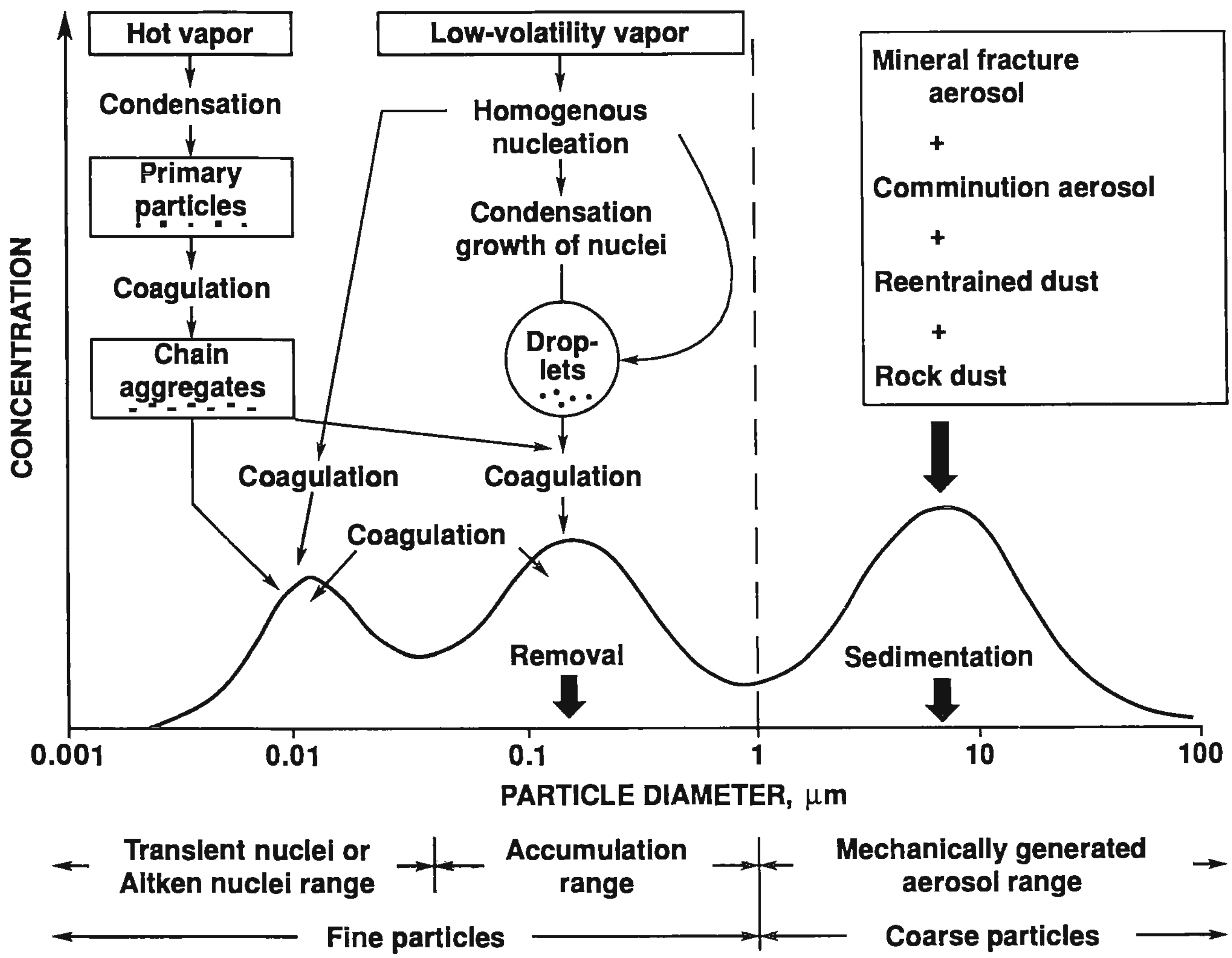

Figure 1.—In-mine aerosol characteristics exhibiting modal nature of size distribution and conventional terminology for description.

as rock fracture and bulk material handling. Mineral dust aerosol reentrained by mine haulage vehicles during the load-haul-dump cycle is an example of an in-mine source that will contribute aerosol to this size range. A division is usually made between the Aitken nuclei and the accumulation range aerosol and the remaining "coarse" aerosol at 1.0 μm. This distinction is possible because sources of aerosol in the two ranges are usually different and the coarse aerosol range contains very little mass transferred from the accumulation range by coagulation.

SIZE-DISTRIBUTION MEASUREMENT OF DIESEL AND COAL DUST AEROSOL

From the aerosol characteristics summarized in figure 1, two general observations apply to diesel exhaust aerosol in underground mines. The first is that diesel exhaust should not be expected to contribute to mine aerosol greater than 1.0 μm in size. It originates as a submicrometer aerosol, and coagulation processes are not sufficient to transfer much mass to the coarse size range. Secondly, mechanically generated aerosols such as coal and mineral do not have significant mass with sizes less than 1.0 μm. These two observations gave rise to the premise on which size-selective sampling was originally proposed for measurement of diesel exhaust aerosol. To test this hypothesis, a series of laboratory and field experiments were conducted.

Laboratory Study

Laboratory experiments were conducted to investigate the feasibility of using the microorifice, uniform-deposit impactor (MOUDI)[4] to measure the size distribution of aerosols containing various mixtures of coal dust and diesel exhaust aerosols (*3-4*). The objective of the work was to determine the mass concentration of diesel exhaust aerosol in an airborne mixture of coal dust and diesel exhaust aerosol from the size distribution of the mixture. A prototype seven-stage MOUDI with cut sizes ranging from 0.1 to 10 μm was used (*8*).

The experiment successfully demonstrated that coal dust and diesel exhaust aerosol can be separated and measured on the basis of size. Data from the tests show that the overall diesel exhaust-coal aerosol size distribution is bimodal; i.e., it has two maxima or modes (fig. 2). The diesel exhaust, or submicrometer mode aerosol, has an aerodynamic mass median diameter (MMD) of approximately 0.15 μm. The coal dust supermicrometer mode has an MMD in the 3- to 10-μm size range. A clear separation between the two modes exists in the 0.7- to 1.0-μm

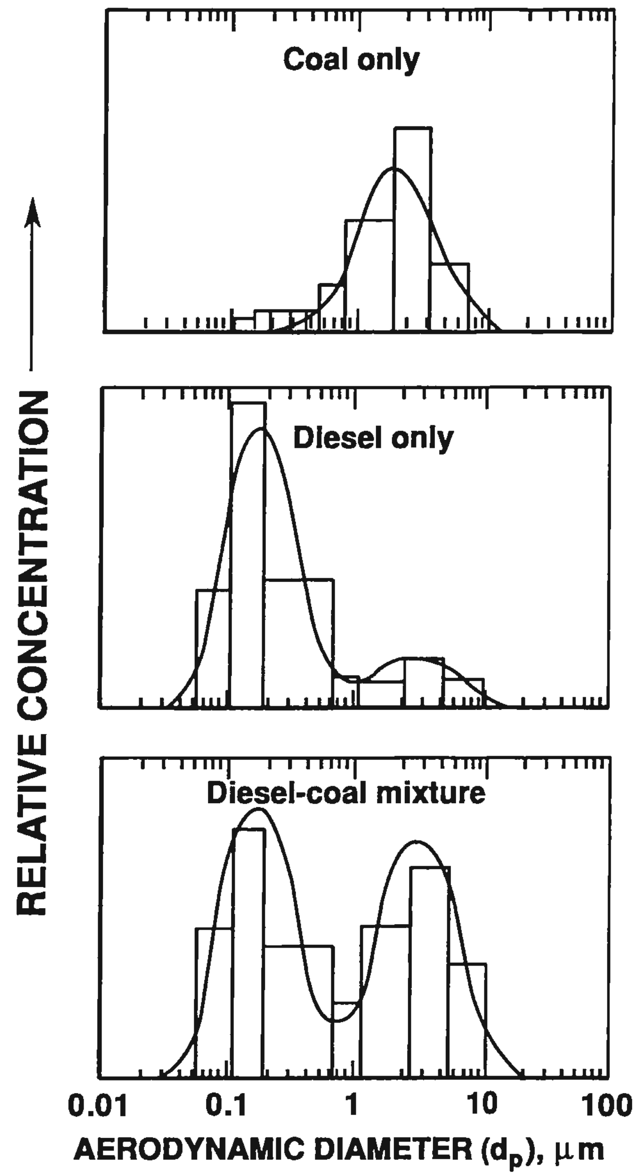

Figure 2.—Laboratory diesel-coal aerosol size distributions versus relative concentration.

size range, with the minimum near 0.8 μm. Analysis of the combined size distribution permits a quantitative determination of the diesel aerosol contribution to within 15 pct.

Field Studies

Five mines were visited during field studies designed to confirm the laboratory results and develop a data base for use in designing a diesel aerosol sampler (*9*). Three of the mines were equipped with diesel haulage equipment and two had all-electric equipment. The electric-equipped coal mines were used to generate comparison samples representative of a mine environment without diesel aerosol.

[4]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

Measurements consisted of collecting size-differentiated aerosol samples at four locations in longwall development sections employing a continuous miner: in the air intake entry, conveyor-beltway entry, air return entry, and haulageway. A 10-stage MSP, Inc. (St. Paul, MN), model 100 MOUDI, operated at a flow rate of 30 L/min, was used for the field size-distribution measurements.

Samples used to develop design and performance criteria were those collected at the conveyor belt or in the haulageway, since they are from areas where workers are exposed. The samples were collected only when the breaker was on and diesel haulage equipment was in use. As a result, the measurements were not representative of worker exposure for the work shift.

Trace-element profiles of mine aerosol and related sources were also measured. This included analysis of indium added to the fuel as a unique diesel source tracer. Source apportionment analyses using CMB modeling were performed on these samples and used to referee results of the size-distribution measurements (*1*). The trace-element analysis used was INAA (*10*).

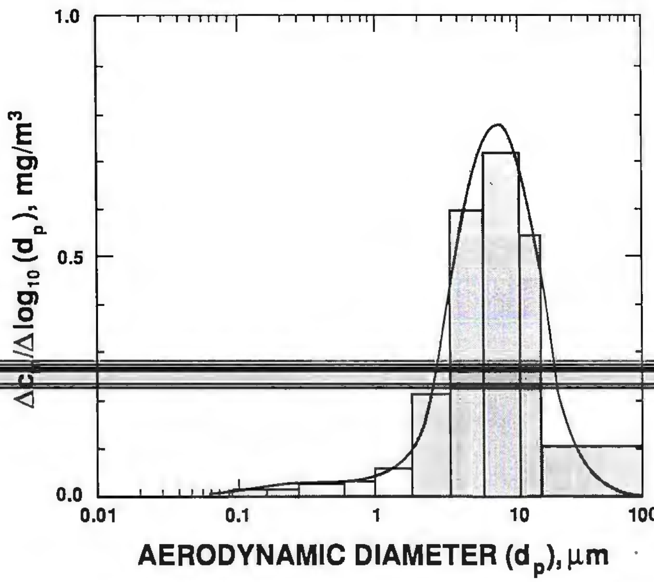

Figure 3.—Average mass size distribution measured in haulageways of the all-electric mines.

Field Measurement Results

Average aerosol mass concentration size distributions measured in the haulageway of the all-electric and diesel-equipped coal mines are shown in figures 3 and 4. The MOUDI collects the sampled aerosol in size intervals by aerodynamic diameter. The number of size intervals provides enough differential size resolution to model the measured aerosol size distributions with empirical functions represented by the continuous curves in the figures. This analysis, termed modal analysis, uses a sum of two log-normal functions to fit the data (*11*). Each function represents one of the maxima or modes evident in the data.

Each mode is identified with the aerosol contributed by a primary aerosol source: diesel exhaust aerosol for the submicrometer mode and mineral dust for the coarse particle mode. Under this assumption, the separate contribution from these sources to the total aerosol concentration can be determined using the modal analysis results. Treating each mode as a source-connected entity also permits the determination of the amount of coarse particle mode aerosol that encroaches on a sample of submicrometer mode aerosol as it might be collected by an ideal single-stage size-selective sampler, i.e., one with a step collection efficiency. This is done by integrating the distribution function for the coarse particle mode over the range of sizes for which the submicrometer mode aerosol is collected. An illustration of such modal overlap for the average diesel-coal aerosol size distribution of figure 4 is given in figure 5. The range of integration is 0.001 to 0.8 µm. Shaded areas indicate the portion of the submicrometer and coarse aerosol that will contribute to an ideal, less than 0.8-µm sample.

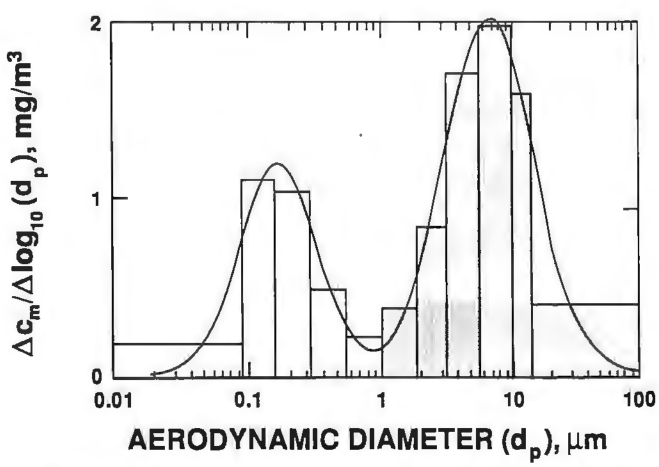

Figure 4.—Average mass size distribution measured in haulageways of the diesel-equipped mines.

Design Criteria

Optimum particle size for separation of diesel from mineral dust aerosol was determined by integrating the log-normal functions that describe the size-distribution modes from zero up to a given separation size (fig. 5). In this way, the aerosol mass collected by an ideal sampler with this separation size was determined. Using these results, the percentage gravimetric error made by assigning the aerosol mass collected by such a sampler to diesel aerosol alone was determined by its difference from the total submicrometer mode mass as a function of separation size. The optimum separation size for the personal diesel sampler is thus determined to be 0.8±0.1 μm.

PERSONAL DIESEL AEROSOL SAMPLER

A prototype personal diesel exhaust aerosol sampler (fig. 6) has been designed for underground coal mines (*6*). The sampler has three stages and employs inertial impaction for separation and collection of the diesel and mineral dust fractions of the sampled respirable aerosol. The first stage is an inerial preclassifier that separates and collects the larger nonrespirable aerosol. The preclassifier used in this design is a 10-mm Dorr-Oliver respirable cyclone. The second stage is a multiple-nozzle impactor with a sharp separation or cut size that only passes aerosol with less than 0.8-μm aerodynamic diameter. Here, aerosol larger than 0.8 μm is deposited on an impaction plate. The third stage is a filter that collects all aerosol less than 0.8 μm aerodynamic diameter. The sampler operates at a flow rate of 2 L/min and is designed to be compatible with commercial personal sampler pumps.

The 0.8-μm cut-size impactor was designed using accepted impactor theory and design guidelines (*12-13*). An impactor with four nozzles was found to exhibit the best tradeoff between pressure drop, overall particle mass loading, and diameter of the particle deposits on the impaction plate. In this development, impactors with 1, 4, 7, and 22 nozzles were tested with no degradation in collection efficiency or precision of the cut size.

Primary limitations on the performance of personal diesel exhaust aerosol samplers are diesel aerosol loss from the sample, variable contamination by coarse particle mode aerosol, and accuracy of the gravimetric analysis performed on the sample. Of secondary importance is the presence of background aerosol in the sample. The latter is due to external, or atmospheric, and nondiesel outby sources of submicrometer aerosol such as welding fumes. The less than 0.8-μm sample contains most of the diesel particulate material present in the mine air, plus a small amount of mineral dust contamination, usually less than

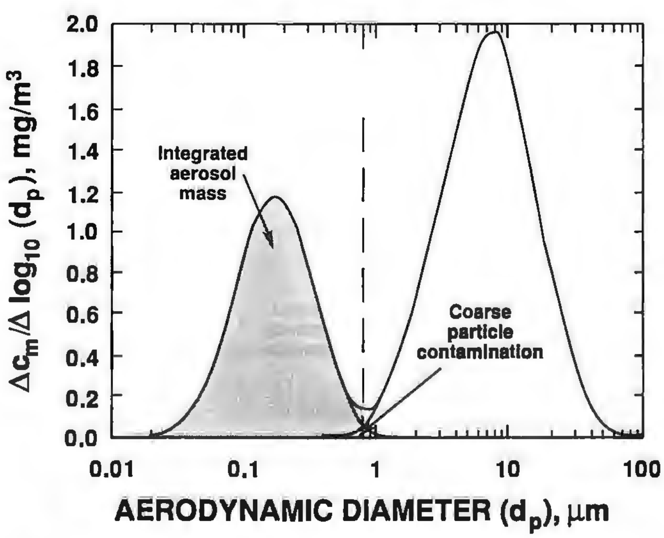

Figure 5.—Integration of aerosol mode functions to calculate aerosol mass less than 0.8 μm.

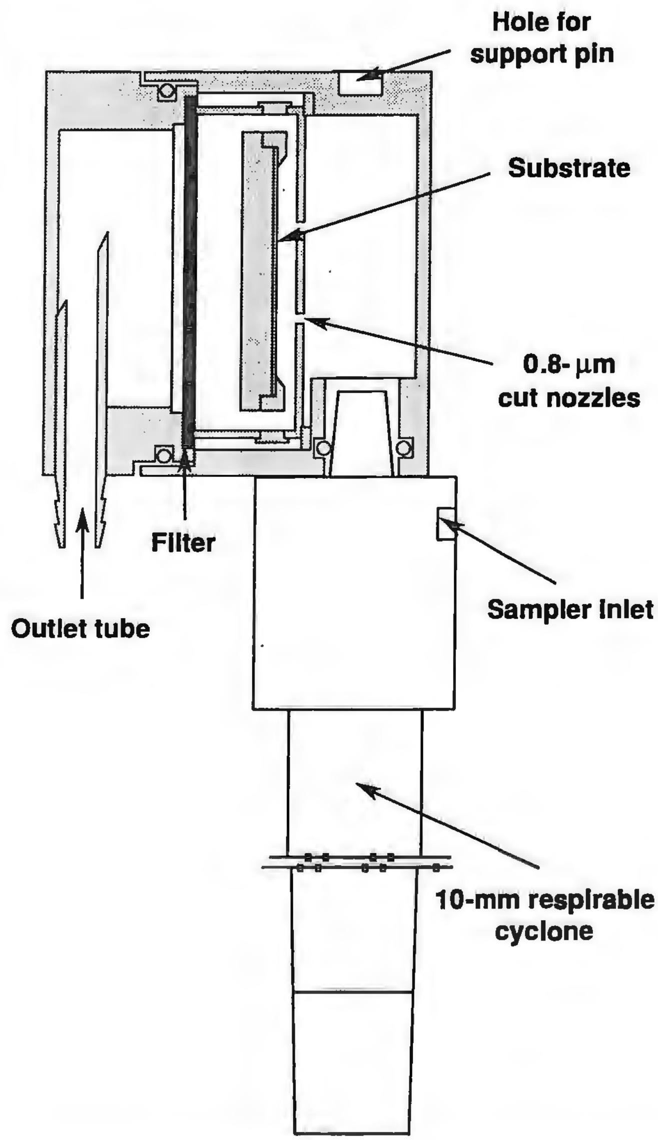

Figure 6.—Schematic diagram of personal diesel exhaust aerosol sampler.

10 pct. If a sample flow rate of 2 L/min is used and gravimetric analysis is within 0.1 mg, a less than 0.8-μm aerosol concentration is estimated to have an a priori limit of detection of 0.3 mg/m³.

LABORATORY CALIBRATION

Collection efficiency of the 0.8-μm cut-size impactor as a function of aerosol size was determined using monodispersed calibration aerosol. These test aerosols were uniform-size polystyrene latex (PSL) particles ranging from 0.5- to 1.05-μm diameter. Figure 7 shows the results of these measurements. This figure presents data for the aerosol collection efficiency of the impactor as a function of particle aerodynamic diameter. The impactor cut size, defined as the particle size corresponding to the 50-pct particle collection efficiency, was found to be 0.76± 0.05 μm. The sharpness of cut is measured by the geometric standard deviation of the collection efficiency curve. This was found to be 1.15±0.05, indicating a sharp cut for the impactor. The geometric standard deviation is calculated as the square root of the ratio of the particle diameter corresponding to the 84.1-pct collection efficiency to the diameter at an efficiency of 15.9 pct.

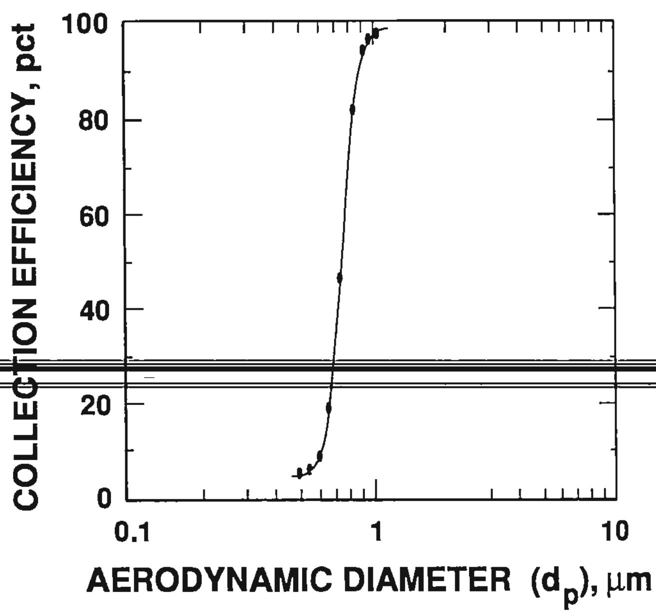

Figure 7.—Particle collection efficiency of the 0.8-μm impactor.

FIELD EVALUATION

The personal sampler has been evaluated in comprehensive sampling studies performed in three underground coal mines. The study and its results have been reported elsewhere (*14*). In each mine, 12 samplers were deployed in 6 different locations of a continuous miner section utilizing diesel-powered shuttle cars. These locations were the intake entry, haulageway, return entry, continuous miner, each shuttle car, and in a few instances, on one of the research staff.

A comparative study was made of data obtained with the personal sampler and data computed from an analysis of detailed size distributions obtained using a MOUDI. The average fraction of respirable material less than 0.8 μm was 30 pct at the continuous miner and in the return entry, 65 pct in the haulageway, and 50 pct for the research staff member who spent time at each test site.

ONGOING AND FUTURE RESEARCH

The sampler is currently being evaluated in both laboratory and field experiments conducted by the Bureau, MSHA, and GMTC-RD. In addition to comparison with the MOUDI, several referee methods, including CMB model analysis of aerosol elemental composition, evolved gas analysis of aerosol carbon and nitrogen, and Raman spectroscopy analysis of sample carbon, are being used in these tests. MSHA is also using this sampler and others in additional field tests that include some metal and nonmetal mines (*15*).

CONCLUSIONS

The primary results of this study are as follows:

1. Based on the premise that diesel exhaust aerosol is predominantly submicrometer in size and coal dust is mostly greater than 1 μm in size, size-selective sampling can be effective as a technique for measuring diesel aerosol concentrations in underground coal mines.

2. In-mine measurement of mine aerosol size distributions and CMB analysis confirms the premise for using aerosol size to separate diesel exhaust and mineral dust aerosol during sampling.

3. A personal diesel aerosol sampler has been developed for measuring the diesel aerosol concentrations in underground coal mines. This device consists of three

sequential stages. The first-stage preclassifier limits the sample to respirable aerosol. The second stage separates the resulting respirable aerosol into two parts by aerodynamic diameter using a single-stage impactor with a cut size of 0.8 μm. The third stage collects the less than 0.8-μm-diameter aerosol on a media that is suitable for gravimetric analysis.

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DIESEL EXHAUST AEROSOL MEASUREMENTS IN UNDERGROUND METAL AND NONMETAL MINES

By Bruce K. Cantrell[1] and Kenneth L. Rubow[2]

ABSTRACT

Two source apportionment techniques have been applied by the U.S. Bureau of Mines to aerosol measurements in diesel-equipped underground noncoal mines. The first technique is based on size-selective sampling and the premise that the diesel exhaust fraction of the aerosol is predominately submicrometer in size while the mineral dust fraction of the aerosol is mostly supermicrometer in size. The second technique, chemical mass balance (CMB) modeling, was used to referee the analysis of diesel and mineral dust aerosol concentrations with the size-selective method.

The size-distribution data were modeled using a lognormal regression to parameterize the submicrometer and supermicrometer fractions of the sampled aerosol and to estimate the mineral and diesel contributions to each. Using this analysis, 97±2 pct of the submicrometer aerosol mass was attributable to diesel exhaust aerosol.

The CMB analysis, applied to both fractions of the respirable mine aerosol, yielded the amount contributed to each by the diesel and dust aerosol sources. On the basis of this analysis, 94±10 pct of the submicrometer fraction was diesel exhaust aerosol. As much as 20 pct of the diesel aerosol, however, was found in the supermicrometer fraction, requiring a correction of the submicrometer fraction results to account for the missing diesel mass. More accurate measurements will require a carbon-specific analysis of the aerosol.

INTRODUCTION

Measurement of the contribution of diesel exhaust to respirable aerosol in mine environments has become increasingly important because of current concerns over the occupational health effects resulting from exposure to diesel emissions. In response to this, the U.S. Bureau of Mines is developing and evaluating new sampling methods for measuring diesel aerosol in underground mines. Two such techniques are being studied by the Bureau, size-selective sampling and CMB modeling. These techniques use measurable physical or chemical characteristics of a mine aerosol sample to infer the amount of diesel particulate material contained in the sample.

Size-selective sampling is being adapted for measurement of diesel aerosol by the Particle Technology Laboratory of the University of Minnesota under sponsorship by the Bureau (*1*).[3] The use of this sampling technique is based on the premise that diesel and mineral dust aerosol can be physically separated by size and collected during sampling using inertial impaction. An independent effort by the National Institute for Occupational Safety and Health (NIOSH) to develop a size-selective sampling technique was also sponsored by the Bureau (*2*).

The second technique, CMB modeling, is being developed by the Bureau as an alternative measurement technique to referee the results obtained using size-selective sampling (*3*). It compares measured trace element

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[3]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

"fingerprints" of aerosol sources with similar profiles of mine aerosol samples. From these, the portions of the sample contributed by each source can be determined. Results of these investigations in underground coal mines have confirmed that diesel and coal dust aerosol are of different size and can be measured separately using size-selective sampling techniques (*4*).

A major difference in diesel usage among underground mines is due to the requirement for use of exhaust gas cooling systems in coal and gassy noncoal mines. The exhaust conditioning system that is generally used in gassy mines is the water scrubber. This device has little effect on most of the gases, but removes some particulate material from the exhaust (*5*). Nongassy mines usually employ exhaust conditioning in the form of catalytic converters, which have a limited effect on primary exhaust particulate. Because of this, exhaust aerosol size distributions in nongassy mines are expected to be different. To determine if size-selective sampling techniques can be used in such mines, the Bureau and the University of Minnesota conducted a second study in three metal and nonmetal mines, two nongassy and one gassy.

ACKNOWLEDGMENTS

The authors would like to acknowledge the assistance of Kenneth Rahn, professor, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI, who offered his staff to perform the instrumental neutron activation analysis (INAA) used in this work. They also provided a preliminary CMB apportionment analysis using a version of the U.S. Environmental Protection Agency computer code (*6*).

FIELD STUDIES

The field study conducted in metal and nonmetal mines is summarized in table 1. The table indicates each mine's geographical region, the material mined, and the type of haulage equipment used. The study consisted of collecting size-differentiated aerosol samples at four locations in a working section employing diesel haulage equipment: air intake entry (I); conveyor beltway entry (B), where applicable; air return entry (R); and haulageway (H). These locations are illustrated in figure 1 for the soda ash mine.

Table 1.—Mine data for metal and nonmetal mines D, E, and F visited in 1987

Mine	Region	Haulage	Type of material
D	Midwest . .	Diesel	Shale.
E[1]	West	. . do.	Soda ash.
F	. . do.	. . do.	Quartzite.

[1]Gassy mine; therefore, water scrubbers were used on diesel equipment.

Aerosol samples were collected using a microorifice, uniform-deposit impactor (MOUDI) and respirable dichotomous samplers (*4*). The MOUDI, used for size-distribution measurements, is a 10-stage cascade impactor with particle separation sizes at 15, 10, 5.62, 3.16, 1.78, 1.0, 0.562, 0.316, 0.178, and 0.1 μm plus an after-filter (*7*). The dichotomous sampler was used to collect aerosol for the elemental analysis used in the CMB model calculations. It consists of an impaction-type inlet designed to pass sample aerosol with an efficiency approximating the American Conference of Governmental Industrial Hygienists (ACGIH) respirable dust sampling criteria, followed by two MOUDI impaction stages, both with 0.7-μm separation sizes, plus an after-filter (*8*). Configured in this way, the dichotomous sampler provides a partition of the collected respirable aerosol sample into two size fractions, greater and less than 0.7 μm. This partition was selected because it was close to the size found to separate diesel exhaust and coal dust aerosol components in the laboratory studies and the impactor stages were available (*1*). Both the MOUDI and dichotomous samplers operate with a 30-L/min sample flow rate.

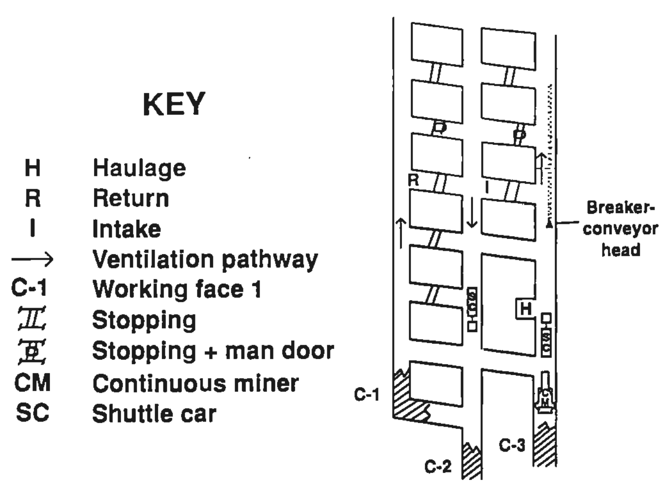

Figure 1.—Sampling site locations used for mine sampling experiment with ventilation vectors.

Trace element profiles of mine aerosol sources used in the CMB analysis were obtained from samples of the material from which the diesel or mineral dust aerosols originate. Exhaust source aerosol samples were collected from the tailpipes of the haulage vehicles operating in the mine. Bulk material samples of the mineral being mined were also collected. In each case, the profiles obtained are assumed to be representative of the aerosols originating from these sources.

To enhance the diesel tailpipe samples, a tracer material, a nominal 10 ppb of indium as indium 2,4 pentanedionate in xylene, was added to the fuel supply for the vehicles operating in the test section of the mines. The trace-element-analysis technique used, INAA, is very sensitive to indium, which is rarely found in nature (*9*).

Aerosol samples at haulageway or beltway locations were collected periodically during the entire mine work shift. Since they were collected in areas where workers are exposed, they are the samples of primary interest. Sample collection was only done when the conveyor belt was on and diesel haulage equipment was in use. The samples collected are therefore biased toward high concentrations of both diesel and mineral aerosol and are not representative of personal exposures during the work shift. Although not analyzed for the study, sampling at the return location was conducted once during the shift, while the continuous miner was in operation.

MEASUREMENT AND ANALYSIS TECHNIQUES

Only two measurement techniques were used in the field study. These were gravimetric analysis of the impaction substrates and after-filters from both the MOUDI and dichotomous samplers and elemental analysis of the dichotomous samples using INAA (*3*).

INAA was performed at the University of Rhode Island (*10*). Analyses were performed on dichotomous substrates and after-filter pairs containing sufficient aerosol mass for irradiation (1 mg or more), quality-control blanks of both substrate and after-filter, and samples of the aerosol source materials. The source materials were analyzed in triplicate, and average values of the resulting elemental concentrations were used in the CMB analysis.

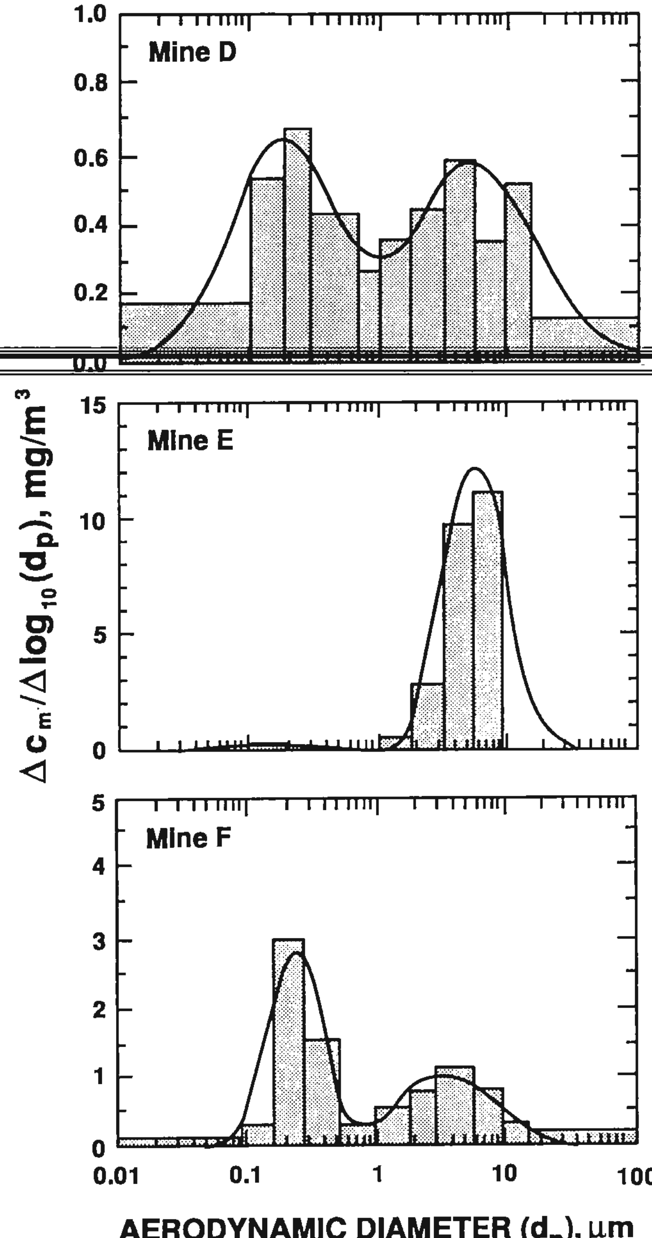

Figure 2.—Average mass size distributions for the haulage entries of mines D, E, and F. (c_m = mass concentration.)

MODAL ANALYSIS

Average aerosol size distributions measured in the haulageway of the diesel-equipped mines visited are shown in figure 2. The measured aerosol size distributions were modeled using a sum of two log-normal functions to fit the data (*11*). Each function represents one of the maxima, or modes, evident in the data. The log-normal distribution parameters, given in table 2 for the average distributions, are the mass median diameter (MMD), geometric standard deviation (σ_g), and mode concentrations.

For coal mines, each mode was identified with the aerosol contributed by a primary aerosol source—diesel exhaust aerosol for the submicrometer mode and mineral dust for the coarse particle mode (*3-4*). Under this assumption, the separate contributions from these sources to the total aerosol concentration can be determined using modal analysis. For these noncoal mines, the results of the size measurements are very similar. Two well-separated aerosol modes are evident for each of the mines. It remains for the CMB analysis to determine whether the same interpretation can be made.

Table 2.—Size-distribution parameters for average distributions measured in haulage entries of diesel-equipped metal and nonmetal mines D, E, and F

Mine	Fine			Coarse		
	MMD, μm	σ_g	Concentration, mg/m³	MMD, μm	σ_g	Concentration, mg/m³
D	0.18±0.03	2.5±0.2	0.6±0.2	5.1±1.0	3.1±0.3	0.7±0.2
E	0.16±0.13	2.4±0.7	0.20±0.06	6.1±3.3	1.8±0.3	7.5±4.0
F	0.26±0.04	1.6±0.1	1.4±0.3	3.8±0.7	2.4±0.3	1.1±0.8

MMD Mass median diameter.
σ_g Geometric standard deviation.

CHEMICAL MASS BALANCE MODEL ANALYSIS

CMB model analysis permits the relating of elements or chemical components in an aerosol sample collected at a given location to those same components in the sources of the aerosol (*6, 12*). The model is expressed as—

$$C_i = \sum_{j=1}^{p} a_{ij}S_j, \qquad (1)$$

where C_i = mass concentration of i^{th} elemental component of sample, mg/m³,

p = number of aerosol sources,

a_{ij} = fractional amount of component i in emissions from source j,

and S_j = amount of aerosol mass concentration attributable to source j.

S_j/(total sample mass concentration) is termed the source apportionment fraction. Apportionment of the source is achieved by measuring trace-element-component profiles of the aerosol sources, thus obtaining values for a_{ij}, analyzing the aerosol in the collected aerosol sample for the same components, and determining S_j using a least squares analysis of the overdetermined system of equations expressed by equation 1.

The CMB analysis used for the work employs effective variance weighing for the least squares calculation of the source apportionment terms S_j in equation 1 (*3, 12*). In this analysis, S_j is determined by minimizing the following chi-square (X^2) function:

$$X^2 = \sum_i \frac{\left(C_i - \sum_j a_{ij}S_j\right)^2}{\sigma_{C_i}^2 + \sum_j \sigma_{a_{ij}}^2 S_j^2}, \qquad (2)$$

where σ_{Ci} = standard error in C_i,

and σ_a = standard error in a_{ij}.

The minimization was carried out using a direct-search technique rather than matrix inversion calculations.

RESULTS AND DISCUSSION

Average values for the CMB source apportionments are given for mines D, E, and F in table 3 for the fine, minus 0.7 μm, and coarse, plus 0.7 μm, portions of the dichotomous samples. Errors quoted in the table are more indicative of the variability of the results from sample to sample than of the true statistical errors. In each case, diesel exhaust is the dominant component of the submicrometer aerosol greater than 92 pct. These apportionments deviate from those of the coal mine samples in that a significant fraction of the respirable coarse aerosol in the mines where the diesel equipment does not use a wet scrubber is diesel, up to 40 pct for mine F (*3*). This translates to approximately 20 pct of the total diesel aerosol being greater than 0.7 μm in size.

Applying modal analysis to concurrent size-distribution samples permits a comparison with the CMB analysis results. Table 4 gives this comparison for coarse particle contamination of the minus 0.7-μm aerosol in the three diesel-equipped metal and nonmetal mines. The two analyses give the same result within the quoted errors.

It is not clear from these results that the size-selective technique used in the measurement of coal mine diesel aerosol can be extended to diesel-equipped metal and nonmetal mines. That technique depends on separating the collected aerosol sample into two size fractions at 0.8 μm (*4*). In metal and nonmetal mines, the substantial contribution to the respirable coarse fraction made by diesel exhaust aerosol compromises the use of size-selective sampling, reducing the accuracy to less than 80 pct. As a result, alternate, carbon-specific methods for determining diesel aerosol concentrations should be used in such mines if higher accuracy is desired. One such method is thermal-evolved gas analysis (*13*).

Table 3.—CMB source apportionment results of respirable size fractions for metal and nonmetal mines D, E, and F, percent

Mine and source	Minus 0.7 µm	Plus 0.7 µm
D:		
Diesel	94 ±12	25±20
Ore	5.6± 0.8	75±13
E:[1]		
Diesel	95 ± 7	<20
Ore	5 ± 5	81± 7
F:		
Diesel	92 ±12	40± 5
Ore	<12	60± 5

[1]Gassy mine; therefore, water scrubbers were used on diesel equipment.

Table 4.—Average coarse particle contamination of minus 0.7 µm samples for metal and nonmetal mines D, E, and F, percent

Mine	Modal	CMB
D	4±2	5.6± 0.8
E	<2	5 ± 5
F	2±1	<12

An evolved gas analysis technique called the thermal-optical method is being evaluated by NIOSH for this determination (*14*). This method, which uses the elementary carbon content of an aerosol sample as a surrogate for the diesel exhaust aerosol portion, is a modification of a technique developed for analysis of atmospheric aerosol (*15-16*). It operates by converting the aerosol carbon to carbon dioxide in a furnace as the temperature is varied over a range of 0° to 750° C. An optical feature provides for correction for pyrolitically generated elemental carbon, or "char," which is formed during the analysis of some samples. Measurement of the evolved gas can be used to quantify volatile carbon, carbonate carbon, and graphitic carbon in the aerosol sample at very low levels. Such methods are all in the research stage and have yet to be validated for use in the underground mining environment. They promise, however, to provide sensitive techniques for measuring diesel exhaust aerosol.

In metal and nonmetal mines, the amount of diesel-related aerosol in a filter sample can also be determined from the mass that is removable from the sample by combustion. This analysis method is termed "respirable combustible dust analysis" (*17*). To derive a measure of diesel exhaust aerosol in the sample, the analysis result must be corrected for the presence of oil mist and the fraction of the collected mineral aerosol that is removed during the combustion analysis. For aerosol samples collected in a diesel-equipped coal mine, such analysis is not appropriate since the principal mineral aerosol involved is also primarily carbon.

CONCLUSIONS

Using the results of the limited CMB analysis, two points can be made concerning the contribution of the various diesel mine sources to both fine and coarse fractions of the respirable aerosol concentrations in the metal and nonmetal mine environment:

1. Diesel exhaust aerosols are the dominant component of the submicrometer-mode aerosol measured in the diesel mines. More than 90 pct of the measured aerosols in this size range is contributed from diesel sources.

2. Unlike coal mines, as much as 20 pct of the diesel exhaust aerosol contributes directly to the coarse part of respirable aerosol in the mine atmosphere.

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A COST-EFFECTIVE PERSONAL DIESEL EXHAUST AEROSOL SAMPLER

By Thomas C. McCartney[1] and Bruce K. Cantrell[2]

ABSTRACT

The U.S. Bureau of Mines has redesigned the University of Minnesota's (University) personal diesel exhaust aerosol sampler (PDEAS) and has evaluated the new sampler alongside the University sampler in laboratory and field tests. The Bureau sampler uses three consecutive stages to separate and collect respirable mineral and diesel aerosol from sampled air. The first stage is a 10-mm Dorr-Oliver cyclone acting as a respirable preclassifier. The second stage is a 0.8-μm impactor that collects aerosol greater than 0.8 μm in size. The third stage is a commercially available after-filter assembly that collects aerosol less than 0.8 μm in size. The sampler is designed to operate with a sample flow rate of 2 L/min.

Laboratory evaluation of the impactor stage has shown that the Bureau impactor has a 50-pct cut point of 0.79$\pm$ 0.01 μm, with a geometric standard deviation (σ_g) of 1.18$\pm$0.05 compared with 0.77$\pm$0.03 μm with a σ_g deviation of 1.07$\pm$0.04 for the University impactor. The impactor section of the Bureau sampler has internal losses of less than 2 pct compared with 10 pct for the University sampler when a 0.8-μm test aerosol was passed through the stage.

Field evaluation and comparison of the Bureau and University samplers yield linear regression relationships of Y = (1.007$\pm$0.04) X + 0.003$\pm$0.11 and Y = (1.067$\pm$0.03) X + 0.112$\pm$0.19 with correlation coefficient (r^2) values of 0.984 and 0.992 for less than 0.8-μm and respirable-size aerosols, respectively. These performance comparisons have determined that the Bureau sampler is completely equivalent to the University sampler. A cost analysis has shown that the complete Bureau sampler can be produced in quantity for under $200.

INTRODUCTION

The University of Minnesota and the U.S. Bureau of Mines have conducted studies of coal mine aerosol in both the laboratory and underground coal mines. These studies have shown that respirable coal dust and diesel aerosol can be differentiated by size (*1-2*).[3] The measured aerosol mass concentration (c_m) size distribution (fig. 1) is bimodal, with the primary modal separation at 0.8 μm. Diesel aerosol has been shown to be predominately less than 0.8 μm in size and coal dust greater than 0.8 μm in size (*3*).

Based on design criteria developed from these studies and accepted impactor theory and design guidelines (*4-5*), a prototype three-stage PDEAS was developed by the University (*6*). The sampler is depicted in the block diagram shown in figure 2. Figure 3 shows the assembled sampler. The first stage is a 10-mm Dorr-Oliver respirable cyclone.

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[3]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

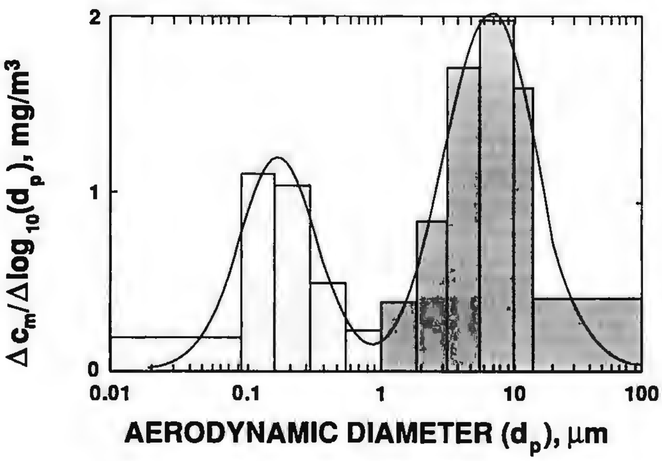

Figure 1.—Bimodal size distribution of mine aerosol.

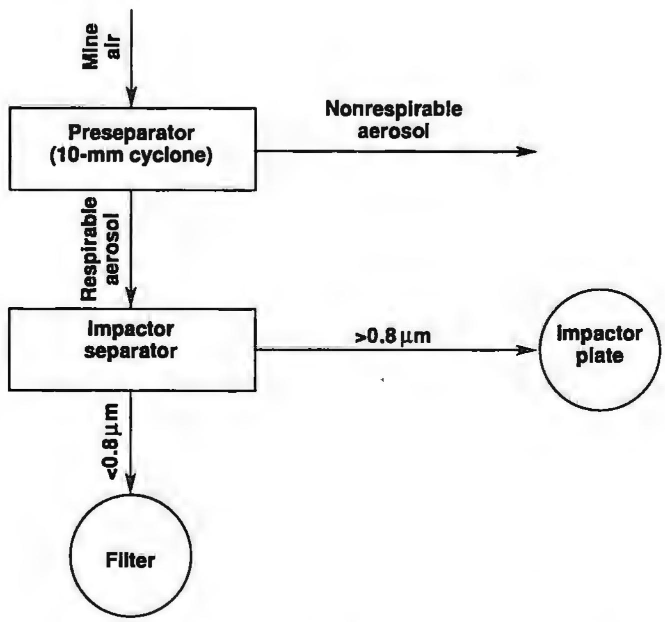

Figure 2.—Block diagram of University sampler.

This inertial preclassifier collects the nonrespirable portion of the aerosol and passes the respirable portion to the impactor stage. The impactor stage uses a plate with four nozzles to obtain a 0.8-μm, 50-pct cut point. The third stage is a 37-mm after-filter that collects the less than 0.8-μm aerosol. The impactor stage and the after-filter are housed in a single unit. The three-stage personal sampler is held in a modified Mine Safety Appliances Co.[4]

[4]Reference to specific products does not imply endorsement by the Bureau of Mines.

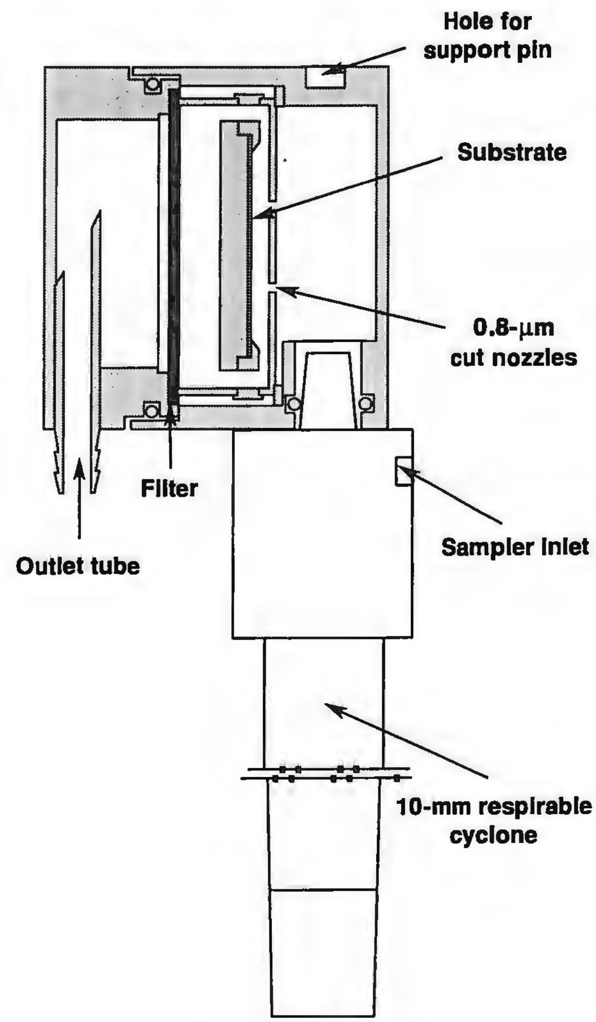

Figure 3.—University sampler.

(MSA) (Pittsburgh, PA) model 456243 personal respirable dust sampler holder.

The University PDEAS (personal diesel-coal dust sampler, model 210, MSP Inc., Minneapolis, MN) has been shown in both laboratory and in-mine tests to be an effective sampler (*6-8*). The impactor-after-filter stage has nine manufactured parts and requires the modification of a standard MSA model 456243 personal respirable dust sampler holder. These factors contribute to a commerical cost of $1,500. Consequently, the Bureau has redesigned the sampler to achieve cost effectiveness. The new sampler was evaluated in both laboratory and field tests to demonstrate equivalence with the University sampler, and a cost analysis was conducted to estimate the cost advantage of the new sampler.

ACKNOWLEDGMENTS

The authors would like to acknowledge Kenneth Rubow, Research Associate, Particle Technology Laboratory of the University of Minnesota, Minneapolis, MN, who offered his staff to aid in the performance of the impactor penetration and loss measurements reported in this paper.

SAMPLER DESIGN

The Bureau sampler was based on the same design parameters as the University sampler. However, a design objective for the new sampler was to use commercially available components where possible. Within the impactor stage, the number of manufactured parts was minimized and the geometries were kept simple. Ease of assembly and operation were also prime considerations in the design.

The three-stage Bureau sampler is depicted in figure 4. The first stage is a 2-L/min, 10-mm Dorr-Oliver cyclone used as a respirable preclassifier. The second stage is a four-nozzle inertial impactor with a 50-pct cut point of 0.8 μm. The impaction surface consists of a doughnut-shaped 37-mm greased aluminum substrate with a central sample exit. This substrate collects the portion of the respirable aerosol sample greater than 0.8 μm in size. The third stage is a filter cassette (MSA model 457193) that collects the aerosol less than 0.8 μm in size. The three stages have been designed to be incorporated into an unmodified personal respirable dust sampler holder (MSA model 456243).

The impactor stage consists of three manufactured parts, excluding the substrate, i.e., the cap, the orifice plate, and the base. The orifice plate is press fit into the cap and the base supports the impaction substrate. Compared to the University PDEAS, the Bureau sampler is easier to assemble. In addition, the impactor stage allows rotation of the substrate without sampler disassembly. Rotating the substrate can prevent overloading by exposing new grease for deposit.

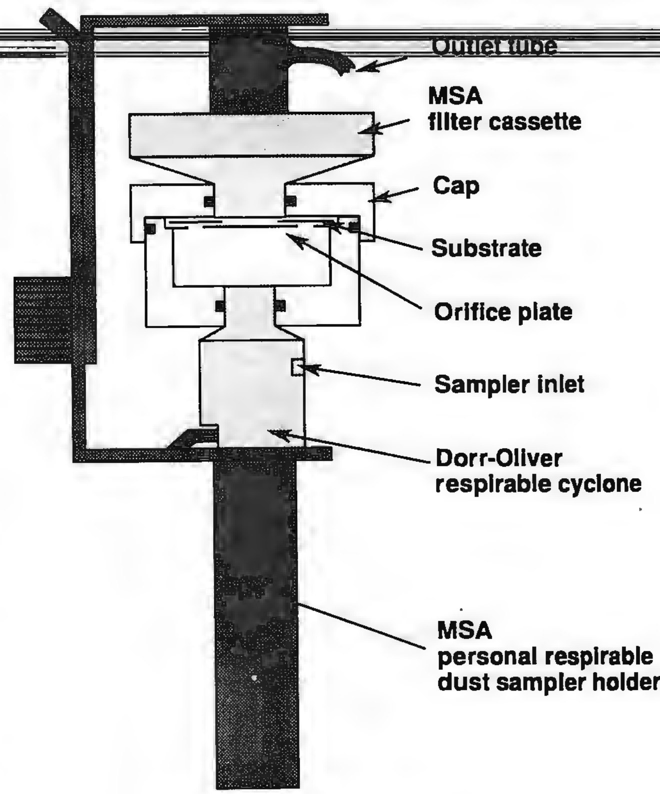

Figure 4.—Bureau sampler.

LABORATORY EVALUATION

The impaction stages of both the Bureau and University samplers were evaluated together in the laboratory. The evaluation was conducted in two parts: (1) a particle deposition characterization and (2) a measurement of collection efficiency as a function of aerosol size. The impaction surfaces (substrates) of both impactor sections were greased with Dow Corning (Midland, MI) high-vacuum silicone grease.

PARTICLE DEPOSITION EVALUATION

The particle deposition evaluation consisted of sampling several sizes of monodispersed aerosol tagged with a fluorescent tracer. All internal surfaces of the impactor and after-filter sections were washed individually after sampling. The rinse liquids were then measured for relative fluorescence levels (*9-10*). Nomenclature for the different surfaces washed is shown in figure 5.

The experimental test arrangement is illustrated in figure 6. Monodispersed, solid-fluorescein aerosols were generated in sizes from 0.80 to 10.7 μm using a TSI, Inc. (St. Paul, MN), model 3450 vibrating orifice aerosol generator (*11*). Electrostatic charges on the aerosol were brought to equilibrium using a polonium radiation source, and a plenum was used to distribute the sample stream. All samplers were operated simultaneously in their design orientations. To facilitate introduction of the aerosol sample into the impactor, the vortex finder of the Dorr-Oliver cyclone was attached to the inlet of each impactor. Sample pumps, operating at 2 L/min, were calibrated using a Gilian Instrument Corp. (Wayne, NJ) model 1100 bubble flowmeter. Calculated aerosol size was confirmed using a TSI, Inc. (St. Paul, MN), model APS 33 aerodynamic particle sizer.

Figure 7 shows percentage deposition for each of the surfaces tested for both the University and the Bureau impactors and after-filter sections for an aerosol size of 0.8 μm. This includes loss to the surfaces of the impactor, i.e., inlet (surface 1), orifice plate surface (surface 2), and substrate support (surface 3), as well as normal collection by the substrate (surface 4) and after-filter (surface 5). Particle deposition in the Bureau impactor was 2 pct total for surfaces 1, 2, and 3 compared with deposition losses of 10 pct for the University impactor.

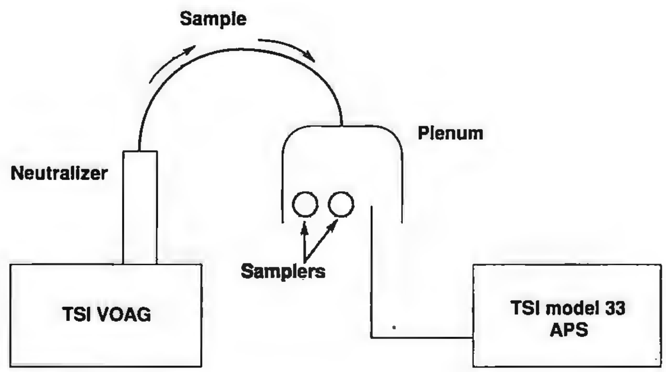

Figure 6.—Schematic of particle deposition characterization test.

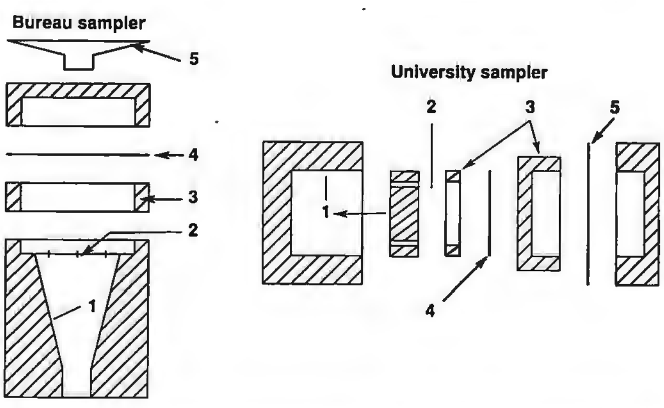

Figure 5.—Surface nomenclature for deposition surfaces. (1 = inlet interior; 2 = orifice plate surface; 3 = substrate support; 4 = substrate; 5 = after-filter.)

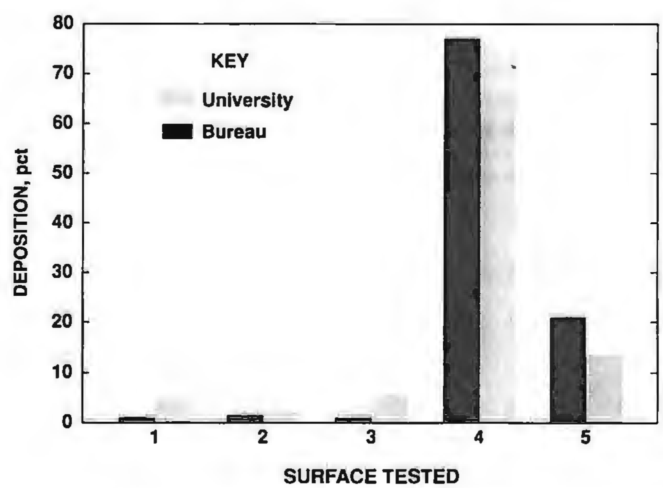

Figure 7.—Percentage of total particles deposited for surfaces tested for 0.8-μm aerosol.

COLLECTION EFFICIENCY

The collection efficiency of the 0.8-μm cut-point impactors used in the Bureau and University samplers was measured as a function of aerosol size using monodispersed polystyrene latex (PSL) particles ranging in size from 0.56 to 1.10 μm. A test schematic diagram of the calibration arrangement is shown in figure 8. An aqueous suspension of the PSL was aerosolized using a Collison atomizer. The aerosol was then passed through a silica dryer, a neutralizer, and a large-volume sample capacitor before entering the inlet of the impactor. The aerosol was sampled and counted in 60-s intervals using a Particle Measuring Systems, Inc. (Boulder, CO) LAS-X single particle counter. The LAS-X sampled at 0.3 L/min. Excess aerosol was dumped to a filter and flowmeter. Sample flow to the impactor was measured using the Gilian bubble flowmeter as shown in the test schematic diagram.

A three-part test protocol was followed. An upstream sample was taken without the impactor in place. Then the impactor was put in-line and a downstream sample was taken. Finally, the impactor was removed for another upstream sample. The two upstream samples were averaged and aerosol removal was determined from the downstream and resultant upstream measurements. All flows were maintained constant at 2 L/min during both upstream and downstream sampling intervals.

The particle collection efficiency is presented as a function of particle size in figure 9. The 50-pct collection efficiency point ($E_{50\ pct}$) for the Bureau impactor was 0.79±0.01 μm with a σ_g of 1.18±0.05, indicating a sharp cut. The σ_g is defined as the square root of the ratio of the particle diameter corresponding to the 84.1-pct collection efficiency to the diameter at an efficiency of 15.9 pct. The University impactor had an $E_{50\ pct}$ cut point of 0.77±0.03 μm and a σ_g of 1.07±0.04. These experimental results agree well with previous experimental findings where the University impactor had an $E_{50\ pct}$ of 0.76±0.05 μm and a σ_g of 1.15±0.05 (*8*).

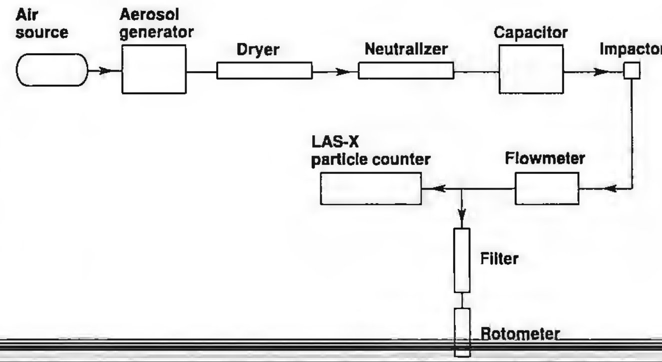

Figure 8.—Schematic diagram of cut-point calibration test.

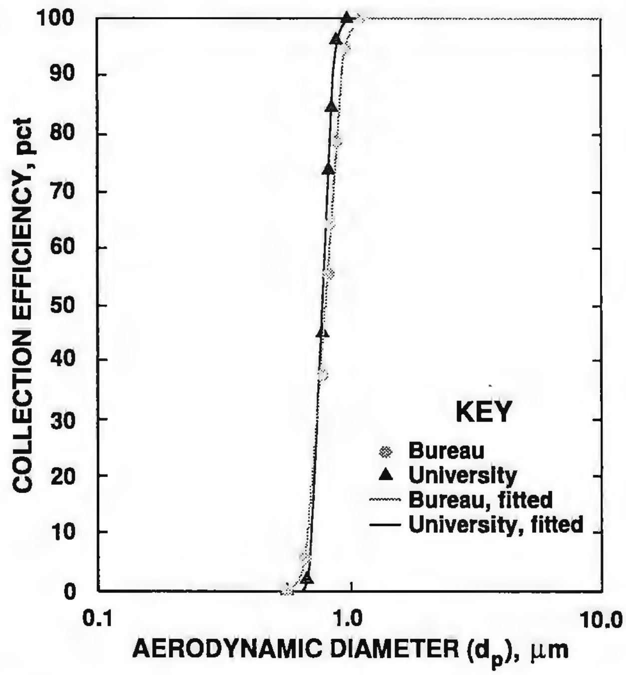

Figure 9.—Particle collection efficiency as a function of particle size.

FIELD PERFORMANCE

The performances of the Bureau and University samplers were compared in one coal mine that uses diesel-powered equipment. Each sampler type was deployed at three locations in a section of the mine: the ventilation intake, the haulage area, and the ventilation return. This produced 10 concurrent samples for the 2 sampler types. The impaction surfaces of both samplers were coated with Dow Corning high-vacuum silicone grease.

Results of the sampler comparison are shown in figures 10 and 11 for less than 0.8-μm and respirable aerosols, and the results of a linear regression comparison is given in table 1. The samplers compare very well with r^2 values of 0.984 and 0.992 for less than 0.8-μm and respirable aerosols, respectively.

Table 1.—Linear regression coefficients for comparison between the University and Bureau personal samplers

Aerosol size range	Slope	Y-intercept, mg/m³	r^2
Less than 0.8 μm	1.007±0.04	0.003±0.11	0.984
Respirable	1.067±0.03	0.112±0.19	0.992

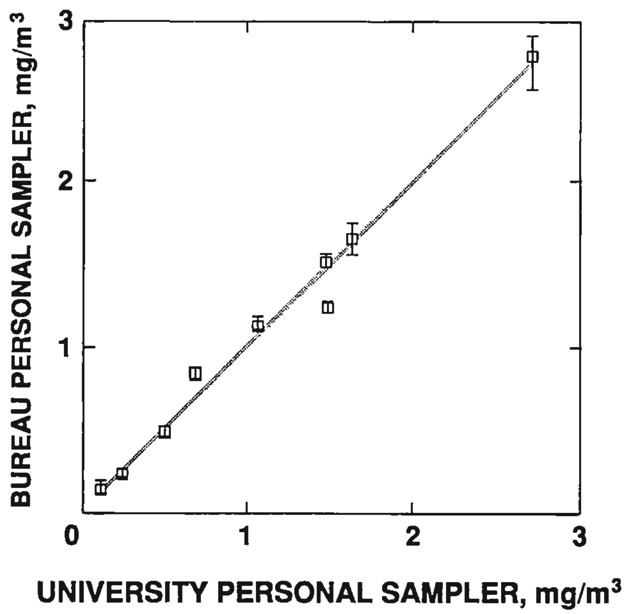

Figure 10.—Performance comparison of Bureau sampler and University sampler for less than 0.8-μm aerosol.

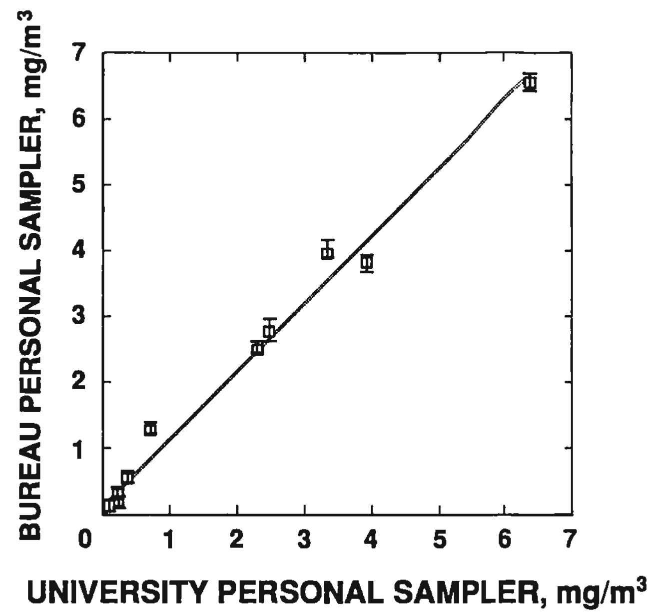

Figure 11.—Performance comparison of Bureau sampler and University sampler for respirable aerosol.

COST ANALYSIS

Manufacturing costs for the impactor section of the Bureau sampler were determined using cost quotations from three independent manufacturing companies; two offering machining services and one offering injection molding services. Figure 12 shows cost per unit as a function of the number of units made for a single production run. For each process, a single production run includes the costs of the mold or the tooling, setup, and labor. The cost of manufacture declines rapidly with the number of units made until the cost per unit is less than $10 for 1,000 or more units. The lowermost curve shows the cost for an injection molding process where the mold cost has not been included.

The commercial cost may be estimated at less than $200 when the costs of the impactor section, filter cassette, cyclone, sampler holder, and profit are considered. This cost is low when compared with the University sampler, which has a commercial cost of $1,500. The University sampler derives its high cost from the fact that it is a research prototype optimized for minimal particle loss. Unlike the Bureau sampler, it was not optimized for cost.

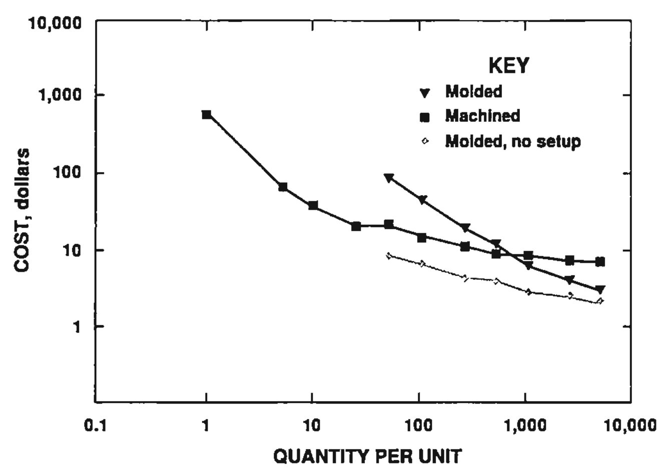

Figure 12.—Production cost per unit as a function of number of units made, impactor section only.

CONCLUSIONS

Laboratory and field tests have shown that the Bureau sampler is equivalent to the University sampler. Evaluation of aerosol deposition on the impactor sections of each sampler also shows equivalency for both impactor performance and internal deposition, which governs sample loss. In-mine comparisons have shown good agreement between the two samplers for concurrent samples.

A cost analysis indicates that the complete Bureau sampler can be produced for less than $200. This low cost was achieved by minimizing the number of manufactured parts and their complexity.

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DIESEL EXHAUST AEROSOL LEVELS IN UNDERGROUND COAL MINES

By Winthrop F. Watts, Jr.,[1] Bruce K. Cantrell,[2] Jeffrey L. Ambs,[3] and Kenneth L. Rubow[4]

ABSTRACT

The University of Minnesota and the U.S. Bureau of Mines collaborated to develop and field test a personal diesel exhaust aerosol sampler (PDEAS). The PDEAS was field tested in five underground coal mines that use continuous miners and a variety of diesel vehicles, including diesel haulage and utility vehicles. One mine was surveyed a second time, with the haulage vehicles fitted with a low-temperature disposable diesel exhaust filter (DDEF). Aerosol samples were collected with a variety of instruments, including the PDEAS and the microorifice, uniform-deposit impactor (MOUDI). This paper presents the diesel exhaust aerosol (DEA) concentration data collected in these mines and assesses the impact of diesel face-haulage equipment, with and without exhaust filters, on underground mine air quality.

The average DEA concentration at the haulageway location for five mines, determined by the PDEAS, was 0.89 mg/m^3, with a standard deviation of 0.44 mg/m^3. DEA contributed 52 pct, of the respirable aerosol at the haulageway location. Use of the DDEF at one mine reduced DEA by 95 pct, with a standard deviation of 6 pct, and filter life averaged 10 h. DEA contributed a large proportion of the respirable aerosol concentrations in mines with diesel equipment, and a substantial reduction was achieved with use of a DDEF.

INTRODUCTION

Diesel equipment is gaining popularity in underground coal mines. There are an estimated 1,951 units of diesel equipment in 152 underground coal mines compared with 1,100 units in 110 mines 5 years ago (*1*).[5] This increased use is due to the recognition that diesel-powered vehicles are more versatile, which can contribute to increased productivity compared with their electrically powered counterparts. Approximately 33 pct of the diesel vehicles haul coal, 45 pct haul personnel and materials, and 22 pct perform other duties, such as roof bolting, rock dusting, and road maintenance. Most mines using diesel equipment are located in Kentucky, Utah, Virginia, and Colorado.

Diesel exhaust contains noxious gases, such as carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, and sulfur dioxide, as well as DEA. The U.S. Mine Safety and Health Administration (MSHA) has proposed air-quality standards for these and other contaminants (*2*). Among these pollutants, DEA is of particular concern because it is almost entirely respirable in size, with more than 90 pct of the particles, by mass, having an aerodynamic diameter less than 1.0 μm. DEA is currently regulated under the 2.0-mg/m^3 respirable coal mine dust standard. MSHA has published an advance notice of proposed rulemaking to establish a separate permissible exposure limit for diesel particulate (*3*).

The U.S. Bureau of Mines collaborated with the University of Minnesota to develop and field test a PDEAS. The PDEAS utilizes size-selective sampling by inertial impaction, followed by gravimetric analysis to measure DEA. The development and laboratory evaluation of the PDEAS was described previously (*4-8*) and is also reviewed in this Information Circular. During field tests of this sampler, numerous air quality measurements were made

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[5]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

sampler, numerous air quality measurements were made in five underground coal mines using diesel haulage equipment. Previous reports (*9-10*) summarized these data. One of these mines was revisited to evaluate the effectiveness of a low-temperature DDEF system to remove diesel aerosol from exhaust. These data were reported elsewhere (*11*) and are reported here only to show the range of DEA concentrations in a mine using state-of-the-art control technology. Complete details of the DDEF system are provided elsewhere in this Information Circular. The objectives of this paper are to present the DEA concentration data collected in these mines and to assess the impact of diesel face-haulage equipment, with and without exhaust filters, on underground mine air quality.

ACKNOWLEDGMENTS

This research was partially supported by the U.S. Department of Interior's Mineral Institute program administered by the Bureau through the Generic Minerals Technology Center for Respirable Dust under grant G-1135142 to the University of Minnesota.

MINE DESCRIPTIONS

Aerosol data were collected in five underground coal mines that use diesel haulage. These mines are designated J, K, L, N, and O. Aerosol data were collected a second time at mine K to evaluate the DDEF system and, for the purpose of this paper, are reported separately as mine M. Mines J and L are located in the Eastern United States and the others are high-altitude mines located in the West. Each mine produces high-volatile bituminous coal with shift-production levels varying from 225 to 900 kg/shift. Seam heights varied from 1.5 to 3.0 m. Mines K, M, and N use continuous mining to develop longwall panels. The others are strictly room-and-pillar operations that use continuous miners.

The number of diesel-powered vehicles used in these mines is summarized in table 1. A total of more than 250 diesel-powered vehicles are used at the five mines (*1*). Mines J, K, N, and O also use diesel power to assist in a wide range of activities, including road maintenance, personnel and materials transport, lubrication, and welding. Mine L has four diesel-powered vehicles, three of which are haulage vehicles (shuttle cars) used to haul coal. All vehicles operating at all mines inby the last open crosscut are permissible, equipped with water-bath exhaust conditioners, as required by MSHA.

Table 1.—Diesel-powered vehicles used in the five mines

Mine	*Number of units*
J	13
K	[1]5
L	4
N	117
O	53

[1]Mine K shares diesel-powered vehicles with a sister mine and the 2 mines combined have 65 diesel units.

SAMPLING AND ANALYSIS METHODS

The PDEAS, described elsewhere (*8*) and shown schematically in figure 1, has three stages and employs inertial impaction for separating and collecting the diesel and mineral dust fractions of the sampled respirable aerosol. The first stage is an inertial preclassifier, a 10-mm Dorr-Oliver[6] cyclone that separates and collects the larger, nonrespirable aerosol. The second stage is a four-nozzle impactor with a sharp 50 pct cut point of 0.8 μm aerodynamic diameter. Most aerosol particles larger than 0.8 μm are deposited on an impaction substrate in this stage. The third stage is a filter that collects the remaining aerosol of less than 0.8 μm aerodynamic diameter. The sampler operates at a flow rate of 2 L/min, which is compatible with both the personal sampler pump and the 10-mm cyclone.

It was shown in the laboratory (*12*) and in underground mines (*4-5, 7*) that inertial impaction, followed by gravimetric analysis, can be used to separate and sample diesel exhaust and mineral dust aerosol fractions and provide estimates of DEA concentrations. These preliminary evaluations of the sampling technique indicate that these

[6]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

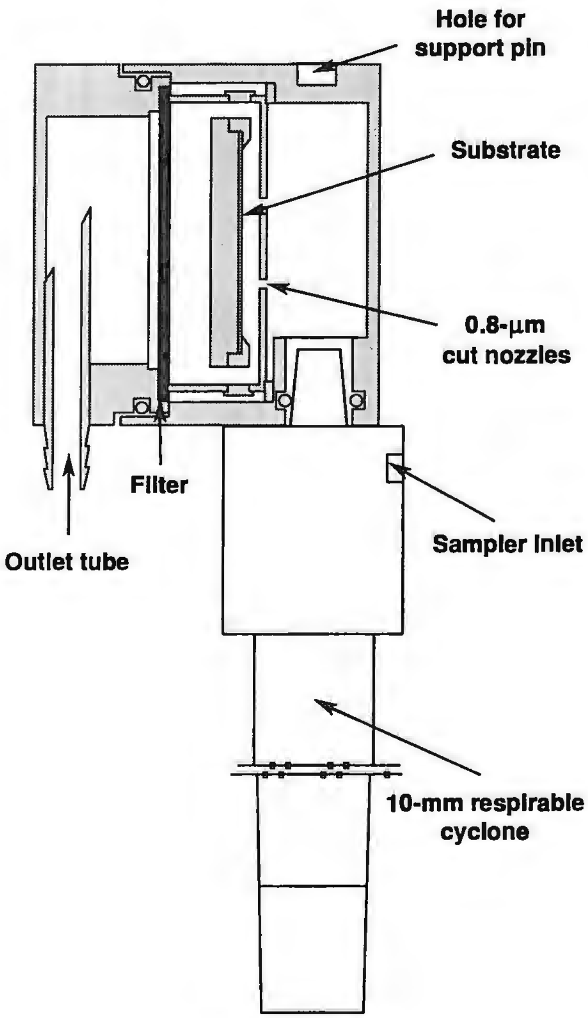

Figure 1.—PDEAS.

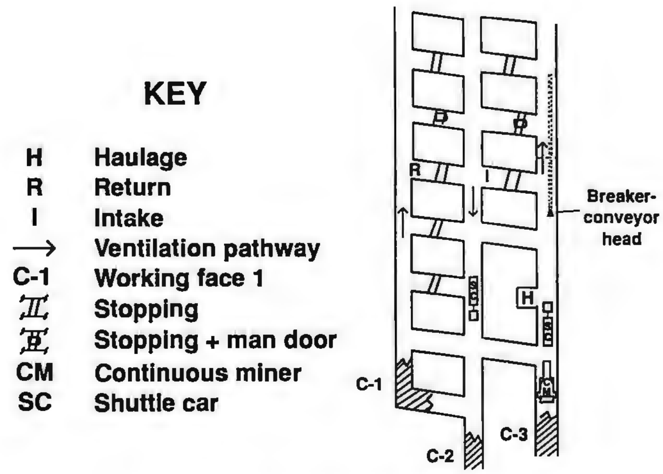

Figure 2.—Organization of typical continuous miner section.

are accurate to within 25 pct, 95 pct of the time, for concentration levels above the estimated limit of detection of 0.3 mg/m^3. Below this level, indications are that the 95-pct confidence interval can exceed 60 pct because of interferences caused by submicrometer mineral dust and background atmospheric aerosol. During PDEAS field tests, aerosol samples were also collected using MOUDI samplers (*13*). Analyses of MOUDI-derived size distributions provided accurate concentrations of DEA and respirable coal mine dust aerosol which were used to measure the performance of the PDEAS.

In each mine, 12 PDEAS's were deployed at different locations in a continuous miner section utilizing diesel-powered shuttle cars. These locations included the intake entry, haulageway, return entry, shuttle car(s), and, in a few instances, on individuals. Figure 2 is a schematic diagram showing a typical room-and-pillar section with the location of the stationary sampling points used in the sampler field tests. Each of the mine sections surveyed used two to four diesel-powered shuttle cars to haul coal cut by an electric continuous miner. Additional samples were collected using a size selective sampler designed by MSHA. These data were reported elsewhere (*14*). Complete details of the mine layout, mining method, production tonnage, and ventilation for each mine are available from MSHA (*15*).

Mine Research Establishment (MRE) equivalent respirable coal mine dust concentrations are reported for PDEAS data. These data were calculated as (1.38 × (mass deposited on the impactor plate of the PDEAS) + mass collected on the after-filter) ÷ the volume of sampled air (*16*). DEA concentrations were determined by dividing the mass collected on the filter by the volume of air sampled. No correction was made for mineral dust aerosol deposited on the submicrometer stages of the impactors or background aerosol entering the section through the intake airway. The 1.38 correction factor is intended to adjust collected sample mass for the difference in penetration efficiency between the 10-mm cyclone preclassifier and the Cassella elutriator preclassifier on which the MRE definition of respirable dust is based (*16*). Since the difference in penetration efficiency affects only aerosol greater than 1 µm in size, the correction factor is applied only to the coarse (greater than 0.8 µm) part of the PDEAS sample.

EVALUATION OF A DISPOSABLE DIESEL EXHAUST FILTER

The DDEF system was evaluated in a continuous miner section in mine M. MSHA safety standards require that vehicles used at the face be equipped with water-bath exhaust conditioners to control exhaust temperatures and to arrest flames and sparks emitted from diesel engines (*17*). Figure 3 illustrates the mounting of the DDEF system and provides a cross-sectional view of the DDEF. Exhaust passes through the water scrubber before passing through the DDEF. The DDEF system was developed to take advantage of the low exhaust temperatures exiting the water scrubber and is described in detail elsewhere in this Information Circular. Filter life averaged about 10 h at this high-altitude mine.

The week-long field study to evaluate the performance of the DDEF's was conducted at mine M. All the vehicles in the section, which included three diesel-powered shuttle cars and one scoop, were equipped with the DDEF system. During the first 4 days, the vehicles were operated with the DDEF installed, and on the last day the DDEF was removed. The sampling protocol and locations were similar to those previously described. The concentration of DEA in the mine environment was measured with the PDEAS and other aerosol instruments. Samples were collected during normal production shifts in the ventilation in the intake, in the haulageway, on the shuttle cars, and in the return. Coal production, measured by tonnage, varied from 270 to 475 kg/shift and ventilation varied from 1,600 to 2,300 m^3/min during the test.

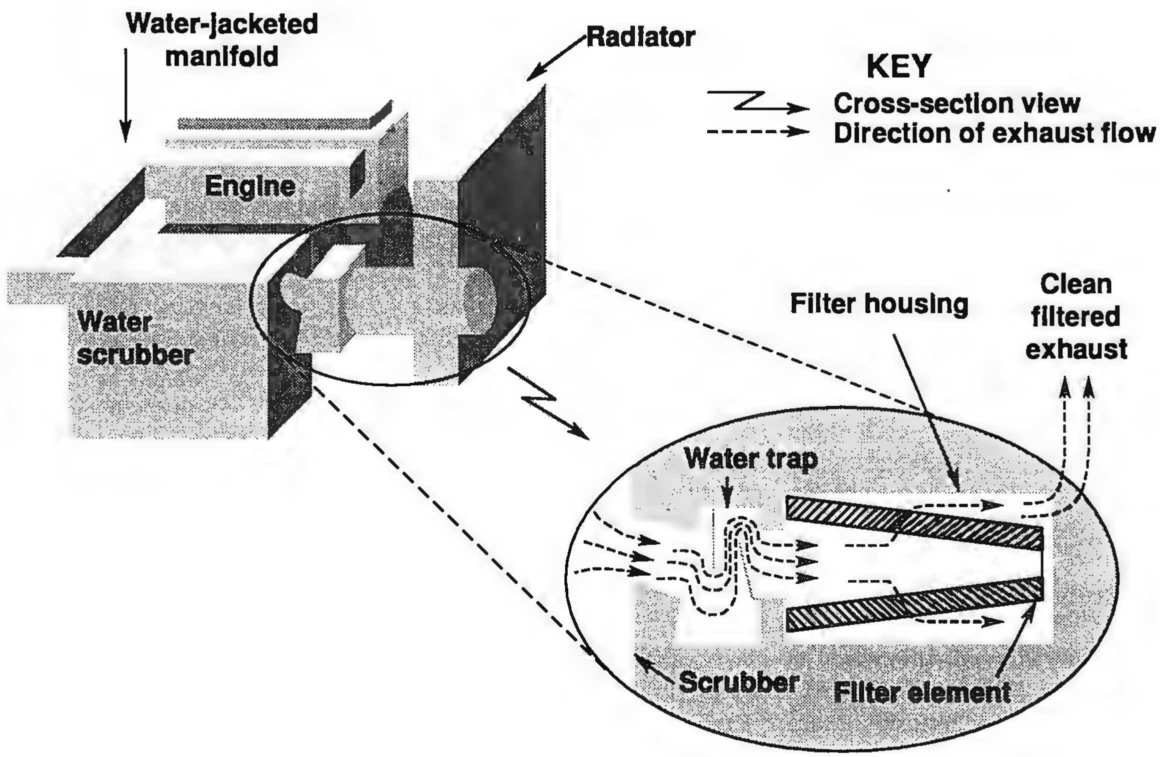

Figure 3.—DDEF.

RESULTS

Table 2 summarizes the results obtained with the PDEAS's for each mine. Samples collected at mine M are reported in table 3. Table 4 summarizes the results from MOUDI samples collected at each mine.

Table 2.—Mine summary of aerosol data obtained from PDEAS

Location	Number of samples	Concentration, mg/m³				DEA, pct	
		Respirable aerosol		DEA		Mean	SD
		Mean	SD	Mean	SD		
Mine J:							
Intake	1	0.12	NAp	0.09	NAp	77	NAp
Shuttle car	6	1.54	0.21	0.98	0.16	64	4
Haulage	7	1.49	0.24	1.01	0.21	68	4
Return	19	2.20	0.20	0.73	0.09	33	5
Scientist	3	1.10	0.26	0.55	0.11	51	3
Mine K:							
Intake	4	0.25	0.05	0.13	0.03	50	4
Shuttle car	8	2.02	0.40	0.68	0.12	35	9
Haulage	8	1.08	0.15	0.67	0.11	62	10
Return	18	1.68	0.34	0.71	0.14	43	10
Scientist	3	0.77	0.14	0.38	0.05	51	8
Mine L:							
Intake	4	0.08	0.04	0.04	0.02	48	22
Shuttle car	13	1.35	0.36	0.57	0.16	42	6
Haulage	10	1.13	0.31	0.74	0.27	64	10
Return	24	1.95	0.54	1.03	0.26	53	8
Mine N:							
Intake	5	0.36	0.12	0.24	0.11	63	6
Shuttle car	12	1.59	0.52	0.74	0.27	47	9
Haulage	10	3.63	1.62	1.39	0.51	42	9
Return	19	8.53	2.47	2.67	1.83	31	2
Scientist	5	1.32	0.18	0.29	0.04	22	4
Mine O:							
Intake	2	0.11	0.07	0.03	0.02	39	9
Shuttle car	12	0.81	0.14	0.53	0.11	65	9
Haulage	7	0.77	0.12	0.53	0.12	68	8
Return	20	9.13	3.87	2.03	0.99	21	3
Scientist	4	2.26	0.86	0.37	0.10	17	4

NAp Not applicable.
SD Standard deviation.

Table 3.—DEA concentrations measured using PDEAS at mine M with and without DDEF

Location	With DDEF				Without DDEF				Reduction, pct[1]	
	Number of samples	Concentration, mg/m³		CF	Number of samples	Concentration, mg/m³		CF	Mean	SD
		Mean	SD			Mean	SD[2]			
Intake	3	0.06	0.02	1.00	1	0.06	0.02	1.16	NAp	NAp
Haulage	7	0.12	0.02	0.90	2	0.50	0.02	1.63	94	6
Return	20	0.09	0.03	0.89	5	0.80	0.03	1.63	98	4
Shuttle car ..	8	0.17	0.05	0.84	2	0.81	0.03	1.63	93	7
Supervisor ..	2	0.13	0.02	1.01	1	0.48	0.02	1.63	90	8
Personnel ...	2	0.09	0.02	0.67	1	0.46	0.02	1.63	100	5

CF Correction factor.
NAp Not applicable.
SD Standard deviation.
[1]Corrected for intake concentration, ventilation, and production changes.
[2]Standard deviation for a single sample is assumed to be the same as for a multiple sample.

Table 4.—Mine summary of aerosol data obtained from MOUDI

Location	Number of samples	Concentration, mg/m³: Respirable aerosol Mean	Respirable aerosol SD	DEA Mean	DEA SD	DEA, pct Mean	DEA, pct SD
Mine J:							
Portal	3	0.017	0.015	0.010	0.011	46	32
Intake	3	0.025	0.023	0.014	0.013	56	10
Haulage	10	1.44	0.37	1.00	0.37	75	8
Return	4	3.00	1.33	0.71	0.21	34	13
Mine K:							
Intake	4	0.31	0.04	0.13	0.07	46	27
Haulage	7	0.98	0.14	0.58	0.13	58	9
Return	6	2.16	0.74	1.02	0.27	50	10
Mine L:							
Portal	3	0.019	0.002	0.009	0.001	57	8
Intake	5	0.13	0.031	0.020	0.014	21	17
Haulage	13	1.62	0.51	0.87	0.17	63	11
Return	5	2.85	0.70	1.24	0.04	53	11
Mine N:							
Portal	2	0.042	0.023	0.009	0.004	23	3
Intake	5	0.28	0.10	0.19	0.093	65	8
Haulage	12	3.96	1.57	1.54	0.52	39	9
Return	5	11.21	5.07	1.97	1.20	18	7
Mine O:							
Portal	2	0.028	0.008	0.006	NAp	17	NAp
Intake	4	0.18	0.044	0.037	0.013	20	6
Haulage	10	0.83	0.21	0.49	0.16	59	12
Return	2	4.57	0.60	0.46	0.05	10	3

NAp Not applicable.
SD Standard deviation.

Sampling times for the PDEAS and MOUDI varied with aerosol concentration and mining activity to avoid overloading the impaction substrates and to minimize particle bounce. The shortest sampling times were in the return airways, where aerosol concentrations were the highest. MOUDI and PDEAS data collected at the mine portal and section intake were almost always collected concurrently over a full, or nearly full, shift because aerosol concentrations were usually low. MOUDI sample collection times at the haulage and return sites averaged 96 min and ranged from 33 to 214 min. Two or three sets of MOUDI samples were collected per shift because longer sampling times result in an overload of the MOUDI substrates. Fewer MOUDI samples were collected in the return airway because of MSHA permissibility requirements. These requirements prohibit the sampling pump from being in the return airway and prohibit the use of the MOUDI motor, forcing manual operation. Usually MOUDI return samples were collected only on the last day of sampling. PDEAS mean sampling times ranged between 193 and 309 min at the haulage and return locations. All sampling was concurrent at the haulage location; therefore, PDEAS samples covered the same time periods as the multiple MOUDI samples, but the PDEAS substrates were not changed. PDEAS samples collected on shuttle cars, or on research personnel, are near full-shift data.

It is clear from MOUDI samples collected at the mine portals (table 4) that little respirable aerosol enters the mine environment from outside sources. Each of the mines is located in a sparsely populated region where air pollution is not a problem. Sources of respirable aerosol outside the mines are natural windblown dust, pollen, fugitive dust generated by vehicular traffic, storage piles, and belt conveyors.

Concentrations of respirable aerosol and DEA at the section intake, shown in tables 2 and 4, were very much dependent upon vehicular traffic in that area. Mines J, L, and O had the least traffic in the section intake. Mine L had only three diesel shuttle cars, which seldom passed the intake sampling points while the samplers were operating. Mines K and N used diesel equipment almost exclusively to move personnel, material, and coal; thus, intake DEA concentrations were higher.

The other sampling locations—haulageway, shuttle car, and scientist—were located near mining personnel and diesel activity. The return sampling site was selected to obtain a well-mixed aerosol sample, sufficiently far from the continuous miner to allow settling of large particles. The return sampling location was the area least likely to have mine personnel on a full-shift basis. It was sampled only for the limited time that the continuous miner was operating.

The respirable and DEA concentrations are higher in the haulage and return entries of mine N and in the return entry of mine O. For mine N, this was due to low-ventilation airflow during the survey. Mine O was unique in that it used a combination of beet pulp and rock dust as fire retardants on mine ribs in the return airway and at the coal face. This caused unusually high dust concentrations during sampling, particularly in the returns, because it flaked and fragmented more than other mine materials and became entrained in mine air.

Results, summarized in table 3, show that in relative terms the DDEF reduced average DEA concentration by 95 pct, with a standard deviation of 6 pct. In absolute terms, DEA concentrations with the DDEF installed were less than 0.2 mg/m³ at all locations. The concentrations and standard deviations shown in table 3 are average values, uncorrected for intake air concentration or production and ventilation changes. However, the DEA reductions (Δ) shown in the table were calculated by including correction factors for these parameters. The equation used to calculate the percentage reduction is

$$\Delta = 100\left(1 - \frac{C_w}{C_{w/o}}\right),$$

where C_w = DEA concentration with DDEF in place,

and $C_{w/o}$ = DEA concentration without DDEF in place.

The percentage DEA reduction is corrected for ventilation, section production, and aerosol background concentration in the intake air by using

$$C = C_m\delta_m - C_I\delta_I,$$

where C = corrected DEA concentration,

C_m = measured DEA concentration,

δ_m = correction factor for C_m,

C_I = measured DEA concentration at section intake,

and δ_I = correction factor for C_I.

Detailed size distribution and indium fuel tracer data further confirm that submicrometer mine aerosol is comprised mainly of DEA, which was effectively removed when the DDEF was installed (*11*).

Figure 4 is a lognormal probability plot that shows the cumulative frequency distribution of respirable aerosol (*A*) and DEA (*B*) concentrations obtained from the PDEAS samples collected in mines J, K, L, N, and O at the haulage, shuttle car, and return locations. The figure plots the cumulative percentage (y-axis) of samples with concentrations less than the concentration shown on the x-axis. Table 5 provides an overall summary of the PDEAS and MOUDI data, by location, for mines J, K, L, N, and O and provides the summary statistics for PDEAS data plotted in figure 4.

Generally, haulage and shuttle car locations have similar distributions for DEA (table 5), with median

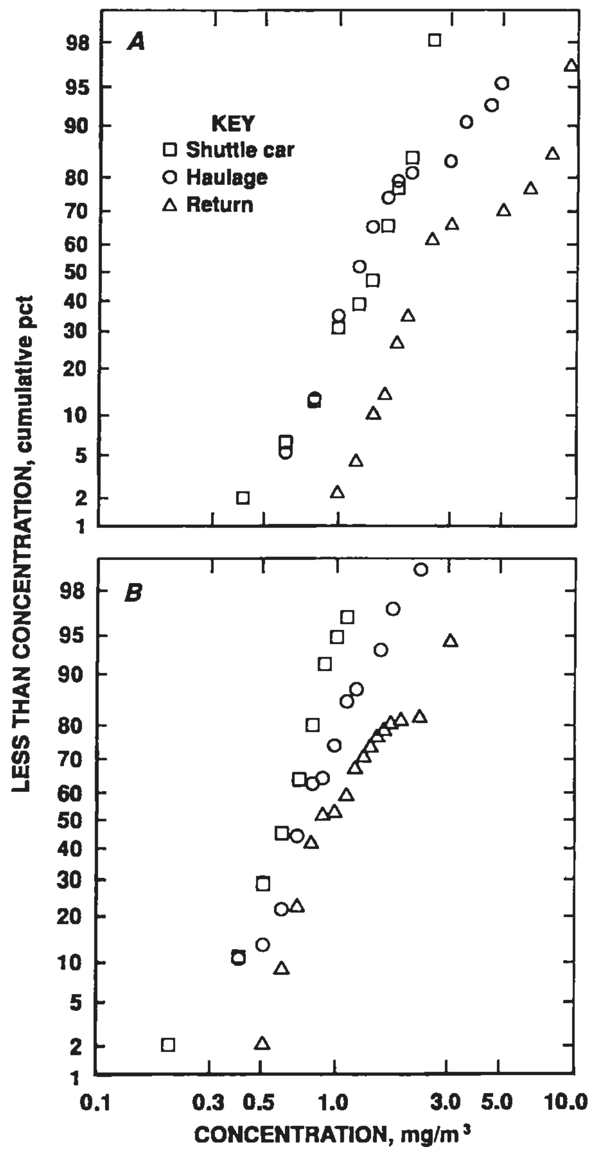

Figure 4.—Lognormal probability plot of PDEAS respirable aerosol (*A*) and DEA (*B*) distributions.

Table 5.—Summary statistics for respirable and DEA samples obtained using PDEAS and MOUDI

Location	Number of samples	Respirable aerosol concentration, mg/m³				DEA concentration, mg/m³			
		Mean	SD	Median	Range	Mean	SD	Median	Range
PDEAS									
Intake	16	0.21	0.15	0.18	0.04 - 0.61	0.13	0.12	0.09	0.01 -0.48
Personnel ...	15	1.42	0.75	1.23	0.57 - 3.71	0.38	0.13	0.35	0.24 -0.70
Haulage	42	1.72	1.38	1.21	0.59 - 6.15	0.89	0.44	0.75	0.31 -2.23
Shuttle car ..	51	1.40	0.54	1.44	0.35 - 2.70	0.67	0.23	0.65	0.19 -1.22
Return	100	4.63	3.97	2.38	0.91 -15.99	1.43	0.97	1.06	.46 -4.03
MOUDI									
~~Portal ......~~	~~10~~	~~0.025~~	~~0.017~~	~~0.020~~	~~0.004- 0.65~~	~~0.009~~	~~0.007~~	~~0.008~~	~~<0.001-0.025~~
~~Intake ......~~	~~21~~	~~0.20~~	~~0.12~~	~~0.19~~	~~0.006 - 0.49~~	~~0.085~~	~~0.096~~	~~0.046~~	~~0.002-0.37~~
Haulage	51	1.91	1.46	1.30	0.49 - 6.96	0.95	0.50	0.78	0.26 -2.39
Return	22	4.75	4.48	2.88	0.72 -18.67	1.18	0.79	1.16	0.40 -4.04

SD Standard deviation.

concentrations of 0.75 and 0.65 mg/m³, respectively. The median MOUDI concentration obtained at the haulage site where sampling was concurrent was 0.78 mg/m³ (table 5). These data suggest that the concentration of diesel exhaust is relatively uniform throughout the section. The median PDEAS concentration in the return location is higher at 1.06 mg/m³ (MOUDI median 1.16 mg/m³), which is expected. Respirable aerosol concentrations are also similar at the haulage and shuttle car locations, and again the return airway respirable aerosol concentrations are higher than concentrations in the haulageway and on the shuttle cars. DEA accounts for a large fraction of the respirable aerosol at every location with significant diesel activity.

DISCUSSION

Other investigators have used size-selective sampling methods to quantify submicrometer aerosol concentrations in diesel-equipped coal mines. McCawley (*18*) reported concentrations of DEA measured as aerosol less than 1.5 μm from two underground coal mines using diesel-face haulage equipment. Measurements were made using a single-stage, single-jet impaction preseparator described by Jones (*19*), a standard 10-mm nylon cyclone and cassette operated at an increased flow rate. The Anderson model 298 cascade impactor was also used. Mean submicrometer aerosol concentrations ranged from 0.1 mg/m³ at the intake to 0.77 mg/m³ at the continuous miner for the two mines.

Haney (*14*) conducted tests of a single-jet impactor designed and built by MSHA at five underground coal mines using diesel equipment. Miner exposure to DEA ranged from 0.18 to 1.00 mg/m³, and area samples collected in haulageways 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, and DEA measurements agreed within 0.06 mg/m³ of each other.

The measurements made for DEA during the evaluation of the PDEAS are quite similar to the measurements reported by previous investigators (*14, 17*). All the DEA measurements made to date suggest that DEA contributes a substantial percentage of the respirable dust in areas of underground coal mines where diesel haulage equipment is used.

The DDEF reduced average DEA concentration by 95 pct, with a standard deviation of 6 pct, and had a filter life of about 10 h. Detailed size distribution and indium fuel tracer data confirmed that submicrometer mine aerosol is comprised mainly of DEA, which was effectively removed when the DDEF was installed.

SUMMARY

Five underground coal mines that use diesel haulage equipment were surveyed using size-selective sampling by inertial impaction with gravimetric analysis to determine the concentrations of DEA. One of the mines was revisited to conduct a separate field study to evaluate the performance of DDEF's. The reduction of diesel exhaust in the mine environment was measured with the PDEAS and other aerosol instruments. The arithmetic mean DEA concentration determined from PDEAS samples at the haulage location for the five mines surveyed was 0.89 mg/m^3, with an average standard deviation of 0.44 mg/m^3. DEA contributed 52 pct of the respirable aerosol at this location. The mean haulageway concentration of DEA calculated from size distribution data obtained from MOUDI measurements was 0.95 mg/m^3, with a standard deviation of 0.50 mg/m^3. It is clear from these data that DEA can contribute significantly to respirable coal mine dust aerosol concentrations in mines using diesel haulage. The use of the DDEF at one mine reduced DEA by 95 pct, with a standard deviation of 6 pct. Clearly, DEA contributes a large proportion of the respirable aerosol in mines using diesel equipment, but a substantial reduction in DEA levels can be achieved with use of a DDEF.

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POLYNUCLEAR AROMATIC HYDROCARBONS AND BIOLOGICAL ACTIVITY ASSOCIATED WITH DIESEL PARTICULATE MATTER COLLECTED IN UNDERGROUND COAL MINES

By Susan T. Bagley,[1] Kirby J. Baumgard,[2] and Linda D. Gratz[3]

ABSTRACT

Michigan Technological University (MTU) and the U.S. Bureau of Mines have collaborated to measure the amounts of several polynuclear aromatic hydrocarbons (PAH's) and the mutagenic activity of diesel particulate matter (DPM) in samples collected in four underground coal mines. The DPM samples were collected in both the section intake and haulageway areas, using size-selective, high-volume samplers. The samples were shipped to MTU for PAH and biological activity determinations.

In general, the PAH and biological activity levels were statistically similar for all four mines; these data, therefore, provide a range of values that might be expected to occur in dieselized coal mines. The differences in levels between mines can be attributed to differences in parameters such as vehicle type, engine operation and maintenance, ventilation efficiencies, and fuel composition. It was also shown that in mines where vehicle engines idled for extended periods of time, the highest PAH and mutagenic activity levels were found. This situation could be remedied through proper training of mine personnel. Results from the section intake samples indicated that the DPM and the associated soluble organic fraction (SOF), PAH, and mutagenic activity may contribute up to 25 pct of the levels measured in the haulageway. These emissions were attributed to outby diesel vehicles and surface vehicles working near the mine intake.

INTRODUCTION

Whole diesel exhaust is regarded as a potential occupational carcinogen by the National Institute for Occupational Safety and Health (NIOSH) (*1*),[4] but the risk of cancer to exposed workers has not been conclusively defined. One problem encountered in defining risk is the chemical complexity of diesel exhaust, making it difficult to define exposure. MTU, through funding from NIOSH[5] grant R010H02611, and the U.S. Bureau of Mines Twin Cities Research Center are working together to define key aspects of the chemical nature and biological activity of DPM collected in underground coal mines. These data can then be used to assist in defining potential risks of exposure to diesel use and to estimate potential benefits from using various types of diesel emissions control devices in underground mines.

As reviewed in detail by Watts (*2*) in this Information Circular, much of the health-related concerns surrounding diesel exhaust focus on the DPM, with additional interest

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[4]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

[5]The content of this paper is solely the responsibility of the authors and does not necessarily represent the official views of NIOSH.

in associated organic compounds, particularly the SOF and PAH. A wide variety of these PAH's have been identified and many are known to be carcinogenic in animal model systems. Many of these carcinogenic PAH's are also mutagenic in biological activity assays, such as the bacterial Ames mutagenicity assay, which provides a simple and rapid method for evaluating DPM-associated biological activity. The combination of selected PAH quantification and biological activity assessment can be particularly useful when making comparisons, such as those between mines, emission control device use or nonuse, and types of engines or fuels.

Information is currently available on DPM levels found in a variety of underground mines, including data (*3*) in this Information Circular obtained in underground coal mines. In contrast, relatively little information has been published specifically relating to the chemical composition or biological activity of DPM. Most of the available chemical and biological information has been obtained from underground hard-rock mines rather than from coal mines (*4-5*); these studies were generally made without separating DPM from other in-mine particle aerosols. An earlier report (*6*) presented some information on the PAH levels and biological activity associated with DPM collected from three underground coal mine haulageway areas, with samples collected only during periods of diesel activity. Diluted laboratory-generated values for the same parameters were compared with the in-mine values and were generally found to be not statistically different, indicating that laboratory-generated data for control devices or fuel effects can be used to make general predictions about in-mine haulage-way concentrations.

In this paper, a broader base of information on levels of selected PAH and biological activity associated with DPM collected in haulageway areas of four underground coal mines is provided. No DPM emission control devices besides the traditional water scrubbers were used in any of the mines. These data were obtained from samples collected on several different days with high-volume samplers operated only when diesel activity was present in the haulageway and represent potential worst case, short exposure time levels. The potential contribution of section intake air DPM and associated PAH and biological activity to the haulageway levels in each mine is also presented. The average, or mean, haulageway data of the mines are compared to determine the potential range of values that might be expected to be observed without DPM emission control device use. These data can then be used along with data from laboratory studies using control devices to estimate potential benefits from in-mine use of control devices.

ACKNOWLEDGMENTS

The authors are indebted to Winthrop F. Watts, Jr., industrial hygienist, Bruce K. Cantrell, supervisory physical scientist, and Keith S. Olson, program analyst, all from the Twin Cities Research Center, and Kenneth L. Rubow, research associate, University of Minnesota, Minneapolis, MN, for collecting the in-mine samples; this project would not have been possible without their efforts. The authors also appreciate the assistance of Cheryl Bohstedt, masters student, and Donna Becker, doctoral candidate, MTU Department of Biological Sciences, Houghton, MI, who conducted the statistical analyses; and Barbara Heard, research assistant, MTU Department of Mechanical Engineering-Engineering Mechanics, who performed sample extraction and data analysis.

IN-MINE SAMPLING

In-mine samples for chemical and biological characterization were collected by Bureau personnel from four dieselized underground coal mines, three high-altitude mines (mines I, K, and O), and one eastern mine (mine L). The number of diesel vehicles in each mine varied and the exact numbers can be found in the referenced material by Watts (*3*). The engines used in the haulageway vehicles were typically naturally aspirated, indirect injection, and water cooled and were equipped with exhaust-gas water scrubbers. At each mine, Bureau personnel collected samples for this study and other samples to characterize the mine atmosphere (*3, 7-8*). Samples were collected on 4 days at mines I, K, and O and 5 days at mine L.

High-volume samplers with size-selective impactors and flow rates of 1.13 m^3/min were used to collect submicrometer (<1.0 μm) particles. The samplers incorporated slotted impactors with cut sizes of 3.5, 2.0, and 0.95 μm to remove coal and rock dust. Particles

<0.95 μm were considered primarily diesel in origin (*9*) and were collected on Pallflex[6] TX40HI20-WW 20- by 25-cm backup filters. These samplers were placed in approximately the same locations in a haulageway and section intake in each mine. Figure 1 is a schematic showing the typical in-mine sampling locations. The haulageway samplers were located one crosscut inby from the feeder-breaker where diesel shuttle cars operated. For the most part, these samplers were operated only when diesel haulage vehicles were operating past the sampling location; sample times varied from 8 to 60 min. Data from these samples represent potential maximum diesel-related emissions in those areas. Figure 2 shows a typical haulageway sampling site with the high-volume sampler located near the right-hand side of the photograph, along with the various other instruments to measure in-mine emissions. The intake samplers were essentially operated continuously during a working shift (up to 6 h). Data from these samples represent potential background contributions from outby diesel vehicles to diesel emissions in the haulageway areas.

[6]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

After sample collection, the backup filters were wrapped in aluminum foil, placed in paper folders, and kept refrigerated at the mine sites until shipment (packed in dry ice) to the Bureau (mine I) or MTU (mines K, L, and O).

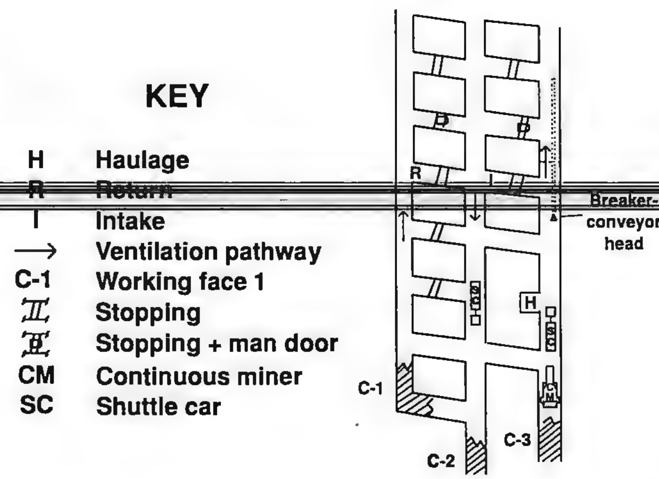

Figure 1.—Schematic showing typical in-mine sampling locations.

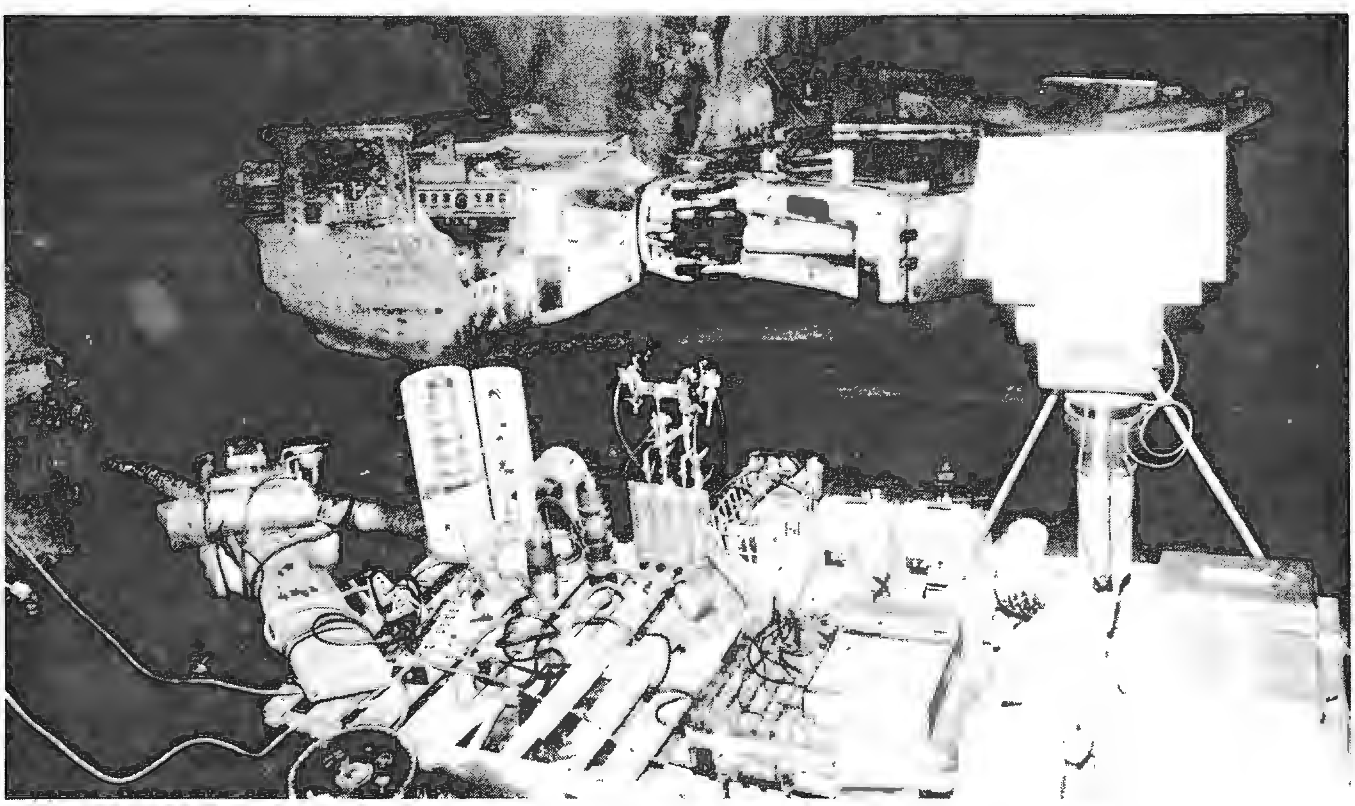

Figure 2.—High-volume sampler (right side) at typical haulageway sampling site.

DETERMINATION OF DIESEL PARTICULATE MATTER AND SOLUBLE ORGANIC FRACTION LEVELS

The mass collected on each filter was considered to be DPM (*9*) and was determined by gravimetric analysis. This procedure was conducted at the Bureau for the mine I filters and at MTU for the mine K, L, and O filters. To minimize filter hydration effects, the filters were equilibrated in a humidity-controlled chamber prior to weighing.

At MTU, the filters were kept at -20° C until extracted. The SOF was removed by Soxhlet extraction (24 h) with dichloromethane, which provided the equivalent of approximately 72 repeated dichloromethane extractions of the DPM. The mine I filters were weighed before and after this extraction, and the SOF levels were determined by gravimetric analysis. For filters from the three subsequent mines, a small aliquot of the total extract (of known volume) was allowed to evaporate to constant mass on a preweighed glass-fiber filter disk (*6*). The mass of the SOF could then be calculated from the mass of extractables found on the disk. For PAH and biological activity determinations, the individual extracts from all haulageway or intake filters from the same day from each mine were pooled to reflect average levels over each day's entire sampling period.

DETERMINATION OF POLYNUCLEAR AROMATIC HYDROCARBON LEVELS

The PAH chosen for quantification and reported on in this study are fluoranthene, benz[a]anthracene, chrysene, and benzo[a]pyrene. These compounds were selected on the basis of their activities as mutagens or carcinogens or, in some cases, their reactivities as precursors to biologically active species. These PAH'S were also known to be components of diesel exhaust, and pure reference standards were commercially available for accurate quantification.

These PAH compounds, typically found in the parts-per-million level with the DPM (or milligrams per cubic meter of underground mine air), are part of a complex sample composed of the products of incomplete combustion of fuel and lubricating oil. Methods employed for the analysis of PAH in diesel emission samples must, therefore, effectively separate the compound to be quantified from interferences in the matrix and provide a means to detect the compound, which is sufficiently selective and sensitive for reliable quantification. Therefore, to achieve these objectives, the SOF sample was first separated into several fractions using column chromatography. The fraction containing the PAH was then analyzed by high-performance liquid chromatography for resolution of the sample into individual components, followed by quantification using a fluorescence detector and comparison to known standards. A detailed discussion of these methods is presented elsewhere (*10-11*).

DETERMINATION OF BIOLOGICAL ACTIVITY

Biological activity was evaluated by assaying the SOF using a modification of the microsuspension version of the *Salmonella typhimurium*-microsome mutagenicity bioassay or Ames assay. Specific details on the conduct of this assay have been presented elsewhere (*6*). Briefly, this assay involves exposure of mutant bacterial strains to SOF aliquots. If no mutagenic organic compounds that can be detected with this assay are associated with the SOF mixture, there will be no increase in bacterial response above normal, expected background levels. The response is designated in terms of revertants, which are bacteria having the original mutation corrected by interaction with one or more mutagenic chemicals. If mutagenic organic compounds that can be detected by this assay are present, there will be a dose-related increase in bacterial response. These dose-response data can be used to calculate an activity value (revertants per microgram of sample); the higher the activity value, the more mutagenic or biologically active the test material is considered to be. The data presented in this paper are only for Ames tester strain TA98 and without the S9 microsomal activation system, i.e., direct-acting activity only.

DATA ANALYSIS

All DPM, SOF, PAH, and biological activity data were converted to a volumetric concentration basis using the total volume flow (cubic meters) for each sample. A mean of daily means value was calculated from the DPM and SOF data from each mine and sampling location. A mean for each mine and sampling location was calculated from the PAH and biological activity data. These data were analyzed statistically by analysis of variance (*12*) to evaluate whether haulageway values for any of the mines were significantly different from each other. For purposes of this paper, the statement "significantly different" means that haulageway mean-mine values were different using a 5-pct significance level; i.e., there was a 1 in 20 probability of determining that the means were not significantly different when, in fact, they were. More details on the analyses of these types of data sets are presented in reference 6.

RESULTS AND DISCUSSION

COMPARISON OF IN-MINE DIESEL PARTICULATE MATTER AND SOLUBLE ORGANIC FRACTION LEVELS

Levels (milligrams per cubic meter) of DPM and SOF in the intake and haulageway areas of four underground coal mines are presented in figure 3. The data represent mean values for samples collected over several days of sampling at each mine. It should be noted again that the haulageway samplers were operated only when dieselized haulage vehicles were operating past the sampling location. These mean DPM values (from 0.90 to 1.9 mg/m^3), therefore, again represent potentially worst case haulageway levels. However, these mean values are not excessively greater than near-full-shift DPM levels obtained in the same mines at the same sampling locations using personal samplers (*3*, *8*). The range of mean-mine values from these samplers was 0.53 to 1.2 mg/m^3. Several other studies have reported full-shift, personal sampler DPM levels of close to 1 mg/m^3 (*7*, *13-14*).

There was a more than twofold difference in mean haulageway DPM levels between the four mines, although there was no significant difference in the mean values. As noted in figure 3 by the standard error (SE) bars, DPM levels varied far more in mine I than in the three subsequent mines sampled. This increased variability at mine I may have been related to greater fluctuations in coal production and, thus, vehicle operation during the specific periods sampled.

Greater variation was found in mean haulageway SOF levels at the four mines, with values ranging from 0.08 to 0.40 mg/m^3 (fig. 3). There was a significant difference between values, with the levels at mine I (the highest values) being significantly different from the levels at the other three mines. The SOF levels for mine I also reflect the greatest within-mine variability. These differences

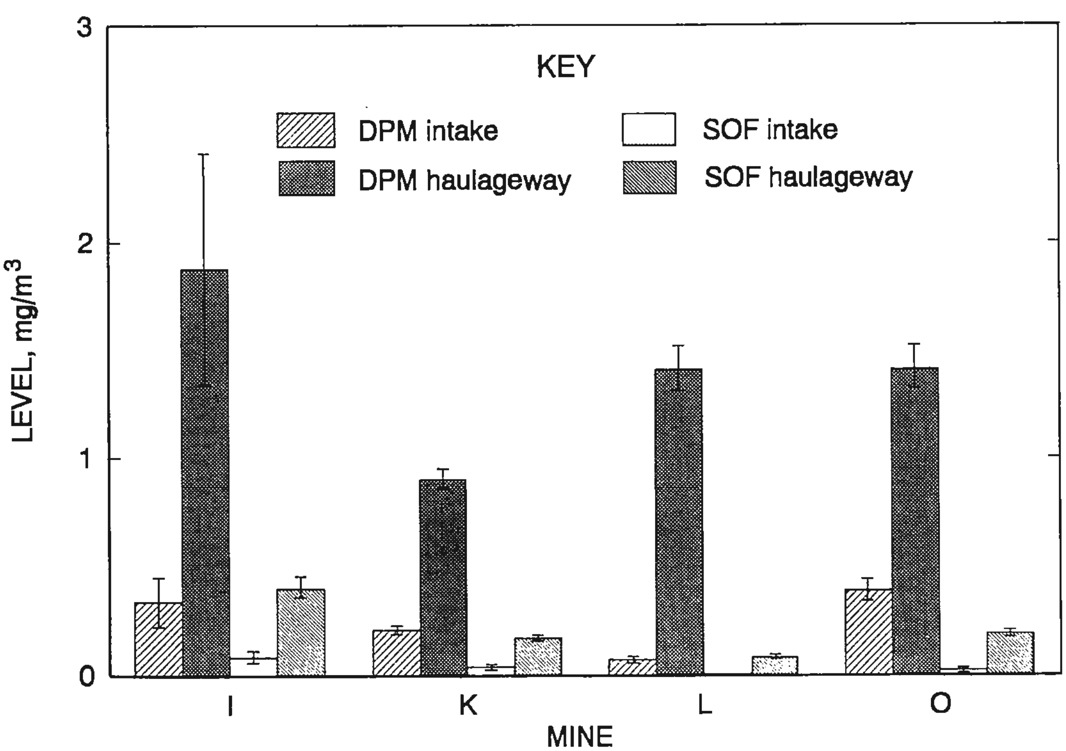

Figure 3.—DPM and SOF levels at section intake and haulageway sampling locations in four underground coal mines. (Presented as mean of daily means, plus or minus SE.)

between mines can again be attributed to differences in vehicle operation, engine type, and fuel composition, as well as possible differences in vehicle maintenance.

As shown in figure 3, the intake DPM and SOF values vary considerably both between and within mines. This would be expected since these samples were collected over a longer period than the haulageway samples and the DPM collected probably originated from the random operation of diesel support vehicles upstream from the intake high-volume samplers. The samples may also contain DPM from diesel-powered surface vehicles operated near the mine intake. At the four mines, the intake air could have contributed from 5 to 28 pct of the collected DPM in the haulageway and from 6 to 24 pct of the SOF. As previously mentioned, the intake levels vary, depending on the activity of the outby diesel vehicles. Therefore, the intake values cannot be subtracted from the haulageway values and only the mean and range of intake values are presented.

COMPARISON OF POLYNUCLEAR AROMATIC HYDROCARBON LEVELS BETWEEN MINES

Values for four biologically active PAH'S associated with the underground DPM are presented in figures 4 (fluoranthene and benz[a]anthracene) and 5 (chrysene and benzo[a]pyrene). As with the DPM and SOF data, the values are presented as mean-mine (with SE) for both the intake and haulageway sampling locations. The relative ratios of the four PAH's in the haulageways are typical of what have been found in laboratory-generated exhaust samples from an engine similar to those used in several of these mines (*11*, *15*).

An examination of the haulageway PAH mean data shows a very broad range of detected values between the mines, with the mean values for mine I appearing far greater than the other mean values. For all four PAH's, the mine I mean values were, in fact, significantly different from the mean values for the other three mines (which were not different from each other). This difference in PAH levels for mine I may be related, at least in part, to its higher SOF levels (fig. 3), which can be related to differences in engine operation. Studies have shown that engines produce the highest levels of fluoranthene, for example, when the engine is under low load or is idling (*16*). In-mine observations indicated that there was considerable idling for haulage vehicles in mine I and little for mine L, which had the lowest levels of SOF and the lowest PAH levels. Mine L also had almost three times the coal production of the other three mines, which may translate into heavier loads on the diesel engines, higher exhaust temperatures, minimal amount of engine idling, and proportionately lower amounts of SOF and some types of PAH's. Other factors that may affect PAH emissions include fuel and engine types. A study by Abbass (*17*) showed that a large fraction of the PAH emissions associated with DPM originate from the fuel and, therefore, PAH levels may vary by more than one order of magnitude.

With the exception of most values from mine L, these PAH levels are generally greater than those reported by Westaway (*18*) for dieselized nickel and salt mines near Sudbury, Ontario, Canada. However, the noncoal mine samples may have been collected over longer time periods, including when no diesel vehicles were operating near the sampling locations.

The intake PAH levels are also presented in figures 4 and 5. There is about the same amount of variation between- and within-mine mean values as for the haulageway samples. The potential contributions of these PAH's in the intake air to the haulageway levels are generally within the same range as for DPM and SOF contributions (about 5 to 28 pct) for mines I and O for all four PAH's and for mine K for fluoranthene and mine L for fluoranthene and benz[a]anthracene. However, much greater contributions for the remaining PAH's were found for mines K (50 to 60 pct) and L (over 100 pct).

It should be noted that it is important to collect and analyze the vapor-phase material as well as the DPM, as some of these PAH's exhibit considerable vapor pressures and are known as semivolatile compounds. In several Canadian studies, higher in-mine PAH levels have been reported when the vapor phase organics, as well as the DPM, have been collected and analyzed (*18-19*). Cleaner diesel exhaust, i.e., lower DPM, can shift the equilibrium distribution of semivolatiles between the particle and vapor phases, as noted in laboratory studies with some types of uncatalyzed emission control devices (*20*). Therefore, measurement of vapor-phase PAH and biological activity will become even more important in the future as the use of control devices intended to lower DPM levels is implemented.

COMPARISON OF BIOLOGICAL ACTIVITY BETWEEN MINES

Comparison of intake and haulageway mean (with SE) biological activity values for mines I, K, and O are presented in figure 6. No assays were performed on the samples from mine L, since the small amount of SOF obtained (fig. 3) was used solely for PAH quantification.

As with the DPM data (fig. 3), no significant differences were found in haulageway biological activity values between the three mines, despite a more than twofold difference in levels. The highest activity levels were found at mine I, which also had the highest within-mine variability. Comparison of these activity levels to those obtained in other in-mine studies is difficult because of differences in the specific type of Ames assay used. For comparison purposes, these mean haulageway activity levels are at least

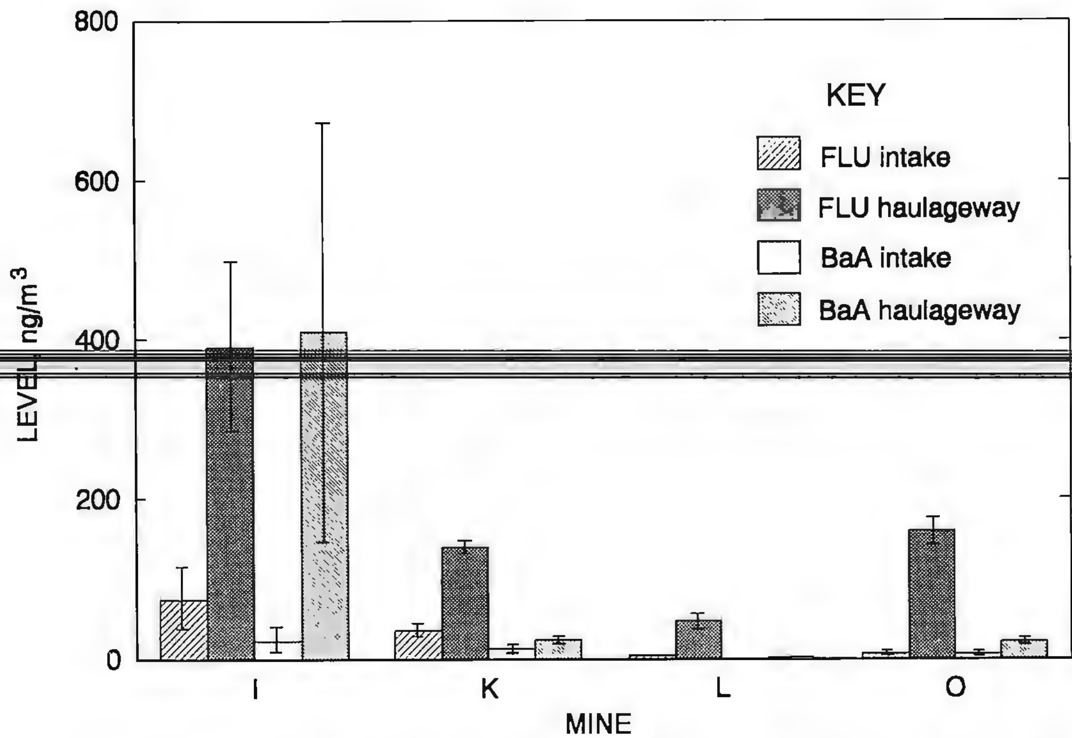

Figure 4.—DPM associated fluoranthene (FLU) and benz[a]anthracene (BaA) levels at section intake and haulageway locations in four underground coal mines. (Presented as mean plus or minus SE.)

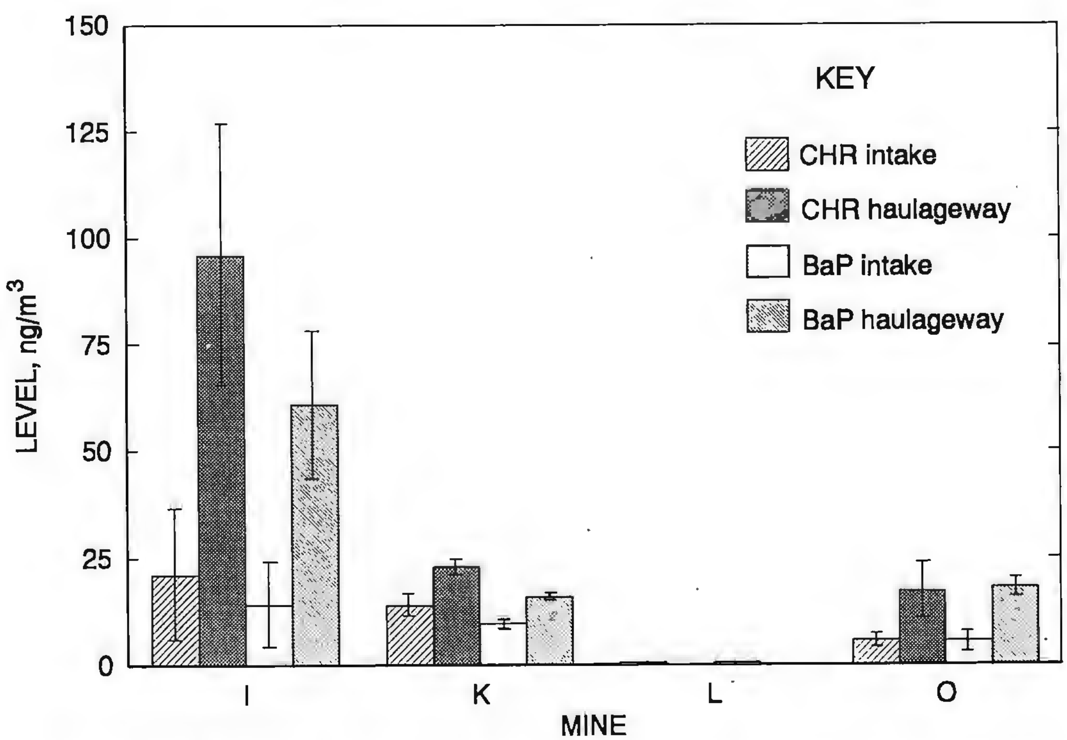

Figure 5.—DPM associated chrysene (CHR) and benz[a]pyrene (BaP) levels at section intake and haulageway locations in four underground coal mines. (Presented as mean plus or minus SE.)

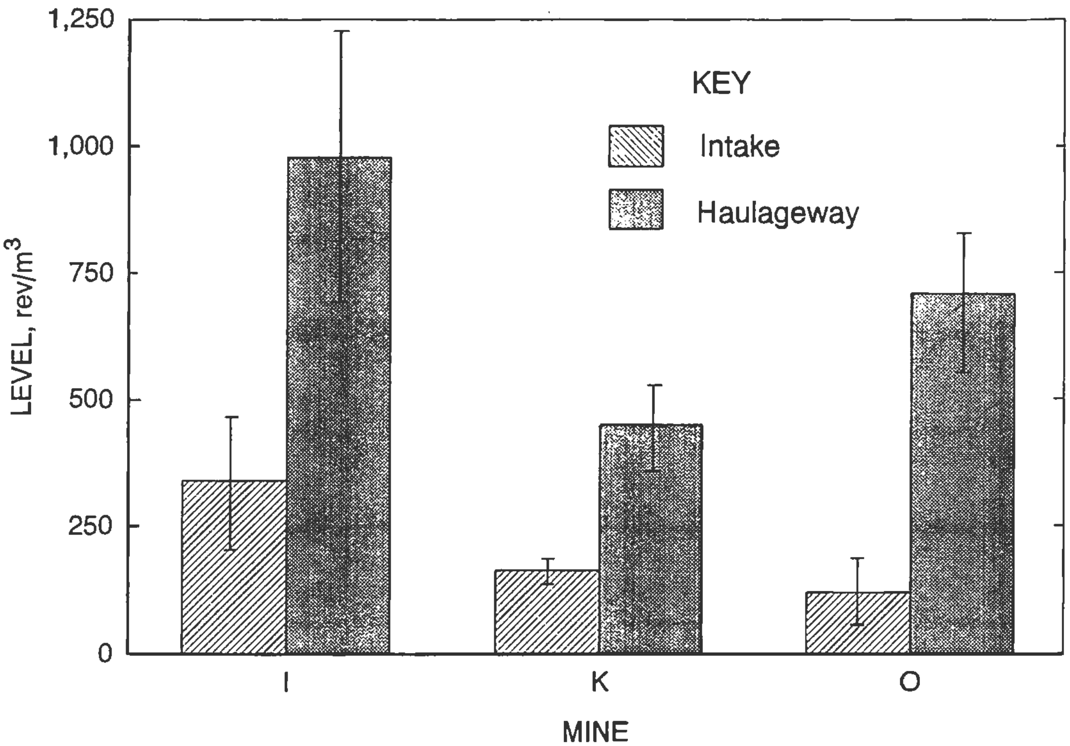

Figure 6.—DPM associated mutagenic activity levels (based on tester strain TA98-S9 revertants) at section intake and haulageway locations in three underground coal mines. (Presented as mean plus or minus SE.)

5 to 10 times higher than mean ambient air samples that also were collected using high-volume samplers and assayed using similar techniques (*21-22*). It should again be noted, however, that the haulageway samples were collected only when the haulage vehicles were present at the sampling sites; therefore, the in-mine values reported in this paper represent potential highest levels in the haulageways.

The biological activity levels associated with the intake air were more variable between mines than at the haulageway, with up to threefold differences in levels. The contribution of DPM-associated activity in the intake air to the observed haulageway levels was within the range of DPM or SOF contributions for mine L, but slightly higher (about 35 pct) for mines I and K. For mine I, at least part of this increased intake contribution may be related to specific mining practices; i.e., very high activity levels were found on one sampling day because a diesel utility vehicle was idling near the sampling point for part of the day.

CONCLUSIONS

The haulageway DPM levels, as determined by high-volume sampling, are typically at the upper end of values obtained with other sampling methods. The data presented in this paper, therefore, represent potential highest in-mine levels that would occur when diesel equipment is operating in a given area.

In most cases, the mine haulageway atmosphere levels of DPM, SOF, PAH, and biological activity are statistically similar for all four mines, thus providing a range of values that might be expected to occur when diesel vehicles without emission control devices are operating. The differences in levels between the mines can be attributed to differences in parameters such as vehicle type, engine operation and maintenance, ventilation efficiencies, and fuel composition. The value of operating at higher loads with well-maintained vehicles is demonstrated by the consistently low levels of SOF and biologically active PAH at mine L.

Potential contributions of intake air to haulageway DPM, SOF, PAH, and activity levels vary considerably both between and within mines, with the maximum potential contribution to the observed haulageway values typically no more than 25 pct. These values can be reduced by managing the operation of outby diesel vehicles.

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MODERN DIESEL EMISSION CONTROL

By Robert W. Waytulonis[1]

ABSTRACT

This paper is an update of the activities of the U.S. Bureau of Mines, other government agencies, and the automotive industry concerning diesel emission control. Enacted and proposed regulations from the U.S. Mine Safety and Health Administration (MSHA) and the U.S. Environmental Protection Agency (EPA) and developments in diesel emission control are presented in terms of their impact on underground coal, metal, and nonmetal mines. Proposed air-quality regulations by MSHA may require the underground mining industry to comply with new standards. Some mine operators may be required to take additional actions to meet new diesel particulate and lower nitrogen dioxide exposure standards. However, the mining industry is in a position to benefit from emission controls developed for on-highway and nonroad diesel engine markets. EPA has enacted regulations to reduce emissions from on-highway diesel trucks and buses and also nonroad engines and vehicles. Engine manufacturers have responded by developing cleaner burning engines. Fuel producers have responded by providing cleaner burning reformulated diesel fuel and developing alternative fuels. Exhaust aftertreatment devices have also been developed to provide additional emission reductions.

Bureau research and development projects are planned, or are underway, to determine the advantages of using modern engines and fuels and new exhaust control devices on mining machines. It appears that the diesel engine will continue to be a practical power source for use in confined environments because there is no other available power source as mobile and efficient.

INTRODUCTION

As part of its diesel research program, the U.S. Bureau of Mines interacts with engine manufacturers, fuel producers, equipment suppliers, mining companies, and MSHA to adapt new emission control strategies to mining machines. Proposed EPA regulations are monitored for their impact on mining. These interactions are shown schematically in figure 1.

The constraints of using diesels in underground mining are much different from those of surface use of diesels. Equipment for production and movement of men and materials must be ruggedly constructed and must not present any additional hazards to the environment. Miners must be protected from safety and health hazards, such as methane gas and coal dust explosions in coal mines and

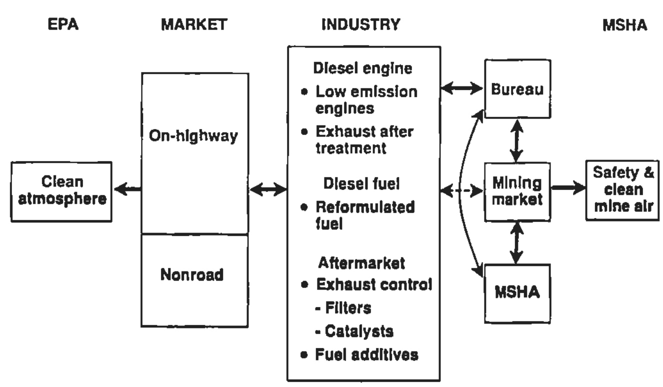

Figure 1.—Interactions between the Bureau, EPA, mine operators, automotive-truck industry, and MSHA.

[1]Supervisory physical scientist, U.S. Bureau of Mines, Twin Cities Research Center, Minneapolis, MN.

radon progeny and mineral dusts in metal and nonmetal (M-NM) mines. Limiting exposure to diesel exhaust pollutants has always been a concern owing to the confined working environment. Exhaust aftertreatment devices to reduce diesel emissions must be rugged, effective, and safe.

MSHA is developing new regulations limiting exposure to diesel exhaust contaminants because of concern for mine worker health (*1*).[2] Diesel particulate matter may be specifically regulated and ambient air-quality standards are being implemented that will lower the limits of nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2), and formaldehyde emissions (*2*) that originate from diesels and other sources. Additional safety and emission restrictions are proposed for diesel engines in coal mines (*3*).

Mine operators have numerous options to reduce diesel exhaust emissions (*4-5*), but some mine operators may need to take new actions to limit particulate matter and NO_2. The most troublesome diesel engine pollutant is the carbonaceous particulate. The carbonaceous core, toxic polycyclic aromatic hydrocarbons (PAH's) and nitro-PAH's, which are attached to these respirable particulates, are the focus of diesel exhaust health concerns (*6*). Focusing on particulate emissions does not mean that the other gaseous emissions are not important.

The oxides of nitrogen (NO_x) emissions from a diesel engine consist of nitric oxide (NO) and NO_2, and NO_x is probably the most difficult gaseous pollutant to control because of its inverse relationship to diesel particulate matter. Controlling particulates via engine modifications without increasing NO_x has proven to be difficult. Lower NO_x levels can be achieved with lower combustion temperatures and pressures, exhaust-gas recirculation, or delayed fuel injection, but all of these tend to increase particulate emissions. This is known as the NO_x-particulate tradeoff (*7*). Since diesel engines operate too lean to allow catalytic NO_x reduction, NO_x control must be achieved by combustion modification (*8*).

EPA is increasingly limiting pollution from diesel-powered trucks and buses (*9*). Between 1988 and 1998, limits for particulates and NO_x will have decreased by 80 and 60 pct, respectively. EPA is also drafting regulations to limit emissions from nonroad diesels, such as those used for marine, recreation, utility, or construction, under authority of the Clean Air Act Amendments of 1990 (*10*). Clean air regulations are rapidly forcing the automotive industry to develop new emission-reducing technology.

Engine manufacturers are developing low-emission, electronically controlled engines, and fuel producers have reformulated fuel properties for low emissions. If engine and fuel refinements are not sufficient to meet EPA standards, exhaust aftertreatment and/or alternative fuels may be necessary. Numerous manufacturers are developing filters, catalysts, and fuel additives to provide additional emission reductions. Alternative fuels, such as methanol and natural gas, are being developed for on-highway vehicles.

Diesel engine manufacturers consider mining a niche market; thus, underground mine operators receive less attention than larger markets. An accurate inventory of diesel units in M-NM mines in the United States is not available, but the author estimates that about 3,000 to 4,000 units are operated in 200 active underground mines. The population of diesels in coal mines is more precise: Currently there are 1,951 units operated in 152 mines (*11*). This compares with roughly 300,000 medium- and heavy-duty trucks made in North America each year for on-highway use (*12*).

New emission regulations and mine air-quality standards will push the limits of conventional control technology. Use of new technological developments may be necessary for greater emission reductions. The Bureau is working with on-highway and nonroad equipment manufacturers, mining companies, and MSHA to determine if modern engines, reformulated fuel, and new exhaust aftertreatment devices are viable for mining machines.

DIESEL-RELATED REGULATORY ACTIONS

Regulations have been proposed by MSHA and EPA that may impact use of diesel engines in mines. Some salient features of the MSHA actions under Title 30 (Mineral Resources) of the U.S. Code of Federal Regulations (CFR) are presented. EPA regulations under Title 40 (Protection of Environment) of the CFR are driving development of new technology, some of which may be applicable to mines.

30 CFR 56 et al.; AIR QUALITY, CHEMICAL SUBSTANCES, AND RESPIRATORY PROTECTION STANDARDS; PROPOSED RULE (*2*)

This proposed rule will affect all mines (coal, hard rock, surface, and underground) and would revise MSHA's existing standards for air quality and chemical substances. This proposed rule contains permissible exposure limits (PEL's) for substances that may pose health hazards at these mines. In addition, the rule contains revised requirements for exposure monitoring, carcinogens, and respiratory

[2]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

protection programs. These actions are part of MSHA's ongoing review of M-NM and coal mine safety and health standards.

The following is a brief discussion of the potential impact of this proposed rule on some pollutants found in diesel exhaust. For NO_2, MSHA is continuing to review medical studies and other documentation to determine whether (1) a PEL of 1 ppm should be implemented as a 15-min short-term exposure limit (STEL), or (2) a 3-ppm, 8-h, time-weighted average with a 5-ppm STEL would be appropriate (*2*). Complying with a low-NO_2 standard, such as the 1-ppm-NO_2 STEL in mines with large openings where ventilation air velocities are low, could be a challenge. Figure 2 is a cumulative frequency plot of NO_2 data intended to provide insight into the effect of a reduced standard on compliance. Based on measurements taken in salt, lead-zinc, and limestone mines by MSHA inspectors over the period of 1986-90, about 50 pct of the samples taken in salt and limestone mines would have been out of compliance with a 1-ppm-NO_2 STEL. Further, about 25 pct of the samples taken in lead-zinc mines would have been out of compliance. Most mine operators have been able to comply with CO limits in the recent past, and the new lower 35-ppm PEL and 200-ppm STEL will not likely create problems in most mines.[3] Likewise, CO_2 and formaldehyde (normally very low) emissions from diesel engines will be manageable with adequate ventilation.

The proposed rule also contains a new concept for controlling exposure to respirable mine dust at M-NM mines, setting a PEL of 5 mg/m³ for respirable mine dust. Respirable mine dust includes all ambient, airborne particulate capable of being inhaled into the lower respiratory tract. The composition of mine dust depends on the minerals being extracted, host rock, impurities present, diesel particulates, oil mists, welding fumes, etc. Sometimes mine dust will contain toxic components such as lead, arsenic, silica, trace elements, or organic materials. Where sampling indicates that specific toxic contaminants are present, mine operators would have to control exposure in accordance with the substance-specific limits. For example, if the dust contains quartz, the limiting standard becomes 100 $\mu g/m^3$ silica (*2*). Likewise, diesel particulate could become the limiting substance, once an exposure limit is set.

[3]Private communication in February 1992 with W. F. Watts, Jr., Twin Cities Research Center, on information contained in MIDAS industrial hygiene data base.

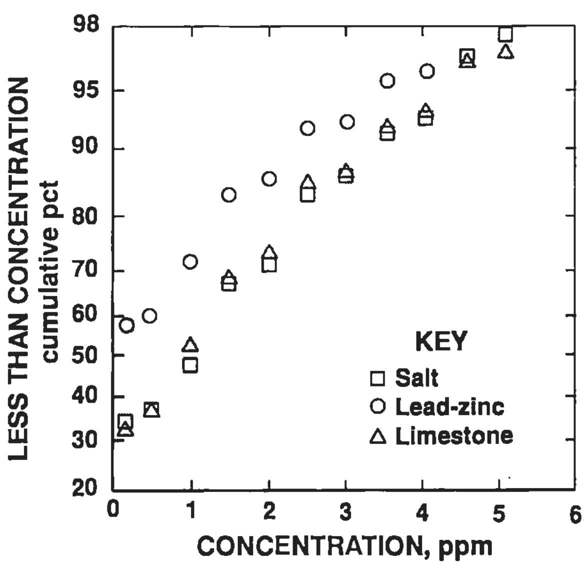

Figure 2.—Cumulative frequency plot of NO_2 data taken by MSHA inspectors during 1986-90 period in salt, lead-zinc, and limestone mines.

30 CFR 58 AND 72; PERMISSIBLE EXPOSURE LIMIT FOR DIESEL PARTICULATE: ADVANCE NOTICE OF PROPOSED RULEMAKING (*1*)

MSHA is in the early stages of developing a PEL to control exposures to diesel exhaust particulate in the mining industry. This notice of proposed rulemaking raises major issues to be considered for possible regulatory action that would affect surface and underground mines in the coal and M-NM mining sectors.

MSHA is seeking further information on the risk associated with exposure to diesel particulate matter, the methodology available for assessing occupational exposures to diesel particulate, and the technology available or under development to reduce the concentration of diesel particulate in the mining environment. After analysis of comments and other information received in response to the advance notice, MSHA plans to publish a proposed rule to assure that miners will not suffer material impairment of health or functional capacity even if they are regularly exposed to diesel particulate for their working life (*1*).

The difficulty of complying with the particulate exposure standard cannot be established until the standard is in place; however, insight can be gained by examining data from previous studies. Respirable dust levels were measured in four M-NM mines and ranged from 0.38 to 2.68 mg/m³, of which diesel particulate constituted 48 to 88 pct. Diesel particulate exposure levels were 0.26 to 2.36 mg/m³ (*13*).

Intake dust levels were measured in five coal mines and ranged from 0.13 to 0.58 mg/m³. Intake diesel particulate levels ranged from 0.04 to 0.29 mg/m³ or 30 to 50 pct of the respirable coal mine dust concentrations. Face worker respirable dust exposures in these mines ranged from 0.73 to 2.85 mg/m³. Worker exposure to diesel particulate ranged from 0.18 to 1.00 mg/m³. The diesel particulate sample collected at a fixed sampling site in the haulageway was similar to the concentration measured on the section workers (*13*).

Bureau measurements of diesel particulate range between 0.2 to 1.4 mg/m^3 in M-NM mines and from 0.2 to 0.9 mg/m^3 in coal mines (*14-16*).

30 CFR 7, 70, AND 75; APPROVAL REQUIREMENTS FOR DIESEL-POWERED MACHINES AND APPROVAL, EXPOSURE MONITORING, AND SAFETY REQUIREMENTS FOR THE USE OF DIESEL-POWERED EQUIPMENT IN UNDERGROUND COAL MINES; PROPOSED RULES (*3*)

This proposed rule is MSHA's response to the final report of its Advisory Committee on Standards and Regulations for Diesel-Powered Equipment in Underground Coal Mines (*17*). This proposal contains approval requirements for diesel-powered equipment used in underground coal mines to protect against fires and explosions and to establish exhaust dilution requirements. Exhaust dilution with ventilation air is necessary to limit exposures of miners to pollutants contained in diesel exhaust.

One important topic addressed is particulate emissions. MSHA seeks to establish a particulate index (PI) that would report the air quantity necessary for dilution of the diesel particulate matter to 1 mg of particulate per cubic meter of air for each MSHA-approved engine rating (*3*). Currently, dilution air requirements are based on exhaust gases, usually NO_x or CO.

The Bureau conducted laboratory tests to determine the PI for a Caterpillar, Inc.[4] (Cat), model 3304 PCNA mine diesel engine. This engine currently has a dilution ventilation requirement of 5.43 m^3/s (11,500 cfm) based on NO_x levels. Laboratory results showed that the 3304 engine has a PI of 5.66 m^3/s (12,000 cfm). If the future particulate exposure limit is less than 1 mg/m^3, exhaust dilution requirements will increase for this engine. For example, if 0.5 mg/m^3 is the particulate standard, the exhaust dilution requirement for this Cat engine would double to 11.33 m^3/s (24,000 cfm).

40 CFR 86; REGULATION OF FUELS AND FUEL ADDITIVES; FUEL QUALITY REGULATIONS FOR HIGHWAY DIESEL FUEL SOLD IN 1993 AND LATER CALENDAR YEARS; FINAL RULE (*18*)

This regulation requires that fuel refiners reduce the sulfur content of on-highway diesel fuel from current average levels of about 0.25 wt pct to levels not exceeding 0.05 wt pct. It also requires that on-highway diesel fuel have a minimum cetane index specification of 40 (or meet a maximum aromatics level of 35 vol pct). Both requirements will take effect at all points throughout the distribution system on October 1, 1993. Special provisions providing for a phasing in of these requirements for small domestic refineries are also included (*9, 18*), but a pending EPA proposal (*19*) would eliminate this exemption. The benefits of using low-sulfur, on-highway fuel in mines is discussed in the "Low-Emission Diesel Fuels" section of this paper.

NONROAD ENGINE AND VEHICLE; EMISSION STUDIES (*20-21*)

Congress asked EPA to focus on quantifying emissions from unregulated nonroad sources after 20 years of highway mobile sources regulation and increasingly costly controls on the automotive industry. As a group, nonroad engines represent the last uncontrolled mobile emission source. The terms "nonroad engines" and "nonroad vehicles" cover a diverse collection of equipment ranging from utility equipment (lawn mowers and chain saws) to recreational, farm, and construction machinery.

Nonroad engines are not presently subject to emission control requirements; consequently, they produce more pollution (per unit of fuel input or work output) than similar emission-controlled engines used on-highway. Collectively, nonroad sources account for more than one-third of total diesel fuel consumption. Since emissions per unit of fuel burned are higher for nonroad vehicles, they account for a large fraction of total emissions (*20-21*).

The Clean Air Act Amendments of 1990 (*10*) directed EPA to regulate emissions from nonroad engines and vehicles if these sources are significant contributors to urban pollution. EPA has completed a study of emissions of CO, volatile organic compounds, and NO_x (*21*) and is determining the significance of emissions from nonroad engines and vehicles. If nonroad diesel emissions are determined to be significant, an advance notice of proposed rulemaking will be published in the Federal Register.

EPA might regulate only NO_x and smoke via the Federal smoke test. An emission cap may be put on CO, hydrocarbon (HC), and particulate. An eight-mode, steady-state engine certification test may be used for engines greater than 37.3 kW (50 hp) used in self-propelled vehicles. Discussions between MSHA and EPA indicate that engines approved by MSHA under 30 CFR 32 (*22*) and 36 (*23*) will be specifically excluded (*24*).

[4]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

ENGINE TECHNOLOGY FOR LOW EMISSIONS

Currently in underground mines, engines meet emission control requirements through the application of a variety of engine modifications and refinements. Traditionally, indirect-injection engines have had lower levels of regulated pollutants in their exhaust, but improvements in direct-injection engines have eliminated this advantage.

Engine manufacturers are required to meet EPA's demanding emission standards for engines destined for trucks and buses. New technology is required to meet these standards without sacrificing the diesel's performance, fuel consumption, and reliability. Modern diesels certified by EPA are clean burning because of refinements in combustion chamber design, piston ring design, and the fuel-injection system. Combustion chamber modifications and higher fuel-injection pressures are now a part of modern truck engines. New piston ring designs greatly lower lubrication oil consumption, a major contributor to organic particulate emissions. Improved pistons, bearings, and cylinder liners accommodate higher cylinder pressures required to meet emission standards.

Turbocharging is becoming more prevalent to optimize power, performance, and emissions. Aftercooling (cooling intake air prior to induction into the combustion chamber) is an effective means to reduce NO_x emissions. Jacket water that cools the intake air charge is already used in some mining engines. Air-to-air aftercooling relies on large quantities of air flowing over a heat exchanger, so it may not be applicable to mining because of its reliance on large quantities of airflow for heat transfer and potential contamination with mine dusts.

Electronic engine control is a major technological improvement; fuel and air control are electronically optimized for low emissions (*25-30*). At least two engine manufacturers, Cat and Detroit Diesel Corp. (DDC), are beginning to market electronically controlled engines for use in mining equipment.

The major components of electronic-control systems consist of the electronic-control module (ECM), the electronic unit injectors, and the various system sensors. The ECM is the brain of the system, receiving electronic inputs from the operator as well as from the engine and vehicle-mounted sensors. This information is used to precisely control engine fueling and to provide feedback to the operator and maintenance personnel on the state of health of the electronic-control system and engine hardware. The ECM controls the basic engine functions, such as rated speed and power, injection timing, engine governing, torque shaping, cold-start logic, transient fuel control, diagnostics, and engine protection. The control logic determines the timing and duration of fueling, which results in precise fuel delivery, improved fuel economy, and engine performance.

Electronic control continually optimizes the fuel-injection timing and rate to match each power requirement. Electronic engines are always in tune. Mechanical governor parts that can wear or become misadjusted are not used. The injector rack and governor have been replaced by electronic components, which have built-in logic to compensate for normal wear (*31*).

Table 1 is a comparison of a modern electronically controlled diesel engine and a typical mining engine. To account for different engine power, emissions are expressed as mass per unit of work. The engine from DDC is a 1991 8V-92TA direct-injection, two-cycle engine with turbocharging and aftercooling, rated at 298.3 kW (400 hp) at 1,800 r/min. Although these emission data are from an urban bus engine, the fuel setting is very similar to the calibration used for a 6V-92TA, 223.7-kW (300 hp) engine recently approved by MSHA. These emission data were furnished by DDC and were measured from the engine, operating on 0.1 wt pct S, No. 2 diesel fuel and without exhaust aftertreatment.

The engine from Cat is a 1979 3304 PCNA, four-cycle, indirect-injection, naturally aspirated engine, updated with high-compression pistons and rated 74.6 kW (100 hp) at 2,200 r/min. These emission data were generated in the Bureau's diesel research laboratory (*32*).

In table 1, NO_x, total particulate, and percentage of the total particulate that are organic HC's are given for six steady-state engine operating conditions for the DDC and Cat engines. The NO_X and particulate emissions from the DDC engine averaged about 20 and 47 pct less, respectively, than the Cat engine. The DDC data were generated using 0.1 wt pct S fuel versus 0.04 wt pct in the Cat engine, so the total particulate emissions would be expected to be even less for the DDC engine if lower sulfur fuel was used. The average percentage organic particulate emissions (average 31 pct for both engines) is given for its implication to be reduced by oxidation catalytic converters. This is discussed in the "Exhaust Aftertreatment" section of this paper.

Table 1.—Comparison of NO_x and particulate emissions from DDC[1] and Cat[2] engines at several speed-percent load conditions

Engine and emission	PT 50	PT 75	PT 100	Rated 50	Rated 75	Rated 100	Average
DDC							
NO_x .... g/MJ..	1.99	2.09	2.94	1.38	1.40	1.76	1.93
Do. .... g/bhp·h..	5.34	5.62	7.88	3.70	3.77	4.72	5.17
Particulate .... g/MJ..	0.052	0.056	0.063	0.052	0.041	0.041	0.052
Do. .... g/bhp·h..	0.14	0.15	0.17	0.14	0.11	0.11	0.14
Do. .... pct organics..	37	20	31	42	34	23	31
CAT							
NO_x .... g/MJ..	3.51	2.30	1.12	3.47	3.59	1.44	2.57
Do. .... g/bhp·h..	9.41	6.18	3.02	9.31	6.94	3.87	6.46
Particulate .... g/MJ..	0.066	0.034	0.194	0.235	0.086	0.060	0.112
Do. .... g/bhp·h..	0.17	0.09	0.52	0.63	0.23	0.16	0.3
Do. .... pct organics..	55	34	2	42	42	11	31

PT Peak torque.

[1]Model 8V-92TA, 298.3 kW (400 hp); data generated with 0.10 wt pct S fuel; PT speed = 1,200 r/min; rated speed = 1,800 r/min.

[2]Model 3304 PCNA, 74.6 kW (100 hp); data generated with 0.04 wt pct S fuel; PT speed = 1,200 r/min; rated speed = 2,200 r/min.

LOW-EMISSION DIESEL FUELS

Several fuel properties have been cited as influencing diesel emissions. These include cetane number, aromatics content, density, viscosity, volatility, and sulfur. Drawing definitive conclusions is difficult because of the interrelationships among fuel properties and because of the differences in engine response to fuel variables (*33*). Fuel producers and engine manufacturers have worked together to optimize fuel properties for low-emissions diesel engines. In a recent comprehensive study, known as the VE-1 Project (*34*), the following conclusions were reached:

- Relatively consistent fuel property effects have been observed for (1) sulfur on particulates, (2) cetane number on all regulated pollutants, and (3) fuel aromatics on particulates and NO_x.
- Distillation characteristics affected gaseous and particulate emissions, but conflicting trends were observed among the various engines tested.
- Different engines have shown widely different emissions on given test fuels and different sensitivities to fuel properties.

Diesel fuel typically contains 0.15 to 0.35 wt pct S. In an engine, about 98 pct of this is combusted to sulfur dioxide (SO_2) and the remainder is associated with the particulate (sulfate). Reducing a fuel's sulfur content reduces SO_2 and sulfates. Additionally, low-sulfur fuel is required for proper operation of catalytic exhaust controls.

Increased cetane number and volatility, as measured by a fuel's distillation characteristics, can reduce HC emissions. Cetane numbers of typical diesel fuels in the United States range between 40 and 57. Reduced aromatic HC's in fuel reduce particulate carbon and NO_x emissions. Typical No. 2 diesel fuel has an aromatic HC content of 20 to 40 wt pct.

Diesel fuel availability and identification by color is shown in table 2. Premium diesel fuels are currently available nationwide. Diesel fuel designated with a blue-green dye can only be used in engines operated off-highway after October 1, 1993. Both 1D and 2D grades of low-sulfur, on-highway fuel will be available nationwide in 1993, designated by being a color other than blue. Small refiners may be allowed 2 years (1993-95) to upgrade their equipment to produce low-sulfur fuel (*18*), but a pending EPA proposal (*19*) would eliminate this exemption.

Table 2.—Diesel fuel availability and identification by color

Type of fuel	Availability	Identification
Premium	Now	Red or purple.
Nonroad	October 1, 1993 ..	Blue-green.
Low-sulfur, on-highway ..	..do...............	Undyed or not blue.
High-sulfur, exempted[1] ..	1993-95	Purple.

[1]On July 17, 1991, EPA issued a notice of proposed rulemaking (*19*) that would eliminate this exemption for small refiners, but as of April 1, 1992, the final rule has not been issued.

Low-emission benefits can be gained by using reformulated diesel fuel. Reformulated fuel, sometimes called clean diesel, premium diesel, high-purity fuel, or low-emission diesel fuel, is the result of refining to a new specification. Generally, the reformulated fuel has lower sulfur, lower boiling range, higher cetane number, and lower aromatics, among other differences (*35*). Although the EPA-approved low-sulfur, on-highway fuel will reduce particulate emissions, the new reformulated fuels will generally lower particulate, CO, HC, and NO_x emissions.

The most feasible fuel alternatives for on-highway use include pilot-ignited natural gas (compression ignition), lean-burning natural gas (spark ignition), and glow-plug-assisted methanol (compression ignition). All these fuels can yield little or no particulate sulfate emission. However, 10 to 50 pct of the diesel particulate can be traced to the lubrication oil. This particulate source limits the gains from using alternative fuels. Reduction of oil consumption is a basic engine design goal of modern engines.

Each alternative fuel also has its peculiar problems of economics, logistics, supply, and engine redesign (*36-37*). These clean-burning alternative fuels are not immediate options for on-highway trucks because of durability, reliability, and efficiency advantages offered by diesels. Natural gas or methanol fuels are not practical for use in underground mines because of safety concerns about flammability, storage, and handling. Additionally, engines running on methanol emit toxic aldehydes.

In considering alternatives to diesel fuel, with the specific objective of cleaner emissions, one fuel emerges as superior: hydrogen. Hydrogen is the cleanest fuel available; the exhaust from an engine with a lean hydrogen-air mixture will contain mainly water vapor and less than 10 pct of the NO_x produced by an indirect-injection diesel engine. Low-pressure hydrogen storage via metal hydrides can provide a safe means to use hydrogen fuel underground. The Bureau has successfully converted and operated a mine vehicle on hydrogen (*38*); however, as long as diesel fuel is available and cost effective when compared with alternative fuels, diesel engines will prevail.

EXHAUST AFTERTREATMENT

Exhaust aftertreatment devices must deal with solid, liquid, and gas-phase compounds. The solids are mostly carbon, and the liquids consist of unburned or partially burned fuel and lubrication oils that are referred to as an organic fraction. Bureau research has focused on particulate reduction, via flowthrough oxidation catalytic converters that remove a portion of the organic fraction, and filters that remove mostly solids.

Table 3 lists some exhaust aftertreatment technologies and their current applicability to underground mining machines. Mining machines are divided into three groups: (1) heavy-duty machines with special safety controls approved under 30 CFR 36 for gassy mines (*23*), such as face haulage vehicles used in coal mines; (2) heavy-duty machines without special controls, such as trucks and front-end loaders used in nongassy mines; and (3) light-duty machines without special controls, such as uncontrolled outby machines in coal mines or utility-service vehicles in nongassy mines.

OXIDATION CATALYTIC CONVERTER

Flowthrough oxidation catalysts can provide a worthwhile contribution to the reduction of particulate emissions. Their effectiveness depends on catalyst formulation, application, engine characteristics, sulfur fuel level, converter size, and catalyst inlet temperature (*39-40*). Oxidation catalysts have very little effect on carbon particulate, but engine tests show they typically remove 15 to 50 pct of the total particulate. This is achieved by oxidizing the particulate organic fraction (*41-43*). Correct matching of application, formulation, space velocity, and inlet temperature are essential for optimum reduction to be realized.

Table 3.—Exhaust aftertreatment technologies and their applicability to underground mining machines

Technology	Heavy-duty, gassy	Heavy-duty, nongassy	Light-duty, gassy-nongassy
Oxidation catalytic converter	No	Yes	Yes
Filter:			
Ceramic (wall-flow)	Maybe	Some	No
Regenerable fiber coil	No	Yes	Yes
Disposable	Yes	No	Yes
Reusable:			
Midtemperature	No	Some	Yes
High-temperature	No	No	Yes

Catalyst manufacturers have collaborated with engine and fuel manufacturers to develop new catalyst formulations for on-highway use. Low-sulfur fuel is necessary when catalytic converters are used because sulfates can be retained in converters, reducing their efficiency and limiting their durability, and because sulfate production at high temperatures substantially reduces effectiveness (*7, 36, 44*). These new catalyst formulations minimize sulfate production; however, their effect on NO_2 emissions is unknown.

The catalytic converter is a potentially good aftertreatment device to reduce unregulated emissions, including mutagenic HC's (*40*), that originate from unburned or partially burned lubrication oil and fuel. Operating on this source of emissions, converters could be helpful in maintaining low total particulate emissions throughout an engine's in-service life. The Bureau recommends using the new oxidation catalytic converters developed for on-highway use if—

- Average exhaust temperatures are consistently above 200° C (392° F),
- Low-sulfur fuel is used, and
- Mine air monitoring for NO_2 is regularly performed.

CERAMIC (WALL-FLOW) PARTICULATE FILTER

Ceramic wall-flow particulate filters found limited use in U.S. and Canadian M-NM mines beginning in the 1980's (*45-46*). Based on subsequent in-mine and laboratory test information, successful use of wall-flow filters has been found to depend on several factors. Operator education concerning the function and limitations of ceramic filters is necessary because the filters are not totally passive exhaust control devices. It is especially important to monitor the pressure drop across the filter, which is an indication of the amount of particulate matter collected. If the accumulation of particulate becomes excessive, engine power will diminish and the particulate could burn (regenerate) in an uncontrolled manner and damage the filter.

Wall-flow filters currently used on mining machines use a catalyst to assist the particulate-burning process by catalytically lowering the particulate ignition temperature; therefore, it is important to use low-sulfur diesel fuel for reasons previously discussed. Vehicles must be screened by measuring their exhaust temperature over numerous shifts because wall-flow ceramic filters rely on exhaust heat for regeneration. A consistently heavy-duty cycle with an exhaust temperature exceeding 400° C (752° F) 25 pct of the time is required. This enables the accumulated particulate to regenerate in a controlled manner.

In new and properly operating filters, particulate removal is 85 to 95 pct. Depending on length of time in service and severity of duty, the filtration efficiency can deteriorate significantly, eventually to zero. The reported service life varies; Bureau tests on a limited number of filters showed that, after about 1,500 h, efficiency dropped as low as 40 pct (*47*). This compares to an average filter life of 2,173 h in Canadian mines (*48*). Initial filter cost, normalized to maximum engine horsepower, is typically $54 per kilowatt ($40 per horsepower).

Wall-flow ceramic filters have questionable reliability-durability and are costly. Experience has shown that only a limited number of mining machines can benefit from their use. Functionally, there are two main drawbacks: (1) The ceramic filter element deteriorates with mechanical and thermal shock and (2) self-cleaning (regeneration) relies on exhaust temperature greater than 400° C (752° F), which is not always possible. New concepts in particulate filter technology are required to solve the regeneration, limited application, and cost problems of these filters in mines.

Manufacturers continue to develop wall-flow ceramic particulate filters for urban buses and have achieved good success, even when the filters are coupled with complex regeneration systems (*49*). These systems warrant further examination for possible application in mines.

REGENERABLE FIBER COIL PARTICULATE FILTER

The Donaldson Co., Inc.'s regenerable fiber coil filter system for urban buses is being evaluated for use on a mining machine. The filter cartridges are made from a ceramic yarn that is more resistant to mechanical and thermal shock than wall-flow ceramic filters. A metallic heating element is embedded in the coil, which is powered by the engine's alternator for reliable regeneration. The filter cartridges are regenerated automatically when they reach a predetermined back pressure. These features overcome the two primary disadvantages of the wall-flow filters previously discussed and may allow fiber coil technology to be applied to more types of vehicles.

In the evaluation of the fiber coil filter system on the Bureau's front-end loader, more than 200 h of trouble-free operation has been achieved. If this successful operation continues, in-mine tests of a fiber coil system will be conducted (*49*).

DISPOSABLE DIESEL EXHAUST FILTER

In coal mines using diesels, heavy-duty permissible machines are the primary contributor of diesel particulate to mine air. A safe, low-cost, efficient filter system was developed to remove diesel particulate from the exhaust of these mining machines equipped with water scrubbers. The maximum exhaust temperature from a properly functioning water scrubber will be about 77° C (170° F), and the fibrous filter element can safely tolerate temperatures up to 100° C (212° F). The filters are about 95 pct efficient, cost about $40, and last from 10 to 32 h in service. Several mine equipment manufacturers now offer disposable filters on machines approved under 30 CFR 36 (*50*).

REUSABLE DIESEL EXHAUST FILTER

Two types of reusable diesel exhaust filters for light-duty mining machines are being developed jointly by the Bureau, Donaldson Company, and several mine vehicle manufacturers.

Midtemperature Filtration

The midtemperature tolerant diesel exhaust filter is made from a synthetic paper developed by Donaldson and can withstand exhaust temperatures of 200° C (392° F). This filter has been shown to be 95 pct efficient in laboratory tests and is currently being evaluated on a Bureau forklift and a mine utility vehicle in Canada. Under normal operation, the filter has a life cycle of about 200 h on an engine with an exhaust particulate output of 2 g/h. The filter is designed to hold about 0.5 kg (1.1 lb) of particulate matter.

The filter can also be adapted for use on vehicles with exhaust temperatures greater than 200° C (392° F). This can be accomplished by installing a temperature-activated bypass valve upstream of the exhaust filter. However, the engine conditions that produce the highest exhaust temperature also result in the greatest particulate production, and this diverted exhaust goes into the atmosphere. Cleaning of the filter is accomplished by a device manufactured by Donaldson (*50*).

High-Temperature Filtration

The high-temperature tolerant filter being developed for light-duty vehicles is made from a fibrous ceramic mat. The target application for this filter is on vehicles with exhaust temperatures from 200° to 400° C (392° to 752° F). Because this filter has a low-particulate holding capacity, it is not suitable for use on heavy-duty vehicles despite the high-temperature tolerance. A temperature-activated bypass can be installed on vehicles with exhaust temperatures greater than 400° C (752° F) to prevent unwanted onboard regeneration of the filter.

To increase the life of the filter, it is located near the end of the exhaust line where the temperatures are lowest. This minimizes venting of unfiltered exhaust to the atmosphere and lowers the pressure drop across the filter, thus allowing a greater amount of particulate to be collected. The filter can be cleaned in a 600° C (1,112° F) oven in about 5 min (*50*).

SUMMARY AND CONCLUSIONS

Occupational exposure to diesel exhaust pollutants is an important environmental issue for the mining industry. Proposed regulations may require mines to use modern engines, fuels, and emission controls to comply with air-quality standards in underground mines. The Bureau has developed several new diesel emission controls for specific mining machines and continues to work closely with MSHA and segments of the automotive industry to make more emission controls available. Based on the current status of control technology and appropriate regulations, the following conclusions have been reached.

1. New emission regulations and mine air-quality standards will require some mine operators to make further reductions of diesel exhaust pollutants. Use of new technological developments may be necessary for these emission reductions. The Bureau is working with on-highway and nonroad equipment manufacturers, mine operators, and MSHA to demonstrate the viability of using modern engines, reformulated fuel, and new exhaust aftertreatment devices on mining machines.

2. It is not yet clear where jurisdiction will be divided between MSHA's mining and EPA's nonroad emission regulations. As of this date, engines approved under 30 CFR 32 and 36 will continue to be under MSHA jurisdiction.

3. The impact of reduced NO_2 and diesel particulate standard cannot be determined until final rulemaking; however, there is evidence that compliance with a 1-ppm-NO_2 STEL and a new particulate limit less than 1 mg/m^3 will require some underground mine operators to take additional diesel emission control actions.

4. Once a diesel particulate exposure limit is established, it could become the limiting substance for respirable dust compliance in M-NM and coal mines.

5. The particulate and NO_x emissions from a modern, electronically controlled diesel engine averaged about 47 and 20 pct less, respectively, than emissions from a conventional mining engine.

6. The benefit of using a low-sulfur, on-highway fuel in mines is to reduce sulfate particulates. A reformulated fuel will lower particulate, CO, HC, and NO_x emissions.

7. Alternative fuels, such as natural gas or methanol, are not practical for use in underground mines because of safety concerns about flammability, storage and handling, and harmful emissions. Hydrogen, via hydride storage, is the ultimate low-emission fuel and the most logical alternative fuel for use underground. However, as long as diesel fuel is available and cost effective when compared with alternative fuels, diesel engines will prevail.

8. The oxidation catalytic converter can be a good aftertreatment device to reduce total particulate and unregulated emissions, including mutagenic HC's. New catalyst formulations minimize sulfate production; however, their effect on NO_2 emissions is unknown.

9. Ceramic (wall-flow) particulate filters have two functional disadvantages: deterioration by mechanical and

thermal shock and reliance on exhaust heat for regeneration. The regenerable fiber coil filter technology appears to overcome these disadvantages and may allow filtration to be applied to more types of mining machines.

10. New filtration technology, such as reusable diesel exhaust filters, shows promise to provide a means of exhaust control for light-duty mining machines.

11. A safe, low-cost, efficient disposable filter system, with a filter life of 10 to 32 h, is commercially available to remove diesel particulate from the exhaust of mining machines equipped with water scrubbers.

12. The diesel engine will survive in underground mining because there is no other power source available that is as mobile and efficient. Modern fuels, new engine designs, and effective exhaust aftertreatment devices can reduce exhaust pollutants to very low levels. These technological developments will allow the diesel to continue to be a practical power source for use in confined environments.

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LABORATORY EVALUATION OF THE EFFECTIVENESS OF OXIDATION CATALYTIC CONVERTERS

By B. T. McClure[1]

ABSTRACT

The U.S. Bureau of Mines is conducting a laboratory evaluation of oxidation catalytic converters (OCC's) as exhaust aftertreatment control devices for underground diesel-powered mining equipment. The objective is to provide information about this technology so that mine operators can wisely select equipment.

Three OCC's manufactured by Engelhard Corp. were evaluated: PTX-523D, PTX-7DVC (ULTRA-7), and PTX-10DVC (ULTRA-10). The performance of these OCC's was characterized by their influence upon the emission of the constituents of diesel particulate matter (DPM) and some gas-phase pollutants when used on a Caterpillar 3304 PCNA engine. The principal gas-phase emissions reported are CO and hydrocarbons as detected by flame ionization (HC-FID).

The use of modern OCC's, in conjunction with low-sulfur fuel, is more attractive to mine operators than older OCC technology. This combination will reduce the emission of CO, HC-FID, and the volatile component of DPM by diesel engines in mines without significantly increasing other emissions. The technology should be evaluated in the field to verify expectations based upon laboratory work.

INTRODUCTION

OCC's are used in underground mines to decrease the miners' exposure to diesel exhaust emissions (*1*).[2] OCC's are effective in decreasing the concentration of CO and many species of hydrocarbons (HC's), which are part of diesel exhaust. They also decrease the offensive odors associated with diesel emissions. The effectiveness of an OCC depends upon oxidation of some constituents of diesel exhaust. Oxidation is enhanced by the catalyst, but this also tends to enhance the emission of some undesirable materials, such as NO_2 and the sulfate constituent of DPM. The latter is particularly important when fuel with normal sulfur content (0.25 to 0.5 pct) is used. Other investigations have found that OCC's sometimes increase the mutagenicity associated with DPM (*2*). For these reasons, the application of OCC's in underground mines has been limited (*1, 3*).

In 1993, over-the-road diesels will be required to meet more stringent emission regulations and low-sulfur (<0.05 wt pct) fuel will be available nationwide (*4-5*). Catalyst vendors and fuel producers are developing new formulations to help comply with the new regulations. Some of these products show promise for application in underground mines.

It is plausible that OCC's reduce the volatile organic portion of DPM (VORG) because OCC's are effective in oxidizing HC emissions, which are certainly a constituent of VORG. VORG probably includes substances suspected as precursors of mutagenic compounds, such as nitrated polynuclear aromatic HC, which are potential health concerns. Ongoing advances in technology provide a basis for optimism that the overall effect of OCC's upon air quality in underground mines may turn out to be salutary when

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[2]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

applied in combination with low-sulfur fuel. For these reasons, the U.S. Bureau of Mines is collaborating with vendors and universities to evaluate promising fuel-OCC combinations for potential application by the mining industry.

To help the mining industry exploit the advances in OCC and fuel technology, the Bureau is evaluating newer OCC's with low-sulfur, moderate-aromatic-content fuel. Three particular OCC's manufactured by Engelhard Corp.[3] have been evaluated: PTX-523D, PTX-7DVC (ULTRA-7), and PTX-10DVC (ULTRA-10). The Bureau measured the quantities of DPM and some of its constituents as well as gas-phase emissions. The principal gas-phase emissions reported are CO, as detected by infrared methods, and HC-FID.

Chemical reactions, such as oxidation, tend to occur more rapidly at higher temperatures. The temperature of diesel exhaust depends upon engine load, so that the performance of an OCC depends critically upon the engine used and its duty cycle. The performance of OCC's is characterized by their influence upon DPM and gaseous emissions under a variety of different engine operating conditions, explicitly including a range of exhaust temperatures. The purpose of this work is to indicate the extent to which OCC technology may be useful to the mining industry.

LABORATORY METHODS AND TESTS

ENGINE

The evaluations reported here were made by installing OCC's in the exhaust stream of a Caterpillar 3304 PCNA mining engine with a 21:1 compression ratio. Before this testing began, the engine was broken in for 100 h and the OCC's were preconditioned for 50 h under heavy loads and/or tested in the laboratory for tens of hours. No significant trends in performance were observed during aging.

FUEL

Low-sulfur (in this case, 0.03 wt pct), moderate-aromatic (20 pct) fuel having a cetane number of 45 was used for these evaluations. This fuel is representative of that which will be available nationwide in 1993.

INTAKE AND EXHAUST CONDITIONS

The intake pressure was adjusted and controlled to minimize day-to-day variation of oxygen concentration at the intake manifold and the consequent variability of emissions caused by changes in atmospheric pressure. The conditions corresponded to an intake pressure 3.7 kPa (15 in H_2O) below standard atmospheric pressure at 0.31 km (1,000 ft) altitude. This intake pressure approximates the test condition at which the U.S. Mine Safety and Health Administration (MSHA) would certify this engine (*6*). It is one-half the maximum intake-restriction pressure sanctioned by the engine manufacturer. The exhaust pressure was set 11 kPa (45 in H_2O) above the intake pressure at fast idle, which is 38 Hz (2,300 r/min). This amounts to setting a fixed exhaust restriction equal to the maximum sanctioned by the engine manufacturer. It also mimics MSHA's certification test conditions.

[3]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

TEST MODES

The general test modes employed in this work are (1) survey or screening tests accomplished by applying a gradual increase of engine load at constant speed, which causes exhaust temperature to increase slowly (ramp), and (2) laboratory transient cycles selected to produce significantly different thermal histories in the exhaust (transient). The transients simulate realistic operation of the engine better than ramps, but are more complex to interpret.

Figure 1 describes one of the transients that was used. It illustrates the variation of speed and load for about 2½ cycles, each cycle consisting of sixteen 10-s segments. This cycle is called a 50/10 cycle because the duration of the segments is 10 s and the maximum torque is 50 pct of rated torque. It produces an average exhaust temperature of about 245° C. An abbreviation, 80/30, is used for a test cycle consisting of 30-s segments of speed-load set points, during which the highest torque is 80 pct of the rated torque. The same speed-torque cycle, consisting of 10-s segments, is abbreviated as 80/10.

The set points for this general sort of transient are shown in figure 9 of reference 7. The cycle illustrated there would be called, in our notation, a 100/30 cycle.

Different portions of the OCC have significantly different thermal histories during a transient, so that the entire OCC structure does not experience the full range of exhaust temperature variation.

SPECIFIC MEASUREMENTS

DPM, hydrated sulfate, and VORG are reported. These constituents are measured by collecting DPM on filters after a sample of the exhaust has been diluted about 10:1 with clean air. This dilution plays an essential role

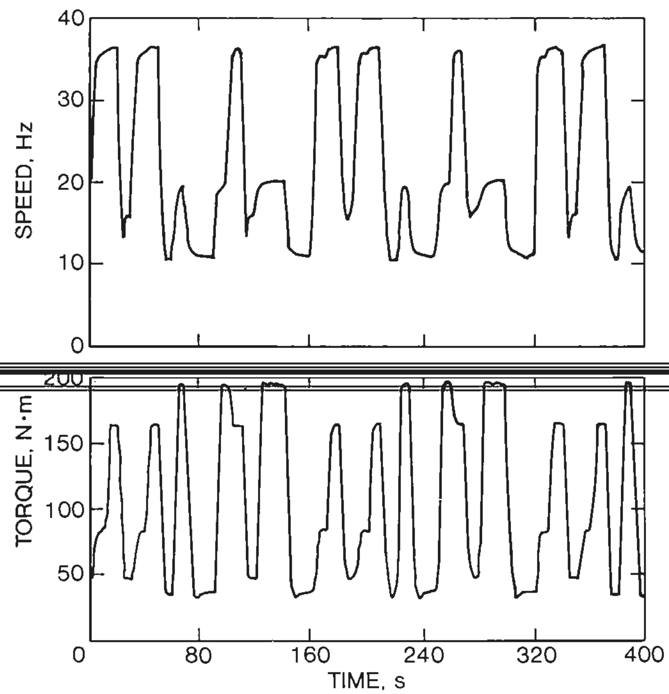

Figure 1.—Actual speed and torque for 2½ repetitions of 50/10 laboratory transient cycle. Highest torque is 50 pct of rated torque for engine.

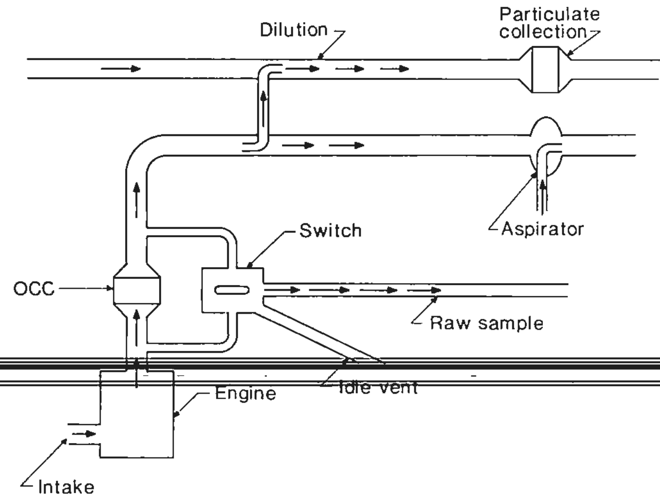

Figure 2.—Relationship of gaseous sample switch to other major elements of test system.

in the creation of DPM in the laboratory, as well as in the mines. The filters are then vacuum sublimated and chemically analyzed for sulfate to estimate VORG, which is important because this fraction contains mutagens or their precursors. Figure 2 of reference 7 shows an overall schematic of the flows through the Bureau's diesel emissions research laboratory system.

Measurements obtained during transient modes include DPM and gas-phase emissions. An OCC's effectiveness in removing gaseous exhaust pollutants is determined by alternately sampling the exhaust upstream and downstream from the OCC, as illustrated in figure 2 and depicted more completely in figure 6 of reference 7. A comparison of the concentrations of emissions upstream and downstream of the OCC yields a direct indication of the effectiveness of the device. Gaseous emissions measured include CO, HC-FID, CO_2, NO_X, SO_2, and O_2, although the results reported here are for CO and HC-FID only.

SCREENING TECHNIQUE

Screening evaluations of OCC's are obtained by observing emissions while increasing the engine load from 27 N·m (20 ft·lbf) to 325 N·m (240 ft·lbf) at a very slow rate: 0.019 N·m/s (5/6 ft·lbf/min). The corresponding rate of change of temperature of the OCC is about 0.023° C/s (2.5° F/min). Figure 3 shows the actual progress of load and temperature during a typical ramp. While this ramp is in progress, the gas-sampling system (see figure 2) is switched from upstream to downstream of the OCC every 12 min. Figure 4 shows the concentration of CO for the ULTRA-10 OCC during a ramp. Such results yield a determination of the efficiency of removal of CO and HC-FID for temperature intervals of about 30° C.

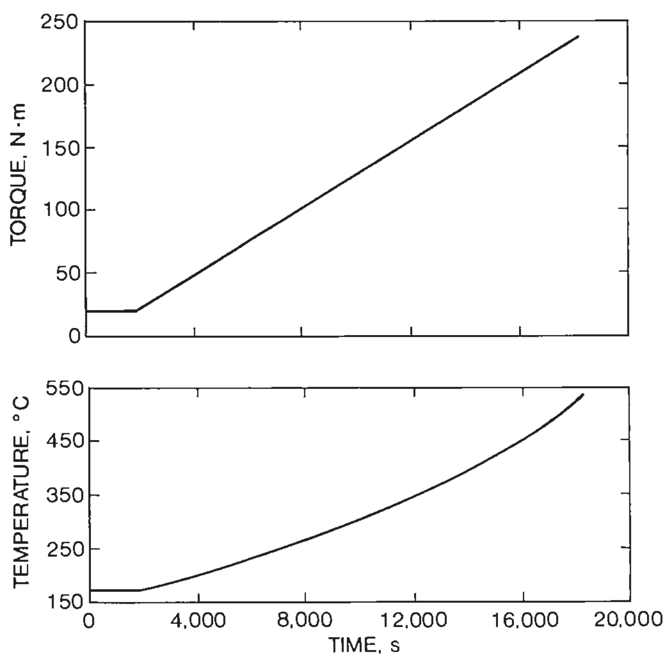

Figure 3.—Temperature of OCC and engine load during typical ramp test.

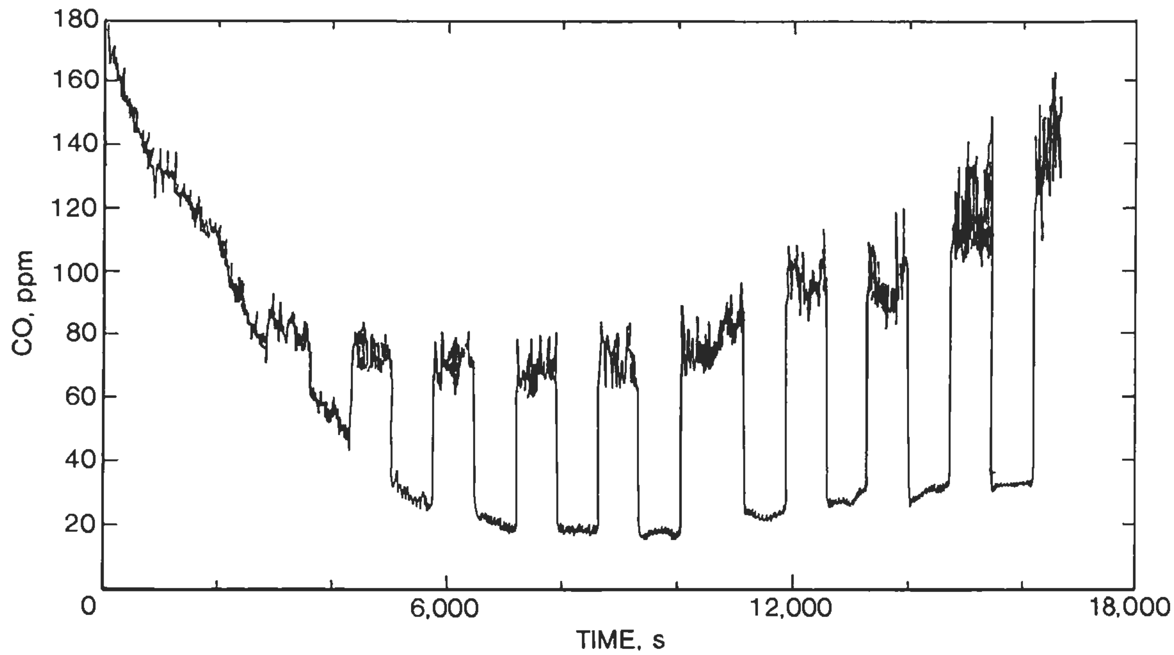

Figure 4.—Concentration of CO measured during ramp test as sample point is alternately switched from upstream to downstream of ULTRA-10 OCC.

TEST MATRIX

Three separate transient cycles have been evaluated with each of the three OCC's. The OCC's chosen include one of traditional catalyst formulation and a size normally used for this engine (PTX-523D); one of normal size, but of more modern formulation, intended to discriminate against sulfate and NO_2 formation (ULTRA-7); and one of modern formulation, but oversized for this engine (ULTRA-10). The transient cycles include the one illustrated by figure 1 (50/10), as well as an 80/10 and an 80/30, as defined in the section "Test Modes."

RESULTS

Four types of results are included in this summary paper: (1) efficiencies of the OCC's in removing CO and HC-FID as a function of temperature at constant engine speed (ramp); (2) average removal efficiency for HC-FID and CO over three types of transient cycles; (3) total effective DPM emitted and its sulfate and VORG components over three transient cycles; and (4) an example of the results of chemical and biological analyses of some of the constituents of total DPM for the 50/10 transient, expressed in energy-specific units. The latter results are condensed from other work, which is cited in the "Energy-Specific Emissions" section.

REMOVAL EFFICIENCY SCREENING

Figure 5 shows the variation in efficiency for CO and HC-FID removal as a function of OCC temperature. These results illustrate some of the differences in performance between the OCC's. Recall that the ULTRA-10 and the ULTRA-7 OCC's have the same catalyst formulation and that the ULTRA-10 OCC is larger. This results in greater removal efficiencies for the ULTRA-10 OCC, particularly at lower temperatures.

TRANSIENT GAS-PHASE REMOVAL EFFICIENCY

Transient evaluations are more likely to correlate with real-world performance than the ramp screening tests given above. Table 1 presents removal efficiencies for CO and HC-FID, along with a characterization of the transients.

Generally, the ULTRA-10 OCC is most effective in removing CO and HC-FID, as would be expected from the screening results presented in figure 5. In several cases, removal is more effective for the 80/30 and the 80/10 transients than for the 50/10 transient. This is explained by the higher maximum torque and consequent higher temperature of these transients.

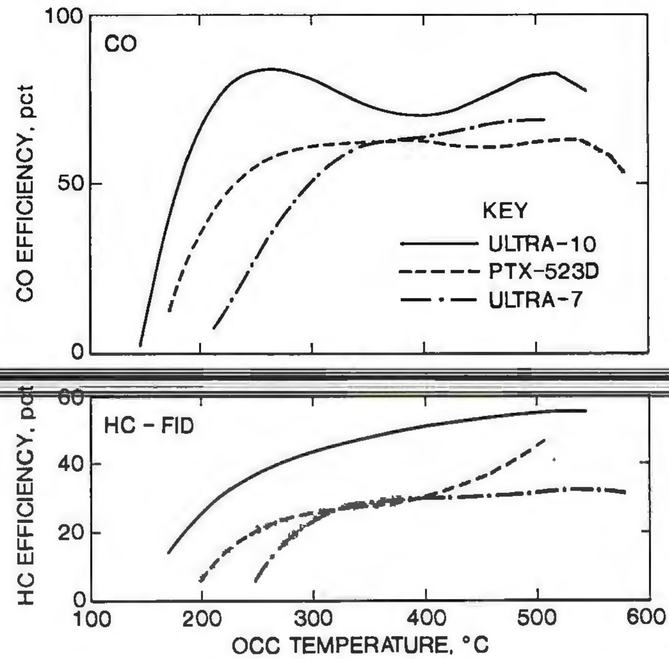

Figure 5.—Removal efficiencies of OCC's as a function of temperature as engine torque is gradually increased. These curves are objectively determined averages (fits) of many screening tests performed over several months.

Table 1.—Removal efficiencies[1] of OCC's for CO and HC-FID when engine is operated under three different transient test conditions

	Transient 1	Transient 2	Transient 3
Characteristic of transient:			
Maximum load ...... pct. .	80	80	50
Segment length .... s. .	30	10	10
Average temperature ... °C. .	330	360	245
CO			
Concentration without OCC .... ppm. .	200	259	159
Removal efficiency for after-treatment device,[2] pct:			
PTX-523D	78	81	74
ULTRA-7	70	73	52
ULTRA-10	82	89	83
HC-FID			
Concentration without OCC .... ppm. .	71	85	75
Removal efficiency for after-treatment device,[2] pct:			
PTX-523D	63	52	52
ULTRA-7	38	44	24
ULTRA-10	66	77	66

[1]Presented as [1-(concentration with OCC)/(concentration without OCC)]·100. These efficiencies are believed to be reliable to 10 pct efficiency.
[2]Engelhard OCC.

TRANSIENT DIESEL PARTICULATE MATTER EMISSIONS

Table 2 summarizes the concentrations of DPM collected downstream of the OCC's for comparison with that collected without an OCC. The values given are averages over several complete cycles of each transient and are further averaged over three types of transients to illustrate the differences between the OCC's. The PTX-523D OCC tends to increase the emission of DPM versus that found without aftertreatment; however, it is the most effective of the devices tested in decreasing VORG. These observations are both related to the catalyst formulation of the PTX-523D OCC, which is more effective than the ULTRA 7 and 10 OCC's in oxidizing both HC and SO_2. The oxidation of SO_2 increases sulfate emission and, indirectly, DPM. The latter proclivity is illustrated in the column headed SU of table 2, which shows that only the PTX-523D OCC yields a significant sulfate component of DPM.

Table 2.—Particulate emissions averaged over three transients, milligrams per standard cubic meter exhaust

Aftertreatment device[1]	DPM[2] Mean	DPM[2] SD	SU[3] Mean	SU[3] SD	VORG Mean	VORG SD
None	86	4	0	0.2	20	2
PTX-523D	90	3	7	0.2	3	2
ULTRA-7	72	4	0.1	0.3	10	1
ULTRA-10	71	7	2	2	10	4

SD Standard deviation.
[1]Engelhard OCC.
[2]Total effective concentration of DPM in the raw exhaust. This concept reflects the fact that most of the DPM is not actually present in raw exhaust, but is created during the dilution process.
[3]Hydrated sulfate portion of DPM.

More detailed results for transient emission of DPM and its constituents are given in table 3, which lists determinations of DPM and two of its constituents for each of the types of transient tests. All OCC's decrease the cycle-average total DPM emitted during light-duty (50/10) transients by an average of about 23 pct. Under moderate transients (80/10 and 80/30), the PTX-523D OCC increases the amount of sulfate collected as DPM from the exhaust by about 10 mg/sm^3 exhaust. As a matter of general interest, work not discussed here shows that under transient conditions, the PTX-523D OCC decreases the concentration of SO_2 in the exhaust by several parts per million, corresponding quantitatively to the observed increase in sulfate emission. The ULTRA-10 OCC yields about 4 mg/sm^3 sulfate while the ULTRA-7 OCC causes no apparent increase.

Table 3.—Details of transient particulate emissions

Aftertreatment device[1]	Transient		Emissions, mg/sm³					
	Max load, pct	Segment length, s	Total DPM[2]		Sulfate		Volatile organics	
			Mean	SD	Mean	SD	Mean	SD
None	80	30	81	1	[3]0.0	0.2	14	1
	80	10	111	4	[3]0.0	0.3	20	2
	50	10	65	NA	0.05	0.1	27	1
PTX-523D	80	30	100	4	12	1	3	1
	80	10	118	4	8	0.2	4	2
	50	10	53	1	0.6	0.08	3	.1
ULTRA-7	80	30	65	1	0.2	0.2	7	1
	80	10	99	5	[3]0.0	0.4	6	1
	50	10	51	2	0.1	0.1	18	1
ULTRA-10	80	30	73	4	4	2	11	4
	80	10	96	8	3	2	7	2
	50	10	45	2	0.1	0.2	13	1

NA Not available.
SD Standard deviation.
[1]Engelhard OCC.
[2]Total effective concentration of DPM in the raw exhaust. This concept reflects the fact that most of the DPM is not actually present in raw exhaust, but is created during the dilution process.
[3]Apparent negative values.

ENERGY-SPECIFIC EMISSIONS

Because the work of a mining engine is determined by the job to be performed and by the habits of the operator, energy-specific emissions are an important measure of the engine-control system's impact upon the environment. Some results expressed in this measure are summarized in table 4, which is a condensed excerpt from table 9 of reference 8. All results are for the 50/10 transient and the ULTRA-10 OCC, but apply to a fuel slightly different from that used in this work. They are a combination of samples, including both DPM (collected on filters) and material contained in the exhaust, but not collected on the filter. Table 4 reports the energy-specific emissions of the soluble organic fraction of DPM (SOF), pyrene, and the mutagenicity of the emissions as well as the influence of the OCC upon each of these emissions. SOF emission is important because this constituent includes some known carcinogens. Pyrene is reported as an example of polynuclear aromatic HC. Mutagenicity is a common indicator of potential adverse health effects.

Table 4.—Effects of ULTRA-10 OCC on energy-specific emission characteristics

Average emission concentration:	
SOF .... mg/MJ ..	140
Pyrene[1] .... ng/MJ ..	12,200
Mutagenicity .... krev/MJ ..	270
Removal efficiency,[2] pct:	
SOF	47
Pyrene[1]	55
Mutagenicity	[3]67

[1]Example of polynuclear aromatic HC.
[2]Presented as [1-(concentration with OCC (concentration without OCC)]·100.
[3]For particulate portion only.

Source: Adapted from McClure (8).

The principal point of table 4 is that the OCC is effective in decreasing energy-specific emissions of these important pollutants, even during a light-duty transient.

DISCUSSION

Ramp and transient evaluations show that the sequence of efficiency (from highest to lowest) for removal of CO and HC-FID is ULTRA-10, PTX-523D, and ULTRA-7 OCC's. The removal efficiencies determined during the 80/10 transient are greater than those measured at any temperature by ramp tests, particularly for HC-FID. This illustrates that although some conclusions based upon ramp or screening tests are useful, ramp and transient evaluations are indeed essentially different. The mode of operation of the engine is vitally important for emissions testing, which is part of the reason that final conclusions must be based upon field evaluation.

The average quantity of DPM emitted during the transient tests is 80 mg/sm^3 exhaust. For moderate transients, the ULTRA-7 and ULTRA-10 OCC's decrease the total DPM emitted, while the PTX-523D OCC causes a small increase. This difference is probably associated with the special catalyst formulation of the ULTRA 7 and 10 OCC's to prevent the formation of sulfate.

CONCLUSIONS

The following conclusions are based upon an evaluation of three Engelhard OCC's using laboratory transient and screening tests performed on a Caterpillar 3304 PCNA engine.

- OCC's can decrease gaseous diesel exhaust emissions without significantly increasing particulate emissions.
- Under some conditions, OCC's significantly decrease the VORG component of diesel exhaust emission.
- If the exhaust temperature for a particular application is marginal for effective operation of an OCC, oversizing the OCC to achieve better low-temperature performance should be considered.
- The Bureau recommends using the modern OCC's developed for on-highway use if (1) average exhaust temperatures are consistently above 200° C and (2) low-sulfur fuel is used.
- The ramp, or screening technique, used in this work is useful in determining gross effects, but is not a quantitative substitute for transient evaluations.
- When applied in combination with low-sulfur fuel, modern OCC's have the potential to play a significant role in decreasing the exposure of underground miners to the harmful components of diesel exhaust.
- OCC's deserve field evaluation in conjunction with low-sulfur fuel.

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DISPOSABLE AND REUSABLE DIESEL EXHAUST FILTERS

By Jeffrey L. Ambs[1] and Terrance L. Hillman[2]

ABSTRACT

The U.S. Bureau of Mines is investigating exhaust filtration devices for diesel-powered vehicles used in underground mines. A disposable diesel exhaust filter (DDEF), developed for heavy-duty permissible, diesel-powered haulage vehicles, was shown to reduce in-mine diesel particulate matter (DPM) concentrations by 95 pct, with a filter life of 10 to 32 h, depending on the application. This system was approved by the U.S. Mine Safety and Health Administration (MSHA), and versions are now being marketed by at least two equipment manufacturers. The Bureau is also evaluating systems for light-duty vehicles used outby in coal mines and nongassy mines. A midtemperature filter, which has a temperature limit of 200° C, is available, and a high-temperature filter, for use on vehicles with exhaust temperatures up to 400° C, is under development. Both of these filters are removable for cleaning and reuse.

INTRODUCTION

This paper provides an update of the U.S. Bureau of Mines activities to develop and evaluate disposable and reusable diesel exhaust filter systems for a variety of mining machines. One solution to the problem of reducing DPM levels in the mine atmosphere is to equip vehicles with disposable or reusable exhaust filters. This paper discusses three types of filters, each designed to be used on vehicles with different exhaust characteristics, with the temperature of the exhaust gases being the primary factor affecting filter choice.

Disposable-reusable filters collect the DPM emitted in the engine exhaust until the back pressure imposed by the filter exceeds that recommended by the engine manufacturer, at which time the filter is removed from the vehicle. Depending on the application, the filter is either discarded or cleaned and reused.

The basic characteristics of the three types of filters and their applications are outlined in table 1. The filter elements (fig. 1) are for use in low-, mid-, and high-temperature-exhaust applications and made of a pleated

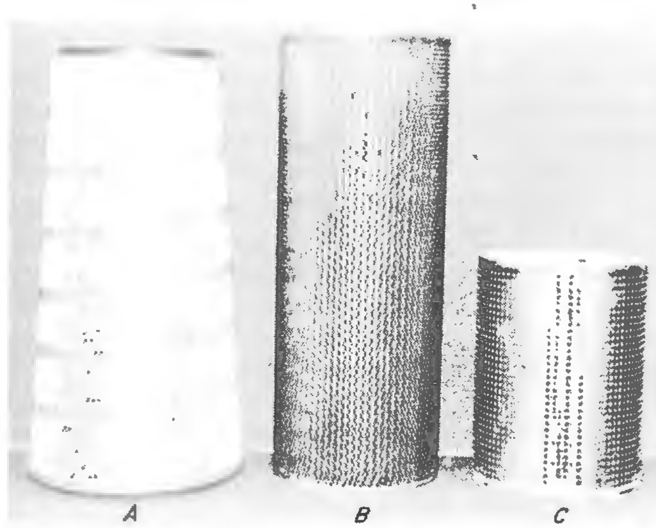

Figure 1.—Low-temperature (A), midtemperature (B), and high-temperature (C) disposable-reusable exhaust filters.

[1]Mechanical engineer.
[2]Engineering technician.
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Table 1.—Exhaust filter system characteristics and applications, by filter type

	Low-temperature	Midtemperature	High-temperature
Maxium recommended temperature	100° C	200° C	400° C.
Primary application	Heavy-duty, gassy	Light-duty outby, nongassy	Light-duty outby, nongassy.
Filter material	Paper	Synthetic paper	Ceramic.
Availability	Now	Now	Under development.
System cost[1]	$3,800 to $5,000	$2,000 to $3,000	$2,000 to $3,000.
Filter cost	$40	$200	Not available.
Filter life[2]	10 to 32 h	Up to 200 h	1 to 4 h.
Type	Disposable	Reusable-cleanable	Reusable-cleanable.
Overtemperature bypass	No	Yes	Yes.

[1]Representative of vehicles with engines below 112 kW for the low-temperature filter and below 37 kW for the midtemperature and high-temperature filters.

[2]Based on the DPM output of the engine; for the low-temperature filter, 49 to 15 g/h; for the midtemperature filter, 2.5 g/h; for the high-temperature filter, 12 g/h.

paper (cellulose or synthetic) or ceramic mat. The low-temperature filter is a disposable filter primarily for use on heavy-duty permissible, diesel-powered vehicles used in underground coal mines and has a maximum recommended temperature limit of 100° C. (While this disposable exhaust filter is currently used on heavy-duty permissible vehicles in underground coal mines, the discussion is applicable to all vehicles approved by MSHA under 30 CFR Part 36 (*1*)).[3] The midtemperature and high-temperature filters are being developed for light-duty vehicles, used outby in underground coal mines and in nongassy mines, and have maximum recommended exhaust temperature limits of 200° and 400° C. In these applications, the midtemperature and high-temperature filters are reusable.

The cost and filter life information reported in this paper are specific for the given vehicles, but should be representative for other vehicles with similar engines. For the low-temperature filter, the data are representative of vehicles with engines up to approximately (112 kW) 150 hp. The information for the midtemperature and high-temperature filters is representative of engines up to approximately (37 kW) 50 hp.

LOW-TEMPERATURE DISPOSABLE EXHAUST FILTER

The Bureau collaborated with the Donaldson Co., Inc., to develop and test a DDEF manufactured by Donaldson[4] for permissible diesel vehicles (fig. 2). These vehicles are the primary source of DPM in the mine atmosphere (*2*) and have special constraints (*1*) that affect the use of exhaust filters. The most important engine constraints are an exhaust temperature limit of 77° C and the requirement to prevent sparks and flames from being emitted in the engine exhaust. The use of water-bath exhaust conditioners (water-bath scrubbers) is the only method currently certified by MSHA for the dual purpose of exhaust gas cooling and spark-flame removal while simultaneously maintaining acceptable engine back pressure. The DDEF system was developed to take advantage of the low-exhaust temperatures exiting the water-bath scrubber.

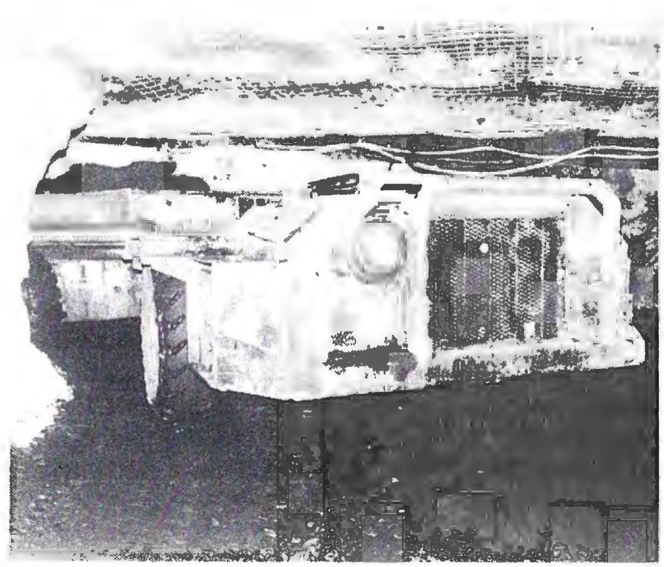

Figure 2.—Jeffrey 4114 RAMCAR with DDEF system installed.

[3]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

[4]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

The DDEF system (fig. 3) consists of a water trap, filter element, filter housing, and exhaust back-pressure indicator. The water trap is bolted directly to the outlet of the water-bath scrubber and prevents water droplets that are carried out of the water-bath scrubber by the exhaust flow from reaching the filter. If water droplets enter the filter, they can saturate the filter, causing high-flow resistance and reducing the effective service life of the filter. Water vapor passes through the filter and is not a problem. After the exhaust exits the water trap, it passes through the DDEF. The filter is similar to intake air filters used by large on-highway diesel vehicles. The current configuration is a cone-shaped, 61-cm (24-in) long filter with 270 5-cm (2-in) pleats and a filter area of 17 m^2 (180 ft^2). Additional filter designs that will reduce the size of the filter or increase the filter life are being investigated.

OPERATIONAL AND INSTALLATION PROBLEMS

The DDEF system was first installed and tested on a diesel-powered, Jeffrey 4114 RAMCAR (shuttle car) manufactured by Dresser Industries, Inc. (While this discussion is specific to the test installation, it is included to illustrate some problems encountered prior to obtaining MSHA approval for the device.) The initial DDEF installation showed promise, but the low-water safety shutdown system on the water-bath scrubber failed to work properly with the filter installed in the system. The safety shutdown system is designed to stop the engine if the temperature of the exhaust exiting the water-bath scrubber exceeds 77° C, or if the water level in the water-bath scrubber is below the level in which it acts as a flame arrester.

A simplified schematic of the Jeffrey 4114 water-bath scrubber, makeup and shutdown system is shown in figure 4. During normal operation, pressurized water is fed from the makeup tank, through the emergency shutdown tank to the pilot valve. When the water float senses a low-water level within the water-bath scrubber, it activates the pilot valve, allowing the pressurized water to enter the water bath.

When the water within the makeup tank has been depleted, the water remaining in the tank that contains the emergency shutdown system drains to the water-bath scrubber by gravity feed. At this time, the emergency shutdown tank is vented to atmosphere. The emergency shutdown tank is sufficiently elevated above the low-water level of the scrubber, such that the waterhead pressure in this tank exceeds the back pressure within the water-bath scrubber (when an exhaust filter is not installed). After a portion of water has drained from the emergency shutdown tank, the emergency shutdown float activates the vehicle safety shutdown system, causing an automatic shutdown of the engine. The addition of an exhaust filter at the outlet of the water-bath scrubber causes higher back pressures to exist within the water-bath scrubber. At times, this elevated pressure is sufficient to prevent the gravity feed flow from the emergency shutdown tank to the water-bath scrubber. Such a situation will allow the engine to continue operation with a water level in the water-bath scrubber that is less than required to provide adequate exhaust gas cooling and flame-spark arresting. By including a vent line from the emergency shutdown tank to the exhaust, the pressure in the emergency shutdown tank will not be lower than the exhaust pressure. The water-bath scrubber will then fill, regardless of the restriction downstream of the water bath.

FIELD EVALUATION OF DISPOSABLE DIESEL EXHAUST FILTER

In cooperation with Utah Fuel Co., a week-long field study was conducted at a high-altitude underground coal

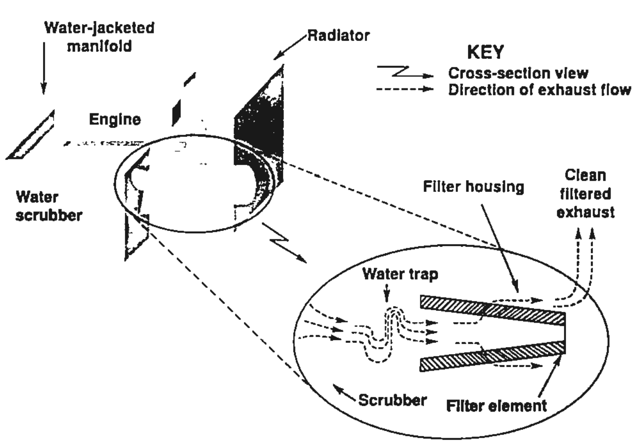

Figure 3.—DDEF system for Jeffrey RAMCAR.

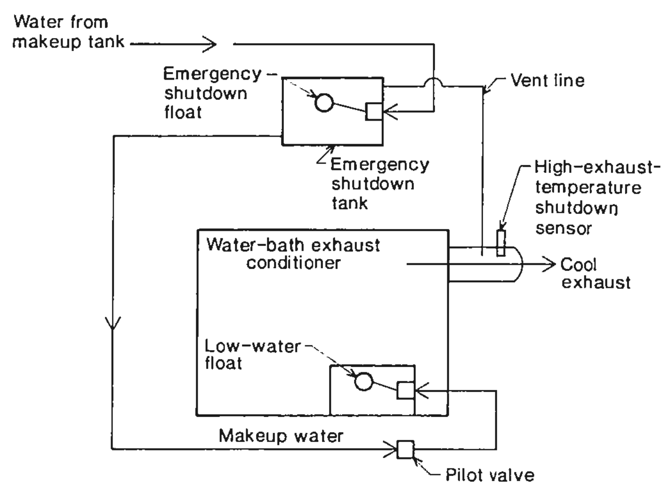

Figure 4.—Simplified schematic of Jeffrey 4114 makeup water and shutdown system.

mine to determine the service life and efficiency of the DDEF system. The exhaust systems of all shuttle cars on a continuous miner section (three Jeffrey 4114 RAMCARs) were equipped with DDEF exhaust control systems.

During the field study, the diesel-powered equipment was operated with and without filters in place. The reduction of DPM in the mine environment was measured with size-selective aerosol sampling, followed by gravimetric analysis. Aerosol samples were collected using a 10-stage microorifice, uniform-deposit impactor (MOUDI) (*2*) and personal diesel exhaust aerosol samplers (*3*) during normal production shifts in the ventilation intake entry, in the haulageway entry, on diesel RAMCARs, and in the return air entry (*4-5*). Table 2 summarizes the results of measurements taken with and without filters installed. The measurements indicate that the DDEF reduced DPM concentrations in the mine atmosphere by 95±5 pct. A description of the field study procedure is given elsewhere in this Information Circular (*6*).

Table 2.—Measured DPM concentration reductions achieved through the use of the DDEF system

Sample site	With DDEF installed, mg/m^3	Without DDEF installed, mg/m^3	Reduction, pct[1]
Intake	0.06±0.02	0.06±0.02	NAp
Haulage	0.12±0.02	0.50±0.02	94±6
Return	0.09±0.03	0.80±0.03	98±4
Jeffrey shuttle car (RAMCAR)	0.17±0.05	0.81±0.03	93±7

NAp Not applicable.
[1]Corrected for ventilation and production change.

During the field evaluation, the usable life of the filters on the shuttle cars (4114 RAMCAR test vehicles) was approximately 10 h before engine back pressure required filter removal. The filters collected between 360 and 490 g of DPM during the tests, corresponding to a DPM emission rate from the vehicles of 36 to 49 g/h.

FACTORS AFFECTING FILTER LIFE

The service life of the DDEF is determined by the exhaust back pressure it imposes on the engine. The total exhaust system back pressure is the sum of the pressure drops across the water-bath scrubber and exhaust piping and the pressure drop across the filter. On the shuttle car (4114 RAMCAR), the maximum back pressure imposed on the engine cannot exceed 8.46 kPa (34 in H_2O). Measurements indicate that the maximum back pressure imposed by the water-bath scrubber and exhaust system is approximately 2.49 kPa (10 in H_2O), so when the pressure drop across the filter reaches 5.97 kPa (24 in H_2O), the filter must be replaced.

The filter life on a water-bath-scrubber-equipped vehicle is dependent on many factors, such as vehicle duty cycle, type of engine, mine altitude, and engine condition, all of which affect the DPM output of the engine. The greater the DPM output from the engine, the shorter the filter life. However, the primary factor contributing to short filter life is water saturation, which is affected by vehicle operating and maintenance procedures. Because of space limitations, the water trap was not sized to handle the extreme amounts of water that can be expelled from the water-bath scrubber at engine startup; thus, a significant amount of water can pass into the filter canister, saturating the filter. Because this is mainly a problem just after the water-bath scrubber has been replenished, the simplest solution is to install the filter after water-bath scrubber maintenance and engine startup have been performed.

SAFETY CONCERNS

In addition to the 4114 RAMCAR, Jeffrey has received MSHA approval to use the DDEF system on the 4110 RAMCAR (fig. 5). Problems with the use of DDEF's on 4110 RAMCARs in the field have been reported, but are of concern for all vehicles equipped with disposable filters. Under certain circumstances, the exhaust temperature will significantly exceed the recommended maximum for the filter. Elevated exhaust temperatures result when the engine shutdown system malfunctions. Sometimes the engine shutdown system is bypassed when the vehicle is used outby where exhaust-gas cooling is not required. When the shutdown system fails to operate, the water-bath scrubber eventually empties of water and the exhaust temperature can exceed the 100° C temperature limit of the filter. This overtemperature condition, which would occur whether or not a filter was installed, can result in the ignition of the filter and collected DPM. To avoid this problem, it is important to keep the safety systems on the vehicle

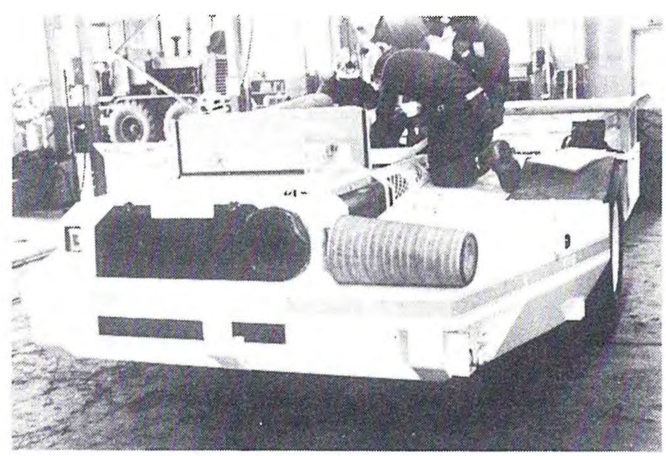

Figure 5.—Jeffrey 4110 RAMCAR showing DDEF installation.

working properly, and if the vehicle is operated outby in a nonpermissible manner, the filter *MUST NOT* be used.

Because of the potential health risks involved with exposure to DPM, proper disposal of the used exhaust filters is also a concern of the Bureau and mine operators. The Bureau recommends that the used filters be boxed or bagged to prevent handler exposure to the collected DPM and then incinerated at an acceptable facility.

AVAILABILITY AND COST

Jeffrey Div., Mining Machinery, Inc., Dresser Industries, has MSHA-approved DDEF systems available for its 4110 and 4114 RAMCARs (*7*). The price of the systems are $3,800 and $5,000, respectively, with a price of approximately $40 per filter. The reported life of the filters is up to 10 h on the 4114 RAMCAR and up to 32 h on the 4110 RAMCAR (table 1).

Wagner Mining and Construction Equipment Co. is in the process of developing a DDEF system for its permissible mine equipment. The system is currently being evaluated by MSHA, and Wagner expects to have systems available in the near future. Wagner has indicated that the filters last 8 h or more in the laboratory under full-load, engine-operating conditions. No system or filter cost is yet available.

MIDTEMPERATURE REUSABLE EXHAUST FILTER

The Bureau is cooperating with Donaldson to adapt a midtemperature reusable exhaust filter to light-duty vehicles used in underground mines. The midtemperature filter system, usable on any vehicle with an exhaust temperature below 200° C, consists of a low-restriction muffler, back-pressure indicator, overpressure relief valve, overtemperature bypass valve, filter housing, and 66-cm (24-in) long filter with a filter area of 6 m^2 (65 ft^2).

While the simplest use of the filter is on vehicles with exhaust temperatures always below 200° C, the filter can be adapted to vehicles with intermittent exhaust temperatures above 200° C by installing a temperature-activated bypass valve upstream of the filter. The bypass valve opens when the exhaust temperature exceeds 200° C and high-temperature exhaust is then diverted from the filter. The filter and high-temperature bypass should not be used on all light-duty vehicles with high-exhaust temperatures. Since high-load, high-exhaust-temperature, engine-operating conditions generate the greatest amounts of DPM, if the exhaust is bypassed, the benefit of the filter is reduced.

The midtemperature filter was initially developed for diesel-powered forklifts (fig. 6) used at freight terminals by the trucking industry (*8*). The filters are popular in Europe where diesel forklifts are widely used, but have found less of a market in this country where propane-fueled forklifts are more prevalent. A study by the National Institute for Occupational Safety and Health (NIOSH) compared diesel-powered forklifts used with and without exhaust filters at a freight terminal transfer station and found that the filters reduced overall worker exposure to DPM by approximately 90 pct (*9*). Diesel Controls, Ltd., is also evaluating the filter on a Toyota Land Cruiser utility vehicle at a mine in Ontario, Canada (*10*). Its evaluation indicates a filter efficiency of approximately 97 pct.

SAFETY CONCERNS

On vehicles with exhaust temperatures that exceed 200° C, it is important to ensure that the overtemperature valve is in place and functioning properly. An event involving a Bureau forklift equipped with a filter recently

Figure 6.—Diesel-powered forklift with reusable filter installed.

occurred, illustrating this important point. The forklift, which was not fitted with an overtemperature valve, normally receives limited usage; however, the exhaust temperature frequently exceeds 200° C. At the time of the incident, the forklift was being operated on a slight uphill grade, which produced a high load and high-exhaust temperatures. When the vehicle was returned to idle, the exhaust system temperature was high enough and sufficient oxygen was present in the exhaust to cause the filter and collected DPM to ignite. The physical evidence at the time was excessive smoke coming from the filter canister. While there was no damage to the exhaust system, the filter was destroyed.

FILTER LIFE AND COST

Under normal operation, the filter has a loading cycle of approximately 200 h on an engine with a DPM output of approximately 2.5 g/h, such as in the forklift application. With a price of approximately $200 per filter (the hardware costs are from $2,000 to $3,000), the ability to clean and reuse the filters is beneficial (table 1). The midtemperature filter is able to withstand up to 10 loading-cleaning cycles before the filter media deteriorates and filter efficiency decreases. The filters are cleaned by jets of pulsed reverse-flow air using a proprietary cleaning device manufactured by Donaldson.

HIGH-TEMPERATURE REUSABLE EXHAUST FILTER

High-temperature, pleated ceramic filters are being developed by Donaldson and evaluated by the Bureau on a Trammer (fig. 7), a light-duty personnel carrier manufactured and provided by the Getman Corp. Despite the high-temperature limit, the filter requires low-exhaust-gas velocities and has a low-DPM-holding capacity, which makes it unsuitable for use on heavy-duty vehicles. The filter can be used on vehicles with intermittent exhaust temperatures above 400° C through the use of an overtemperature bypass, as described in the "Midtemperature Reusable Exhaust Filter" section. A bypass is required to prevent high-temperature exhaust gases from igniting the DPM collected by the filter.

When the high-temperature filter requires cleaning, the filter is placed in an oven capable of maintaining a temperature of 600° C. Once the filter has reached 600° C, the collected DPM burns off the filter in about 5 min.

The high-temperature filter is still in the development phase, and candidate filter medias are still being identified for future durability testing. Preliminary testing has identified filters that will last from 1 to over 4 h, with a simulated duty cycle generating 12 g/h of DPM (table 1). The hardware is essentially the same as with the midtemperature filter, so the price of the high-temperature filter hardware should be in the $2,000 to $3,000 range as well. The price of the filters cannot be determined until a final filter design is chosen.

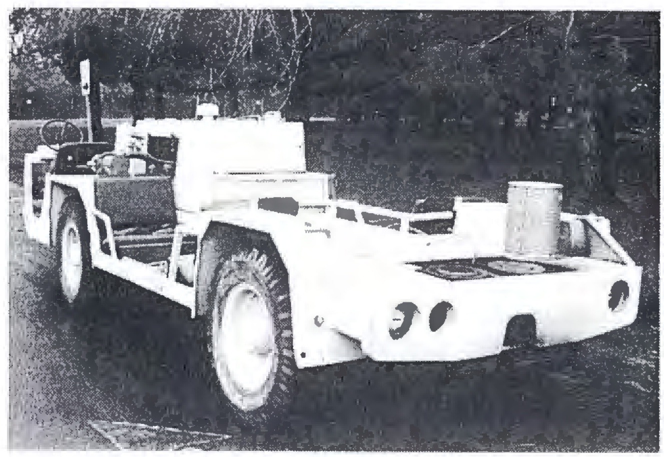

Figure 7.—Light-duty personnel carrier with prototype reusable filter installation.

SUMMARY

The Bureau has been cooperating with the private sector to develop disposable and reusable diesel exhaust filters for a variety of mining vehicles. While the feasibility of using filter systems on vehicles used by the mining industry has been demonstrated, it is up to mine operators to make it known to equipment manufacturers that exhaust filtration systems are needed. It is the manufacturers' responsibility to adapt and design these systems to customer requirements.

The DDEF has been shown to reduce in-mine DPM levels by 95 pct, with a filter life of 10 to 32 h on heavy-duty permissible mining vehicles. The filter is widely accepted by the underground coal mining industry, with over 100 units ordered. Jeffrey's Mining Machinery Div., Dresser Industries, has MSHA-approved systems available for its 4114 and 4110 RAMCARs. Wagner expects to have MSHA-approved systems available to the industry soon.

While heavy-duty vehicles are the primary sources of DPM in underground mines, a future DPM exposure limit may make it necessary to control DPM from light-duty vehicles as well. A midtemperature filter is available for use on vehicles with exhaust temperatures below 200° C. This system, and the high-temperature filter system under development, will most likely find limited usage unless regulations move the industry to install exhaust filters on more vehicles in mines.

It is important that all safety systems, MSHA mandated and those designed into the filter systems, be installed and maintained in peak operating conditions whenever filters are used in underground mines. Because of the potential fire hazards of using disposable-reusable filters on vehicles with high-exhaust temperatures, it is imperative that the filter systems be properly engineered for the intended application. As filtration systems become increasingly used, steps to monitor and control fire hazards will be necessary.

Because of potential health risks associated with exposure to DPM, proper handling of the used filters is also important. The Bureau recommends that used filters be boxed or bagged and then incinerated at an acceptable facility.

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IN-SERVICE PERFORMANCE OF CATALYZED CERAMIC WALL-FLOW DIESEL PARTICULATE FILTERS

By K. L. Bickel,[1] P. Thomson,[2] and T. L. Hillman[3]

ABSTRACT

Catalyzed diesel particulate filters (CDPF's) are used for reducing diesel particulate matter (DPM) concentrations in underground mines. The U.S. Bureau of Mines is conducting research on how CDPF's perform. Two CDPF's, with two different catalysts, are used on vehicles in two mines. The CDPF's are periodically removed from service and evaluated in the laboratory to determine their DPM collection efficiency, regeneration temperature, and effects on gaseous hydrocarbon (HC) and carbon monoxide (CO) emissions. This paper summarizes the results of the laboratory evaluation and the mines' experience with the CDPF's.

Both CDPF's have operated over 2,000 h. One was evaluated after 1,646 h; its collection efficiency at one operating condition was 87.3 pct. After 2,135 h of operation, it was removed from service because it was damaged. The second CDPF continues to be used after 2,328 h of service. The laboratory evaluation indicated its collection efficiency decreased after 1,584 h of use and its regeneration temperature increased from 405° to 420° C. The mines' experiences with the two CDPF's varied. While being used on mine vehicles, both CDPF's became plugged with DPM on a number of occasions because of insufficient regeneration.

CDPF's are capable of lowering DPM concentrations in diesel exhaust. They can also lower emissions of CO and HC, depending on the type of catalyst used. In this study, the performance of the CDPF's changed with use. Recommendations are given in this paper for proper use of CDPF's in mines.

INTRODUCTION

One device for filtering DPM from exhaust is the ceramic wall-flow diesel particulate filter (DPF). The DPF has a cellular ceramic substrate enclosed in a steel housing (*1*).[4] It has square, porous channels running the length of the filter. At the inlet end, every other channel is plugged with ceramic material, while the adjacent channel is plugged at the outlet end (fig. 1). The exhaust gas enters a channel and is forced to pass through the channel wall, where filtering takes place. The exhaust exits through an adjacent channel. DPF's remove 63 to 95 pct of the DPM from exhaust (*2-4*).

On a vehicle, the DPF is located in the exhaust stream, as close to the engine as possible. As DPM collects, the back pressure on the engine increases. After sufficient DPM is collected and the exhaust temperature exceeds 550° C, the DPM burns. This self-cleaning process is called regeneration. Unfortunately, few vehicles operate in such a way that the exhaust reaches regeneration temperatures often enough for the DPF to remain clean.

Several methods have been investigated for providing heat to the DPF for regeneration. These methods include the application of electric heaters and fuel burners (*5*).

A method of increasing the frequency of regeneration involves applying a catalyst to the DPF to lower the regeneration temperature. The catalysts are usually base

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[4]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

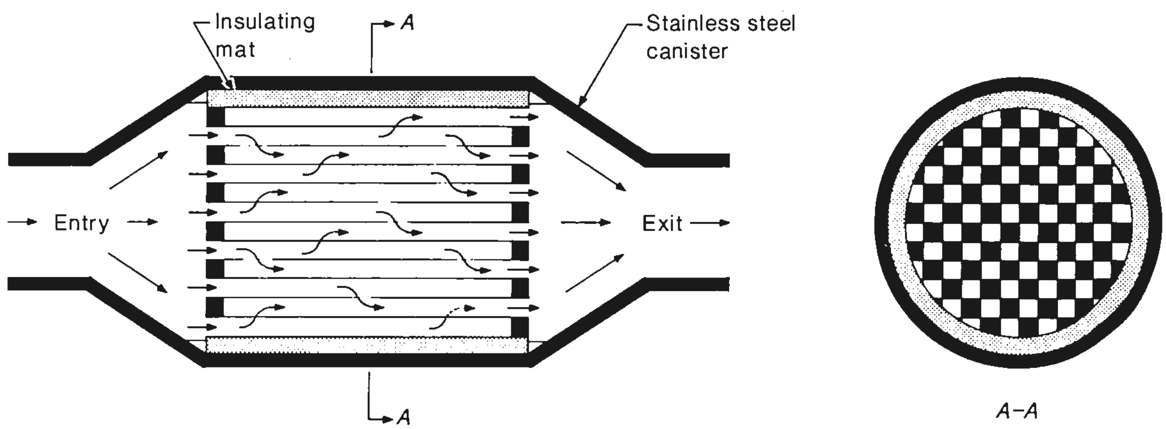

Figure 1.—Schematic of CDPF.

metal or noble-metal based. Typically, regeneration will occur when the temperature of a CDPF exceeds 400° C (*6-7*). CDPF's can be used on nonpermissible mine vehicles that have exhaust temperatures exceeding 400° C during much of their duty cycle. These vehicles tend to be production equipment that move ore or waste and may include other vehicles whose engines operate frequently at high power, e.g., those that climb a ramp many times each shift.

If the CDPF reaches regeneration temperature frequently enough during a vehicle's duty cycle, the engine back pressure will remain within acceptable limits. However, if the duty cycle or condition of the engine changes such that regeneration does not occur, or occurs less frequently, the CDPF may become heavily loaded with DPM. An uncontrolled regeneration can occur when regeneration is initiated in a heavily loaded CDPF. If the DPM burns too quickly, the heat will not dissipate fast enough, causing high-temperature gradients that may crack or melt the ceramic substrate. In a laboratory investigation of uncontrolled regeneration, Baumgard (*8*) reported exhaust temperatures exceeding 925° C and CO emissions exceeding 5,000 ppm. He concluded that as long as the engine back pressure remained below the engine manufacturer's recommended limit, uncontrolled regeneration was unlikely to occur.

The primary reason to apply a catalyst to the DPF is to lower the regeneration temperature, but some catalysts will also reduce CO and gaseous HC emissions. Bagley (*2*) reported a decrease in CO emissions of 79 pct and HC emissions of 59 pct using a CDPF on a mining engine when tested over a transient engine cycle. Similar reductions have been reported with the use of oxidation catalytic converters (OCC's) (*9*). The CDPF should not be confused with an OCC, whose primary purpose is to reduce gaseous emissions, not DPM (*10*).

Catalysts used on OCC's may store sulfur in the form of sulfate at low-exhaust temperatures and release it into the exhaust stream in the form of particulate at high-exhaust temperatures. Henk (*11*) reported that at temperatures below 450° C, a platinum-on-aluminum oxide catalyst formed very high levels of sulfate. The sulfate can then be stored on the alumina wash coat and released into the exhaust at temperatures above 450° C. Sulfur storage and release can be minimized using a silica-based wash coat.

Catalyst durability is an important issue in catalyst design. In a paper discussing the durability characteristics of palladium catalysts, Sims (*12*) states that there are two basic modes of automotive catalyst deactivation. One mode is thermal deterioration, caused when the catalyst is exposed to high temperatures and sintering of the catalyst occurs. Sintering reduces the active surface area and catalytic performance suffers. A second mode of deactivation is caused by sulfur, lead, and phosphorus from the fuel or oil poisoning the catalyst. Brear (*13*), in a study of OCC's for a heavy-duty diesel engine, listed the following causes for the loss of catalyst performance with service:

1. Loss of active surface area due to sintering of the wash coat.
2. Interactions between catalyst support materials and interactions between components of the catalyst.
3. Volatilization of catalytic components.
4. Loss of physical integrity of the catalyst structure due to phase changes.
5. Catalyst deactivation by poisons, mainly phosphorus from the lubricating oil and sulfur from the fuel.

The use of CDPF's in mines has met with varied success. A study of 18 CDPF's in mines in Canada reported that 8 had been removed because of plugging, failure, odor, or some other reason. These CDPF's operated an average of 1,704 h. The 10 remaining CDPF's were still operable and had accumulated an average of 1,984 h of operation. One operated for over 4,000 h. Problems reported include poor regeneration, leading to plugging of CDPF's; and unusual odors that concerned some vehicle operators. Because the CDPF removes visible smoke from the exhaust, operators and mine mechanics cannot determine if the engine is smoking, one of the easiest methods of determining if there is an engine malfunction (*7*). In a trial of DPF's and CDPF's on load-haul-dump (LHD) vehicles, front-end loaders, and bulldozers at a Canadian mine, McKinnon (*14*) concluded that DPF's and CDPF's can be used successfully underground and that vehicle maintenance costs are decreased. Maintenance costs decreased because vehicles were frequently removed from service if they were smoking, and the incidence of smoke-related maintenance decreased with the use of DPF's.

Sherwood (*15*) reported that a DPF operated for about 5,000 h on an LHD vehicle, in an underground mine. The DPF was removed and analyzed. No cracking or melting of the substrate was seen, but ash accumulation was high. The baseline back pressure had increased from 2.5 to 4.0 kPa (10 to 16 in H_2O) over the life of the DPF because of the ash accumulation.

The objective of this paper is to summarize a U.S. Bureau of Mines study to determine whether the regeneration temperature, collection efficiency, and effect on CO and HC emissions of CDPF's change with use. The study is ongoing; this paper describes only the results that have been obtained thus far. Two CDPF's that are being used on vehicles in two different mines have been evaluated in the laboratory. During laboratory evaluation, no attempt is made to duplicate mine conditions or vehicle duty cycles. The CDPF's are evaluated only under selected engine operating conditions that are not intended to reflect the mine vehicle's engine operating conditions. However, the selected parameters evaluated under the controlled conditions of the laboratory provide an indication of how well the CDPF is working at points during its service life.

EXPERIMENTAL METHODS

TEST FACILITY, CATALYZED DIESEL PARTICULATE FILTERS, AND ENGINE

All laboratory tests are conducted in the Bureau's diesel emission research laboratory (*16*). Testing is conducted using a Caterpillar[5] 3304 prechamber, naturally aspirated engine, rated at 74.6 kW (100 hp) at 2,200 r/min, with a peak torque of 380 N·m (280 lb·ft) at 1,200 r/min. A low-sulfur fuel (0.03 to 0.04 wt pct) is used for all tests.

The two CDPF's being evaluated, hereafter referred to as CDPF-A and CDPF-B, are made of Corning EX-66 cordierite, with a mean pore size of 35 μm and 15.5 cells per cm^2 (100 cells per in^2). CDPF-A measures 28.6 cm (11.25 in) diameter by 35.6 cm (14 in) long. CDPF-B measures 38.1 cm (15 in) diameter by 38.1 cm (15 in) long. Their collection efficiency is about 65 to 70 pct, uncatalyzed (*17*). The application of the wash coat and catalyst increases the collection efficiency. The wash coat increases the surface area of the ceramic substrate so that more of the catalyst can be applied. Each CDPF is coated with a different catalyst, supplied by two different manufacturers, and mounted in a steel canister.

[5]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

A 28.6-cm (11.25-in) diameter by 35.6-cm (14-in) long CDPF costs about $6,000. A CDPF measuring 38.1 cm (15 in) diameter by 38.1 cm (15 in) long costs about $8,000 to $9,500. These prices are for a new CDPF mounted in a canister without a control panel or any associated hardware.

The CDPF's are prepared for laboratory evaluation by instrumenting them with thermocouples to measure inlet and outlet temperatures (fig. 2). One 0.16-cm (0.063-in) diameter K-type thermocouple is placed 2.5 cm (1.0 in)

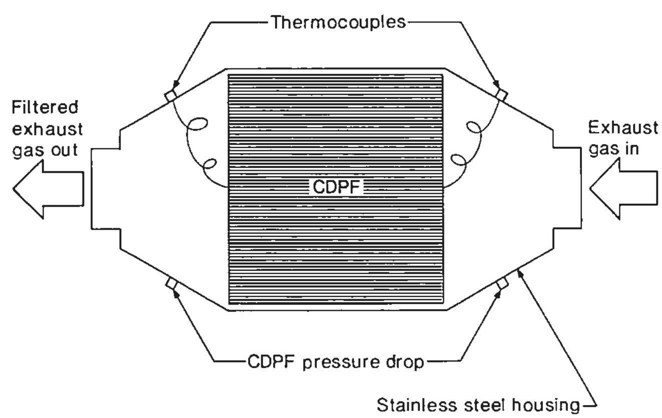

Figure 2.—Location of thermocouples and pressure ports on CDPF.

into the substrate, on both inlet and outlet ends. The thermocouples are installed through thermo-couple fittings welded to the canister.

The difference in pressure between inlet and outlet, or the pressure drop across the CDPF, is an indication of how much particulate is contained in the CDPF. When the CDPF is regenerating, the pressure drop decreases. Pressure ports are installed at the inlet and outlet ends of the canister to monitor the pressure drop.

TEST PROCEDURE

CDPF's returned from the mines for evaluation are examined visually for physical damage, and the inlet and outlet ends are inspected for evidence of plugging. If plugging is suspected, the CDPF's are installed in the laboratory and the engine back pressure is determined. The CDPF's are then removed and blown out with compressed air to remove as much DPM as possible. This prevents an uncontrolled regeneration, which could damage the ceramic substrate. Testing proceeds only when the back pressure is less than 7.5 kPa (30 in H_2O).

The CDPF's are evaluated in the laboratory after 800 to 1,700 h of operation on the mine vehicle. All testing is done using the Caterpillar diesel engine, which is different from the engines used on the mine vehicles. The test procedure is designed to determine the CDPF's particulate collection efficiency and its effect on CO and HC emissions. Testing is also conducted to measure regeneration temperature, the temperature at which the amount of DPM being collected equals the amount being regenerated, as measured by the change in pressure across the CDPF. Engine baseline emissions and emissions with the CDPF are collected each time the CDPF's are evaluated. No attempt is made to duplicate the conditions the CDPF experienced in the mine.

Diesel Particulate Matter Collection Efficiency Testing and Gas Sampling

The CDPF collection efficiency is determined under steady-state engine conditions. CDPF-A was evaluated at mode 4 only (table 1), after operating 1,646 h. Mode 4 was selected because the CDPF's temperature is about 300° C at that condition, well below its regeneration temperature. Little conversion and release of sulfate is expected at this condition.

Table 1.—Six steady-state engine conditions

Mode	Speed, r/min	Load, pct
1	1,200	50
2	1,200	75
3	1,200	100
4	1,800	50
5	1,800	75
6	1,800	100

CDPF-B was evaluated after 839 h of vehicle operation and again after 1,584 h, under six steady-state modes (table 1). These modes were selected because they represent operating modes an LHD vehicle might experience in a mine (*18*) and because they have a wide range of exhaust temperatures, including two modes (modes 3 and 6) where the CDPF will regenerate.

During the collection efficiency tests, DPM samples are obtained with and without the CDPF installed. One to three samples are obtained at each mode. Sampling times vary from 15 to 30 min without the CDPF, and 60-min samples are taken with the CDPF installed. CO and HC emissions are measured (*16*).

Regeneration Temperature Testing

During the regeneration temperature test (also called a ramp test), the engine is operated at a constant speed of 1,800 r/min and the load is increased from 27.1 N·m (20 lb·ft) to 339 N·m (250 lb·ft) at a rate of 1.02 N·m/min (0.75 lb·ft/min). The CDPF temperature increases slowly, from about 170° to 520° C. The pressure drop across the CDPF is monitored to determine the regeneration temperature. This test differs from the test for collection efficiency, where the engine operates at one steady-state engine condition and the exhaust temperature is constant during each mode. By slowly increasing the exhaust temperature, the regeneration temperature can be easily determined.

MINE APPLICATION

CDPF-A was installed on a 2.7 m^3 (3½ yd^3) Wagner ST-3½ LHD vehicle at an underground gold mine. The LHD vehicle has a Caterpillar 3306 prechamber, naturally aspirated engine, rated at 111.9 kW (150 hp) at 2,200 r/min. The engine is derated to operate at an elevation of 915 m (3,000 ft) above sea level. The CDPF was installed in a protected location near the engine area (fig. 3), replacing the muffler and OCC. The LHD vehicle's duty cycle is such that it will travel up and down a 16-pct ramp a distance of about 214 m (700 ft) between loading and dumping.

CDPF-B is installed on an 3.8 m^3 (5 yd^3) Eimco 925 LHD vehicle at a second underground gold mine. It is powered by a Deutz F10L413 FW diesel engine, rated at 172.3 kW (231 hp) at 2,300 r/min. The CDPF is installed by the engine compartment of the machine, just after the point where the two exhaust manifold pipes merge. It replaces the OCC and muffler. The LHD vehicle spends most of its time mucking and loading trucks. It will seldom travel up a ramp loaded with ore. It will travel up or down a 15-pct ramp between workplaces or to maintenance shops, on an as-needed basis.

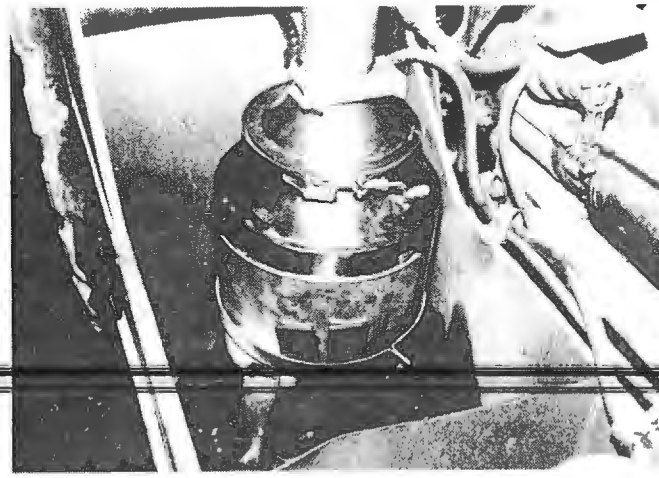

Figure 3.—CDPF-A on Wagner LHD vehicle.

RESULTS AND DISCUSSION

MINE EXPERIENCE

CDPF-A was used for 1,646 h on the Wagner LHD vehicle and then evaluated by the Bureau. After evaluation, it was reinstalled and operated for an additional 489 h. It was permanently removed from service when an inspection revealed that pieces of the ceramic substrate had broken off after 2,135 h of operation. It is not known what caused the damage to the CDPF.

CDPF-B was evaluated at the Bureau after 839 and 1,584 h of operation on the Eimco LHD vehicle. It remains in service after 2,328 h. The CDPF will be reevaluated before 2,800 h of use.

Both mines have experienced problems with plugging of the CDPF's. When the LHD vehicles are used for light-duty work that differs from their normal use, vehicle operators are instructed to periodically work the machine "hard" to regenerate the CDPF's. In other instances, the CDPF's have been cleaned using compressed air or steam cleaning. More cleaning and maintenance of the CDPF's has been needed than was initially expected.

The reaction of the vehicle operators to the CDPF's is generally good. Most miners like the CDPF's and feel there is less smoke in their work areas. Some operators in one mine complained of a burning sensation in their eyes when the CDPF was new, but this disappeared after 8 to 10 h of operation. This has been attributed to curing of the sealing material between the CDPF and its stainless steel housing (*3-4, 6-7*). The material is an intumescent sheet containing inorganic fibers, vermiculite, and organic binders that expand when heated, holding the CDPF in place.

It has been observed in one mine that the CDPF can mask high concentrations of gaseous pollutants. In work areas that are not well ventilated, diesel smoke may accumulate and operators can see that the area is poorly ventilated. When the CDPF is used, the smoke is removed and gaseous pollutants can continue to accumulate without an increase in smoke.

LABORATORY EVALUATION

The CDPF's were examined for damage when they were received from the mines. No damage to the canister or inlet and outlet faces of the ceramic substrate was observed. The CDPF's appeared to be in good physical condition. Portions of the inlet face, however, were completely clogged with DPM. The clogged portions tended to be close to the perimeter of the ceramic. A heavy buildup of DPM could also be seen on the walls of other channels.

When the CDPF's were received, the engine back pressure exceeded 10 kPa (40 in H_2O) and the CDPF's were "blown out" using compressed air. The DPM was captured in a bag to avoid exposure to DPM. The back pressure of the cleaned CDPF's was brought below 7.5 kPa (30 in H_2O) before testing.

Regeneration Temperature

The regeneration temperature of CDPF-A was 405° C after 1,646 h of operation. The regeneration temperature of CDPF-B increased from 405° C after 839 h, to 420° C after 1,584 h.

It is not known why the regeneration temperature of CDPF-B increased. It is possible that the DPM buildup simply covered much of the active portion of the catalyst. This masking of sites for catalytic activity may reduce the effectiveness of the catalyst. It is also possible that the catalyst performance has been affected by poisoning, sintering, or some other cause (*12*). Niura (*19*) reported that the regeneration temperature of three base-metal CDPF's increased by 20° to 50° C after thermal aging. The CDPF's used in the study were thermally aged using a diesel fuel burner for regeneration.

Gaseous Emissions

When tested after 1,646 h, the CO emissions with CDPF-A increased 12.1 pct compared with the engine baseline condition (table 2). This increase is not significant. The HC emissions were reduced by 48.4 pct after 1,646 h of operation.

After 839 h, CDPF-B reduced CO emissions by 21.3 to 64.8 pct, depending on the engine mode. After 1,584 h, the CDPF reduced CO by 14.3 to 57.5 pct. The CDPF was effective at lowering HC emissions, with reductions of 5.4 to 89.7 pct after 839 h and 23.1 to 76.5 pct after 1,584 h.

The amount of CO and HC reduction is dependent on the catalyst and the exhaust temperature. Similar CO and HC reductions with increasing temperature were observed by Bagley (*2*) in a study of a CDPF with a platinum-based catalyst.

Diesel Particulate Matter Collection Efficiency

After operating for 1,646 h, the DPM collection efficiency for CDPF-A was measured at 87.3 pct at mode 4 (table 3). This compares favorably with other studies of catalyzed and uncatalyzed diesel filters that report DPM removal efficiencies ranging from 63 to 95 pct (*2-4, 8*).

After 839 h, the DPM collection efficiency of CDPF-B ranged from 85.5 to 94.5 pct at modes 1 to 5, respectively. At mode 6, its DPM collection efficiency was 48.1 pct. The lower collection efficiency at mode 6 may be due to the release of sulfate (*11*). At mode 6, the CDPF regenerates. Particles can be driven off the CDPF during regeneration, leading to lower collection efficiencies (*20*).

After 1,584 h, the collection efficiency of CDPF-B decreased at five of the six engine modes by at least 15 pct, compared with the testing at 839 h. The collection efficiency ranged from 81.9 pct at mode 5 to 41.2 pct at mode 3. The lowest collection efficiencies were at modes 3 and

Table 2.—CO and HC exhaust concentrations, CDPF temperature, and percentage change in emissions for CDPF-A and CDPF-B

Time of operation, h	Mode	CO concentration, ppm		HC concentration, ppm		Reduction in CO emissions, pct	Reduction in HC emissions, pct	CDPF temperature, °C
		Without CDPF	With CDPF	Without CDPF	With CDPF			
				CDPF-A				
1,646	4	75.3	84.4	110.4	57.0	-12.1	48.4	306
				CDPF-B				
839	1	57.2	45.0	25.7	24.3	21.3	5.4	235
	2	66.0	26.8	43.4	15.3	59.4	64.7	334
	3	203.3	73.8	39.4	6.3	63.7	84.0	537
	4	91.1	46.0	59.4	28.6	49.5	51.9	294
	5	104.5	36.8	68.2	15.2	64.8	77.7	405
	6	124.3	63.7	64.2	6.6	48.8	89.7	577
1,584	1	45.3	38.8	45.1	34.7	14.3	23.1	256
	2	64.1	39.3	54.2	25.0	38.7	53.9	344
	3	290.7	152.4	47.4	13.6	47.6	71.3	547
	4	82.7	50.6	64.8	38.7	38.8	40.3	293
	5	93.6	45.5	74.0	25.9	51.4	65.0	400
	6	195.7	83.2	63.0	14.8	57.5	76.5	576

6, where regeneration occurs. Sulfur stored during testing at lower exhaust temperatures may have been released at modes 3 and 6. Although no damage could be seen on the inlet or outlet face of the ceramic substrate, it is believed that the CDPF sustained internal damage. The damage could have occurred because of mechanical shock and vibration, cracking or melting of the ceramic due to uncontrolled regeneration, or a cracked substrate, resulting from high-thermal gradients during repeated regenerations.

Table 3.—CDPF-A and CDPF-B particulate collection efficiency

Time of operation, h	Mode	DPM concentration, mg/sm³		CDPF collection efficiency, pct
		Without CDPF	With CDPF	
		CDPF-A		
1,646	4	40.4	5.1	87.3
		CDPF-B		
839	1	21.1	3.0	85.5
	2	24.0	2.1	91.2
	3	137.7	17.7	87.1
	4	44.7	3.2	92.7
	5	34.5	1.9	94.5
	6	40.3	20.9	48.1
1,584	1	24.6	9.6	60.9
	2	23.1	9.0	60.8
	3	143.9	84.6	41.2
	4	42.6	9.9	76.8
	5	38.0	6.9	81.9
	6	63.2	31.4	50.3

CONCLUSIONS

The regeneration temperature of CDPF-B increased from 405° to 420° C after 839 and 1,584 h of operation, respectively. The regeneration temperature of CDPF-A was 405° C after 1,646 h of operation.

CDPF-A had little effect on CO emissions, but reduced HC emissions by 48.4 pct after 1,646 h of use. After 839 h, CDPF-B reduced CO emissions by 21.3 to 64.8 pct and HC emissions by 5.4 to 89.7 pct, depending on the engine mode. CDPF-B was still effective at lowering CO and HC emissions after 1,584 h. In most instances, the emissions reductions were within 20 pct of the reductions measured after 839 h.

CDPF-A remained effective at filtering DPM after 1,646 h, with a collection efficiency of 87.3 pct at mode 4. The CDPF was removed from service after 2,135 h, after it was damaged. The collection efficiency of CDPF-B decreased when measured after 1,584 h of operation, indicating damage to the substrate. However, its collection efficiency still ranged from 50.3 to 81.9 pct and the CDPF remains in service after 2,328 h.

Both CDPF's became plugged with DPM while being used. This could be caused by a change in duty cycle or engine condition that resulted in lower exhaust temperatures, or an increase in the regeneration temperature of the CDPF's.

The reaction of vehicle operators to the CDPF's was mixed. Some operators reported an unpleasant odor when the CDPF was new. The odor disappeared after 8 to 10 h of use. Another reported problem was that the smoke from the exhaust could no longer be used as an indicator of exhaust buildup in a work area. Excessive levels of pollutants could accumulate and the vehicle operator would not be aware of it.

CDPF's can lower DPM concentrations in exhaust. Depending on the type of catalyst used, the CDPF's can also reduce emissions of CO and HC. Their performance, however, may change with use. This change could be due to physical damage to the ceramic or to a change in the catalyst that affects performance.

RECOMMENDATIONS

CDPF's are for use only on vehicles with consistently heavy-duty cycles that produce exhaust temperatures adequate for regeneration. The ability of the catalyst to lower the temperature where regeneration occurs may degrade with time, hindering regeneration. This may result in DPM buildup in the CDPF, which can lead to damage to the ceramic, decreasing its collection efficiency. The following recommendations are made to help ensure proper CDPF operation. These recommendations are based on what has been learned and observed thus far during this ongoing study:

1. Use low-sulfur fuel. A fuel sulfur level of 0.05 wt pct or below is recommended, if available. This will limit the production of sulfate and lower the risk of catalyst poisoning by sulfur.
2. Perform vehicle screening. The exhaust temperature of each candidate vehicle should be measured over several duty cycles. A rule of thumb is that the CDPF temperature should exceed 400° C for at least 25 pct of its duty cycle. The duration of the periods the CDPF is above 400° C and the peak temperatures of the CDPF are also factors to be considered. The portion of the time that the CDPF must exceed 400° C to achieve proper regeneration may vary with the catalyst. The exhaust temperature should be measured where the CDPF will be installed. On a V-type engine, where two CDPF's are required, the temperature of each exhaust bank should be determined. If the vehicle's duty cycle changes, or if there is a change in engine condition, the exhaust temperature should be remeasured to ensure that the CDPF will regenerate adequately.
3. Minimize loss of exhaust heat and back pressure. The CDPF should be installed as close to the exhaust manifold as possible. Consideration should be given to insulating the exhaust line to the CDPF, especially if exhaust temperatures are marginal for regeneration. The number of pipe bends and length of exhaust pipe should be kept to a minimum to reduce back pressure.
4. Monitor back pressure. A back-pressure gauge should be installed in the operator's cab. When the back pressure becomes excessive (exceeding 30 kPa (40 in H_2O) for most engines), the CDPF should be regenerated by operating the vehicle at a high-load condition. If necessary, the DPM can be removed by blowing out with compressed air.
5. Periodically inspect the CDPF, gauges, and alarms. The inlet and outlet faces of the CDPF should be inspected periodically because DPM buildup on the inlet face can indicate a regeneration problem. Inspection can be done each time the vehicle is brought into the shop for preventive maintenance. Back-pressure gauges and alarms should also be checked at this time. If cracking or melting of the ceramic is observed on the inlet or outlet face, its collection efficiency has been diminished. While the CDPF may still be capable of filtering particulate, consideration should be given to replacing it.
6. Educate operators. Vehicle operators should be instructed on how a CDPF works, how to determine if it is becoming plugged, and what to do if it does become plugged.

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APPLICATION OF URBAN BUS DIESEL PARTICULATE CONTROL SYSTEMS TO MINING VEHICLES

By T. R. Taubert[1] and C. G. Cordova[2]

ABSTRACT

Since 1988, the U.S. Environmental Protection Agency (EPA) has progressively reduced the allowable levels of diesel particulate matter (DPM) that on-highway trucks and buses can produce. Engine manufacturers have met the regulations through improvements in engine design and the use of electronic controls. As allowable DPM levels continue to be reduced, transit authorities and engine manufacturers are evaluating various diesel exhaust filter systems as one alternative to meet the reduced emission levels. Two systems that show promise for improved DPM control are the ceramic wall-flow diesel particulate filter (DPF) bus system and the regenerable fiber coil (RFC) DPF (RFC-DPF) bus system. Both use an electric heater to regenerate, or clean, the filters. The U.S. Bureau of Mines is investigating the feasibility of these two systems for diesel-powered underground mining equipment.

INTRODUCTION

EPA has enacted regulations governing pollutants for on-highway diesel-powered trucks and buses (table 1). From 1988 to 1991, the standard for on-highway DPM was reduced from 0.6 to 0.25 g/bhp·h and the NO_x standard was reduced from 10.7 to 5.0 g/bhp·h, as measured by the Federal Test Procedure (*1*).[3] By 1993 (1994 for trucks), DPM emissions must be reduced an additional 60 pct.

EPA is also in the process of determining whether nonroad engines are significant contributors to air pollution (*2*). If so, the Clean Air Act Amendment mandates that they be regulated (*3*).

The U.S. Mine Safety and Health Administration (MSHA) has proposed regulations for underground mining engines. MSHA has published an advance notice of proposed rulemaking to establish a personal exposure limit for DPM in underground mines (*4*). It is uncertain if MSHA or EPA will have jurisdiction over mining engines. Nevertheless, future regulations are likely to be enacted and may force the adaption of on-highway emission control technologies to mining equipment.

Table 1.—EPA heavy-duty emission standards for trucks and buses, grams per brake horsepower hour

Year	HC	NO_x	CO	DPM
1988	1.3	10.7	15.5	0.6
1990	1.3	6.0	15.5	0.6
1991	1.3	5.0	15.5	0.25
1993[1]	1.3	5.0	15.5	0.10
1994	1.3	5.0	15.5	0.10
Do. ...	1.3	5.0	15.5	[2]0.05
1998	1.3	4.0	15.5	0.1

HC Hydrocarbon.
[1]Buses only.
[2]The standard for buses is 0.05 or a higher standard of 0.07 if 0.05 is not feasible.

To meet upcoming EPA regulations, engine manufacturers are refining their engine designs to improve combustion and produce fewer pollutants. It appears that

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[3]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

most on-highway, four-stroke diesel engines will not require exhaust filter systems to meet the 1994 on-highway truck emission standards. However, because most buses use two-stroke diesel engines (usually producing more pollutants than four-stroke diesel engines), it is unlikely they will meet the 1993 bus emission standards without using exhaust filter systems.

There are several diesel exhaust filter systems being evaluated worldwide to help urban buses meet future emission standards and to control pollutants from buses already in use. The U.S. Bureau of Mines has determined that the two most promising diesel exhaust filter systems for use on mining equipment are the Donaldson Company Inc.[4] (DCI) ceramic wall-flow DPF bus system and the DCI RFC-DPF bus system. These two filter systems operate automatically using microprocessor controls and vehicle-generated electricity to assist and control regeneration. The primary differences between the two systems are the type of filter medium used and the type and location of the electric heater element.

DIESEL PARTICULATE FILTER BUS SYSTEM

DESCRIPTION OF OPERATION

The filter medium used in the DPF bus system is the DPF. DPF's are made from a porous ceramic cordierite ($2MgO \cdot 2Al_2 \cdot O_3 \cdot 5SiO_2$) substrate similar to ceramic automotive catalytic converters. The cordierite is extruded to form porous channels running the length of the substrate with alternate, adjacent channels blocked off at opposite ends (fig. 1). Exhaust enters open channels at the front of the substrate and is forced through the porous ceramic walls where it is filtered. DPF's come in varying sizes, shapes, pore diameters, cell densities, and wall thicknesses, depending on the exhaust flow rate and filtration efficiency. Typical filtration efficiencies range from 60 to 90 pct (*5*).

During operation, the DPF accumulates DPM, resulting in an increase in engine back pressure. When the engine back pressure exceeds the manufacturer's maximum recommended level, the DPF must be cleaned. This cleaning process, termed regeneration, is accomplished by burning off the collected DPM. When there is sufficient DPM within the DPF and the exhaust temperature exceeds 550° C, the DPM ignites and burns, reducing engine back pressure. However, few diesel engines produce exhaust temperatures greater than 550° C, often enough for the DPF to fully regenerate and maintain acceptable back pressures. The regeneration temperature can be lowered by applying a catalyst to the DPF. Depending on the catalyst formulation, the regeneration temperature can be reduced to approximately 400° C (*6*). Still, few diesel engines operate with high enough exhaust temperatures to provide frequent and reliable regeneration. A discussion of the use of catalyzed DPF's that use self-regeneration for cleaning can be found in the paper "In-Service Performance of Catalyzed Ceramic Wall-Flow Diesel Particulate Filters" in this Information Circular.

The primary advantage of a DPF over other diesel exhaust filters is its large surface area in a relatively small volume. This allows higher DPM loading and lower engine back pressure. The primary disadvantage is the DPF's inability to withstand thermal stresses caused by

[4]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

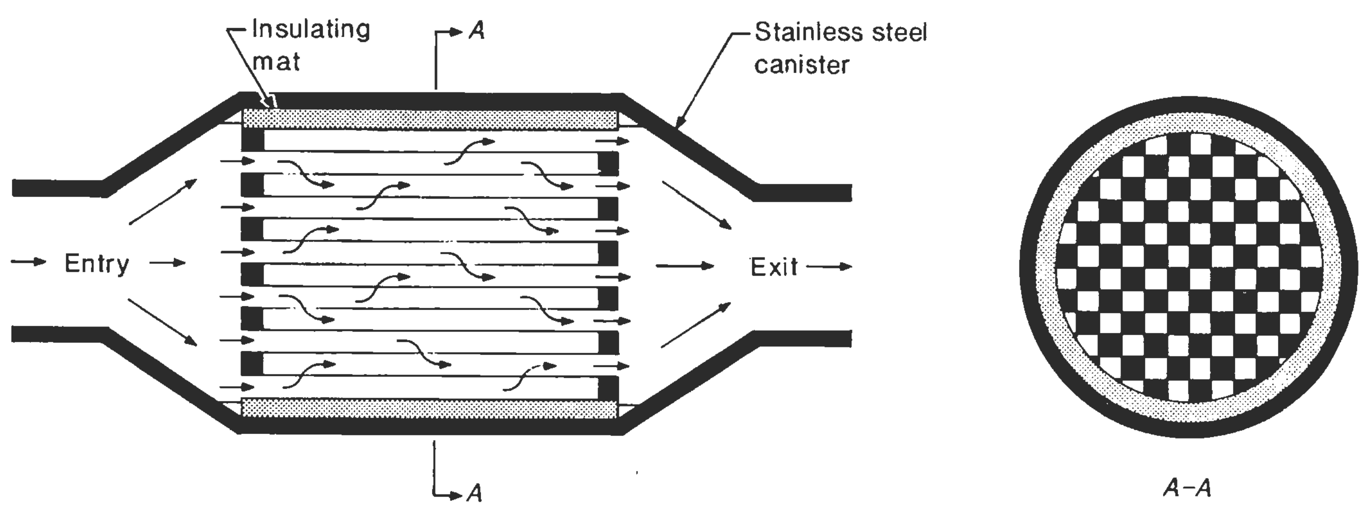

Figure 1.—Schematic of ceramic wall-flow DPF.

temperature gradients within the substrate. During regeneration, localized areas of extremely high temperature can occur, especially if the DPF is overloaded. These areas are prone to stress-induced cracking, which may lower filtration efficiency and decrease filter life. Systems that assist and control regeneration offer the potential to minimize stresses and increase filter life.

The Bureau is investigating DPF systems that use an assist for aiding regeneration. Several methods for assisting regeneration are reported in the literature, including electric heaters (*7-13*), diesel fuel burners (*14-17*), and fuel additives (*18-20*). Of the methods being investigated, electrical regeneration is the most practical, because of its simplicity, durability, and its ability to withstand fouling by DPM, and because it does not add potentially toxic compounds to the exhaust.

DCI has developed and is marketing a DPF bus system that uses an electric face heater to assist regeneration. The system is designed to function automatically (figs. 2-3). Two 26.7-cm-diameter (10.5 in) by 30.5-cm-long (12 in) DPF's are assembled in parallel. The DPF's may have a catalytic coating applied if carbon monoxide and hydrocarbon reductions are required.

Upon engine startup, pneumatic valves direct the exhaust to one DPF, while the other is on standby. The system microprocessor receives information on engine and DPF conditions, including engine intake airflow, DPF inlet temperature, and pressure drop across the DPF. These values are used to calculate a parameter called the K-factor, which is a measure of the amount of DPM collected in the DPF (*8*). When a predetermined K-factor is reached (corresponding to 4 to 6 g DPM per liter of substrate), the system is regenerated. The K-factor must be calculated precisely for efficient operation. If the DPF contains too much DPM when regenerated, excessive DPF temperatures may occur, causing damage. If there is insufficient DPM, the DPF will not regenerate completely, resulting in a need for more frequent regeneration.

Regeneration is conducted in a bypass mode, with the exhaust redirected to the DPF on standby. This minimizes the amount of energy lost to the exhaust gases and allows the necessary temperatures to be reached with a minimum fuel penalty. A 24-V dc electric face heater, producing 5.5 W/cm^2 of DPF frontal area, is energized and a blower is turned on. The blower cycles from low to high speed (through a 12- and 24-V hookup) to slowly increase the temperature of the DPF and provide air to control the rate of burning and aid the propagation of the flame front. Once the DPF face temperature reaches approximately 760° C, the blower is switched to high until the temperature at the front of the DPF drops approximately 65° C. The blower is then switched to low until the temperature again reaches 760° C, at which time the heater is de-energized and no longer needed to maintain the flame front for regeneration. Regeneration is controlled by the microprocessor and completed in 15 to 20 min.

In addition to controlling the DPF bus system, the microprocessor continuously monitors the status of the various components to detect operational faults (*11*). When a fault is detected, the system goes into a default mode and displays error codes so that maintenance personnel can quickly troubleshoot and repair the system.

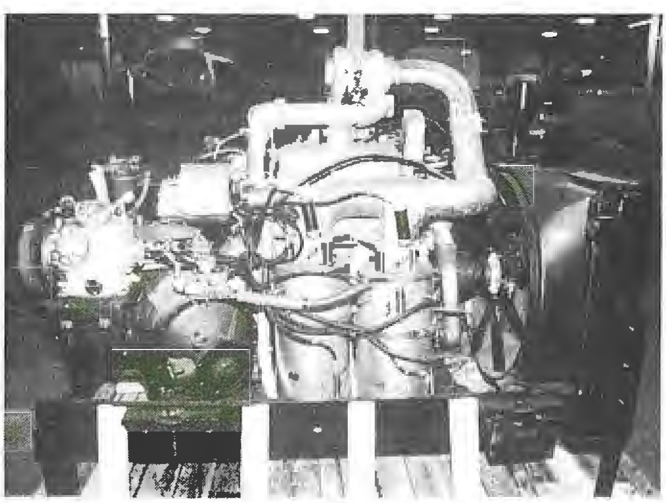

Figure 2.—DPF bus system on two-stroke diesel engine.

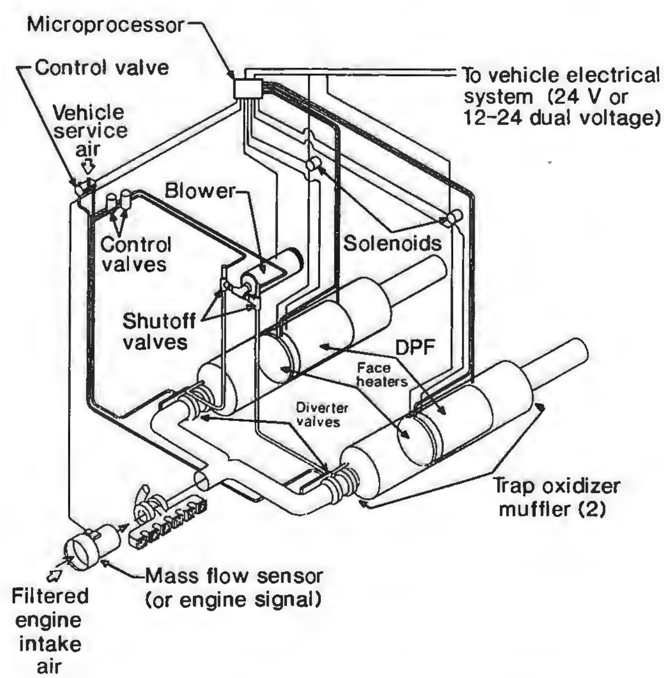

Figure 3.—Schematic of DPF bus system.

FIELD EXPERIENCE

There are several field evaluations of the DPF bus system being conducted in the United States, the most comprehensive by the New York City Transit Authority. The system is installed on 398 new buses equipped with 207-kW (277 hp) Detroit Diesel 6V-92TA two-stroke engines. The price of each system is approximately $9,000, but will probably be reduced if manufactured in volume.

Initially, there were minor hardware and software problems, including blower-bearing failure, blower tube cracking due to vehicle vibration, and failure of heater cables and protective boots. Most of these problems have been corrected through component redesign and software modifications.

To date, the DPF bus systems used by the New York City Transit Authority have accumulated 12 million miles of transit service. Typical time between regeneration is 4½ h with a fuel penalty of 2 to 3 pct. Because of the success of the program, 1,998 existing buses will be retrofitted with DPF systems over the next 3 years (*21*).

REGENERABLE FIBER COIL DIESEL PARTICULATE FILTER BUS SYSTEM

DESCRIPTION OF OPERATION

The filter medium used in the RFC-DPF bus system is a high-temperature 3M Corp. Nextel 312 or 440 ceramic fiber. Individual RFC cartridges are built by winding these fibers around a perforated metal support tube that has one end blocked (fig. 4). Exhaust is forced radially through the RFC cartridge wall where it is filtered. Winding geometries, fiber and wall thicknesses, and the number of RFC cartridges can be varied to achieve the desired filtration efficiency and filter loading. An electric heater is incorporated within each RFC cartridge to assist regeneration. Filter systems can be adapted to a wide range of engine displacements by varying the number of cartridges used.

The RFC-DPF has several innovative features. Individual cartridges can be removed and replaced if failure occurs. Because the cartridges contain their own heating element, they can be used on a variety of vehicles. Electric power for regeneration is supplied from vehicle-generated power. Also, cartridges are made from a wound fiber, which allows the cartridges to flex and, therefore, be less susceptible to breakage from thermal cycling and vibration.

In 1987, Hardenberg evaluated the use of RFC-DPF bus systems in Germany (*22-23*). He found that while the cartridges were durable, they had a low capacity for DPM and noncombustible material and, therefore, required frequent regeneration.

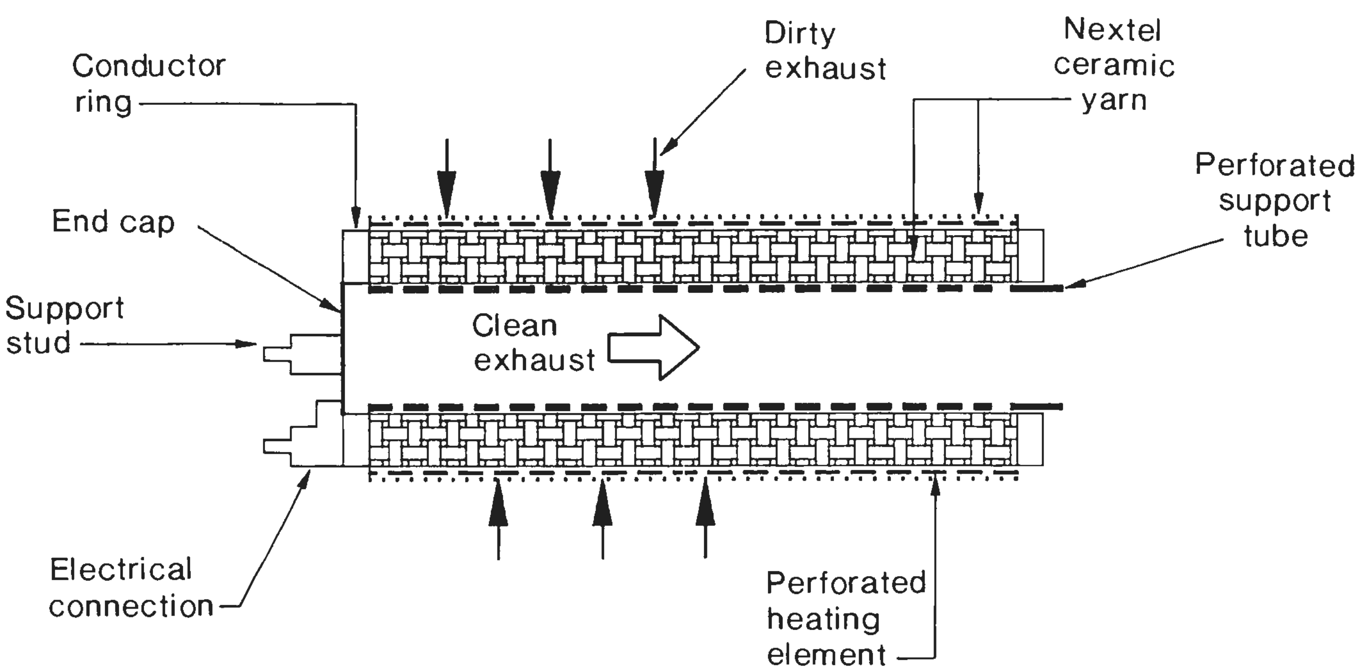

Figure 4.—Cross-sectional view of outside-to-inside flow RFC cartridge.

Recently, DCI and 3M Corp. began redeveloping and marketing RFC cartridges. New RFC cartridge designs emphasizing DPM depth loading have increased DPM capacity and reduced the power required for regeneration (*24*). Still, the RFC-DPF capacity for DPM is lower than DPF's. However, their use, in combination with cleaner burning engines and the potential for greater durability, makes the RFC technology more attractive.

EVALUATION OF REGENERABLE FIBER COIL DIESEL PARTICULATE FILTER BUS SYSTEM

The Bureau, in cooperation with DCI, retrofitted a 1.9-m^3 (2.5 yd^3), 132-kW (177 hp) front-end loader with a RFC-DPF bus system. The system, supplied by DCI, integrates 3M Corp. RFC cartridges with a DCI microprocessor-controlled regeneration system. There are several filter housing variations for RFC-DPF bus systems, depending on the cartridge used. The system being evaluated by the Bureau uses twelve 50-cm-long (20 in) by 6.4-cm-diameter (2.5 in) outside-to-inside flow cartridges. The cartridges are housed in two 30.5-cm-diameter (12 in) by 91.4-cm-long (36 in) aluminized steel canisters, each divided in the middle to form two chambers. Each chamber contains three cartridges and a pressure port. The cartridges are connected electrically by four-gauge cables to high-current relays (fig. 5). The relays are connected to a power distribution bar that is fed from a high-output alternator (24 V, 220 A) and battery system. Each of the four chambers is connected to a pressure transducer, which, along with the relays, is wired to a microprocessor that monitors and controls the system. The complete installation is shown in figure 6.

Like the face-heated DPF bus system, the RFC-DPF bus system is designed to operate automatically. Upon engine startup, the microprocessor closes the inlet exhaust valve to chamber 1, putting the chamber on standby. The three remaining chambers are used for filtration. When the microprocessor determines that a chamber has reached the engine's recommended back pressure limit, regeneration begins. The inlet exhaust valve of the regenerating chamber is closed and the inlet exhaust valve of the

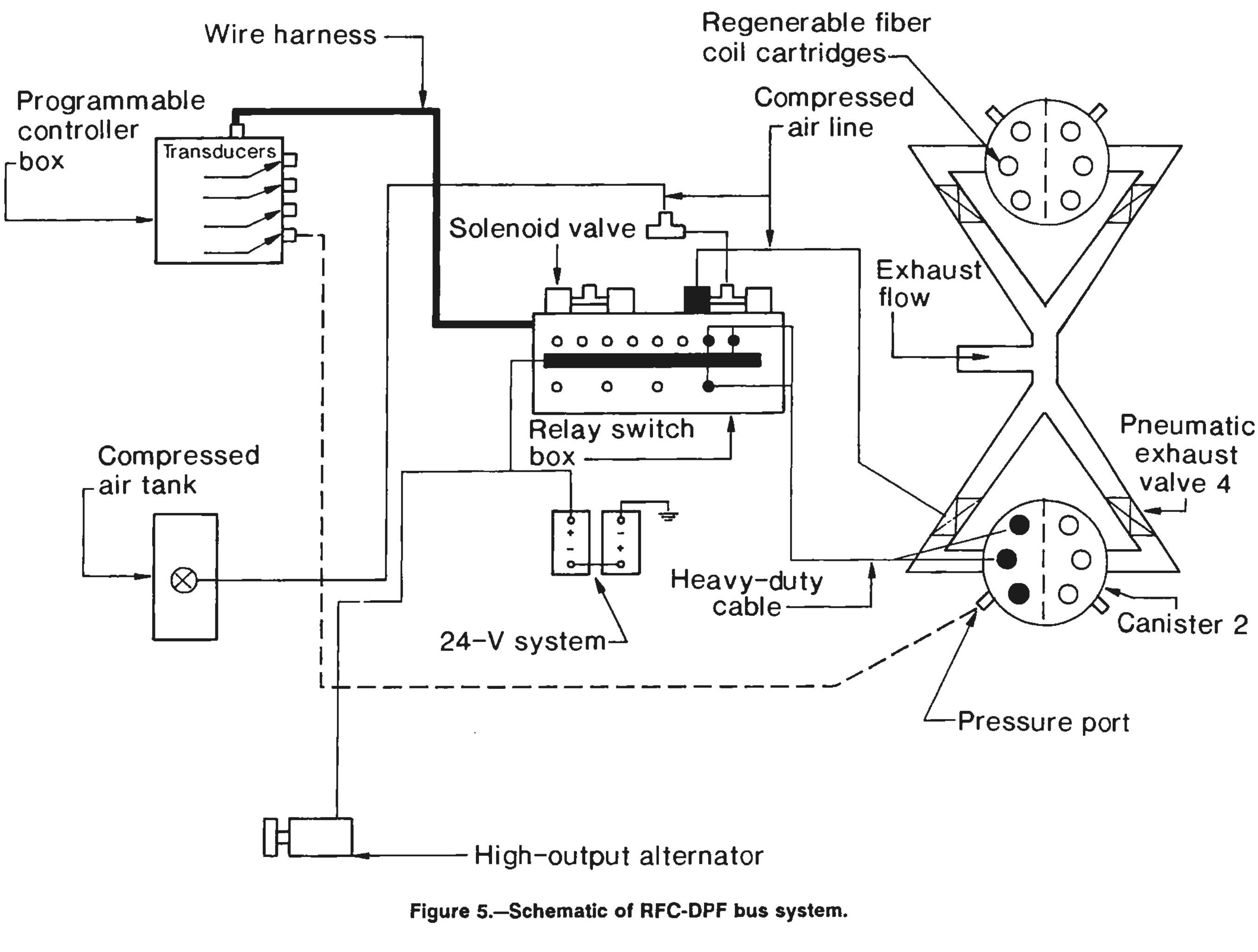

Figure 5.—Schematic of RFC-DPF bus system.

Figure 6.—RFC-DPF bus system on front-end loader.

chamber on standby is opened. The microprocessor then signals the relay of the first cartridge in the chamber, completing the electrical circuit and beginning regeneration. During regeneration, the cartridge heater receives approximately 130 A at 24 V (3.1 kW) for 330 s, sufficient energy to burn off the collected DPM. The process is repeated for the remaining two cartridges in the chamber. On completion, the regenerated chamber remains on standby until another chamber needs regeneration.

A month-long evaluation of the RFC-DPF bus system on a Bureau loader was performed at a granite quarry. During the evaluation, the vehicle accumulated 113 engine hours without failure. Regeneration occurred approximately 45 times, or once every 2½ engine hours, with an estimated DPM collection efficiency of 65 to 75 pct. After the field evaluation, the loader was returned to the Bureau and has since accumulated an additional 100 h of trouble-free operation.

SUMMARY

The U.S. Bureau of Mines is investigating automated diesel exhaust filter systems that use regeneration assist for diesel-powered underground mining equipment. Assisted regeneration expands the application of diesel exhaust filters to vehicles that do not have sufficient exhaust temperatures to promote self-regeneration. Two promising systems are the DPF bus system and the RFC-DPF bus system.

DPF's have high-DPM capacity and high-filtration efficiency. Their primary disadvantages are the inability to withstand thermal stresses during regeneration and the need for high-exhaust temperatures to regenerate. The

DPF bus system measures and controls DPM loading levels in the DPF and assists regeneration to minimize thermal stress, extending DPF life.

RFC cartridges appear to offer improved durability over DPF's, but have lower DPM capacity, resulting in more frequent regeneration. Further development of RFC cartridges is expected to provide better depth loading for higher DPM capacity and to reduce the energy needed for regeneration.

The DPF bus system and the RFC-DPF bus system use different filtration material and exhibit different performance characteristics. The favorable results from the field evaluations suggest that long-term underground evaluations are warranted.

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APPENDIX

In the appendix, the first paper describes the capabilities of the diesel engine research facility located at the Bureau, Twin City Reseach Center. This facility is a state-of-the-art engine laboratory capable of performing emission testing, exhaust control evaluations, and safety tests. The next three papers[1] are previously published reports that describe the effects of engine maintenance on emissions and performance and the use of carbon dioxide as a surrogate measure of pollutants. Although the Bureau has not performed research on these topics since 1987, the papers are included because the information they contain is still pertinent. A glossary and a list of abbreviations and acronyms are also included.

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U.S. BUREAU OF MINES DIESEL EMISSION RESEARCH LABORATORY

By C. F. Anderson,[1] J. D. Gage,[2] M. J. Vogel,[3] and N. D. Lange[4]

ABSTRACT

The U.S. Bureau of Mines diesel emission research laboratory (DERL) is used to investigate the effectiveness of diesel emission controls used in underground mines. This paper describes the capabilities and operation of this laboratory, providing a better understanding of research results reported in this Information Circular.

This laboratory provides the necessary facilities to conduct research programs leading to improvements in mining health and safety. A computer-operated system controls a diesel engine, dynamometer, and associated laboratory equipment. Steady-state and transient test methods are used for research evaluations. Specific duty cycles are used for laboratory operation and to simulate in-mine operating conditions for evaluation of emission control units. Engine intake and exhaust pressures can be controlled to simulate operation at various altitudes. Transducers, actuators, and closed-loop controllers provide consistent control and accurate measurements. Exhaust gases and particulate matter are sampled and analyzed using standardized procedures.

INTRODUCTION

The DERL is located at the U.S. Bureau of Mines Twin Cities Research Center in Minneapolis, MN. It is a state-of-the-art engine test cell facility, which is continuously improved with instrumentation upgrades to ensure the best technology for research activities. Research includes emission testing, exhaust control evaluation, and safety testing as a part of the Bureau's program to improve mining health and safety. Figure 1 shows the major elements of the laboratory and their interrelationships. Each element is described below to provide an overview of its function and described in more detail in subsequent sections of this paper. The objective of this paper is to furnish sufficient background about the DERL so that the research results reported in this Information Circular can be better understood.

Flexible computer control and data acquisition are provided by a Digalog Cellmate II[5] computer, referred to in figure 1 as the test cell controller. This computer provides central control over engine test conditions, monitors safety parameters, and acts as a file server to record and process data. A closed-loop system feeds data to and from the test cell controller. The real-time data-acquisition system collects information, such as engine temperature, fuel rate, exhaust pressure, and exhaust gas concentration occurring during the test.

Various computer-controlled engine test conditions (most commonly steady state, transient, and ramp) are used to evaluate emission control units. Steady-state tests consist of fixed speed and torque (load) stages used for the evaluation of emissions at fixed operating conditions. Tests consisting of continuously changing engine speed and load represent transient operation. Ramp tests, used to

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[2]Electronics technician.
[3]Physical science technician.
[4]Student trainee (electrical engineer).
U.S. Bureau of Mines, Twin Cities Research Center, Minneapolis, MN.

[5]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

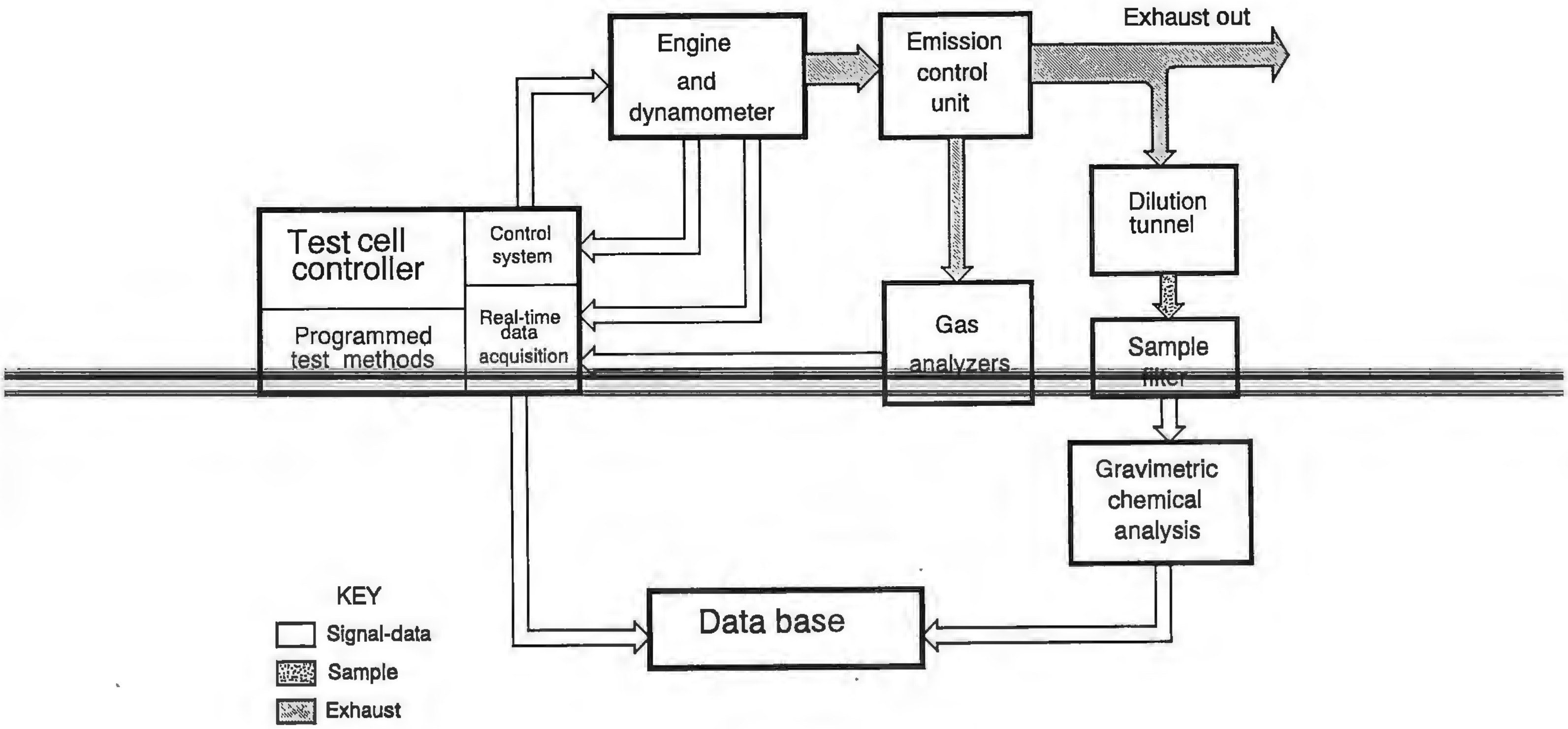


Figure 1.—Major elements of DERL.

determine the efficiency of emission control units as a function of temperature, involve increasing the engine load slowly over a period of hours while the engine speed remains fixed. Since exhaust temperature is closely related to load, a ramp test provides a specific temperature profile for device evaluation. Examples of temperature profile tests are used by McClure (*1*).[6]

The engine test cell accommodates engines with ratings up to 370 kW (500 hp). The engine is coupled to an eddy current dynamometer, which controls the load on the engine by absorbing power. Exhaust gas passes through the emission control unit, and parameters are measured both upstream and downstream of the unit to determine changes in the exhaust composition. Data are recorded by the test cell controller.

An exhaust sample is mixed with filtered air in the partial-flow dilution tunnel, the rate being approximately 3% of the total exhaust flow. Diesel particulate matter (DPM) is collected when the diluted exhaust is passed through a sample filter. The mass of the DPM is determined by gravimetric analysis, and the total volatile component is determined by a vacuum sublimation method. Additional methods are used to determine the sulfate, volatile organic, soluble, and soluble organic fractions.

A gas-handling and analyzing system is used to evaluate exhaust gases. Beckman instruments are used to measure hydrocarbon (HC), oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitric oxide (NO), and total nitrogen oxides (NO_x). A Fourier transform infrared (FT-IR) spectroscopic analyzer is used to evaluate a broad range of gases that are present in the exhaust. This FT-IR technique provides a tool for better understanding the chemistry of exhaust gas.

All experimental data are stored by the test cell controller, merged with the gravimetric and chemical analysis data from other sources, and then recorded in a data base. The information from the data base is networked to other computers for analysis and evaluation.

LABORATORY EQUIPMENT

Equipment used in the DERL is specifically designed and selected, providing the experimental facilities necessary for diesel emission research investigations. A computer-based test cell controller integrates test methods with process controllers, actuators, transducers, and data acquisition, providing a systems approach to experimental testing. The laboratory test cell portion, consisting of an

[6]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

engine-dynamometer unit, pressure control equipment, dilution tunnel, and sampling systems, is used to create, observe, and measure experimental processes. Operation, integration, and capability of this equipment is presented in the following sections.

TEST CELL

The test cell portion of the DERL is designed for adaptability and versatility while conducting a variety of experiments involving engine emission control units. Seven major elements of the test cell are represented schematically in figure 2. An engine, coupled to a dynamometer (*B*), generates exhaust emissions, which are routed to an emission control unit (*C*). Manifold pressures are managed by the intake (*A*) and exhaust (*F*) systems. Exhaust gas (*D*) is sampled close to the emission control unit. A portion of the exhaust is mixed with air in a dilution tunnel (*E*) and DPM is collected in the sampling system (*G*). Each of these elements are discussed below in further detail.

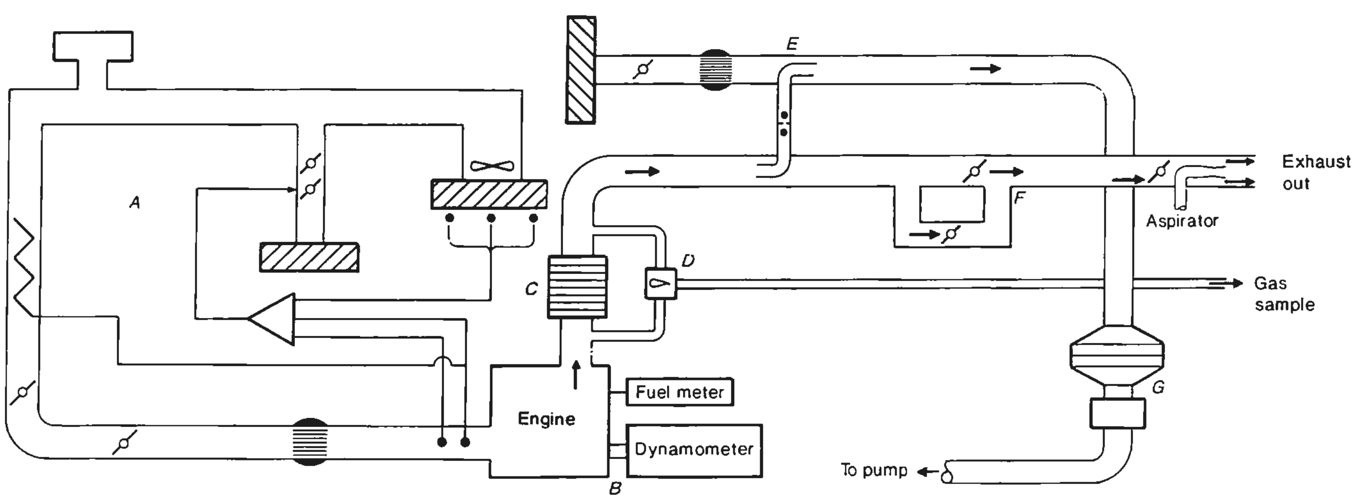
Engine and Dynamometer

Engine and dynamometer are coupled with a rubber-element drive shaft and are rigidly attached to an inertia bed-plate centered in a soundproofed engine room (fig. 3). Engine torque is developed against the retarding forces of an eddy current dynamometer and measured with a reaction arm load cell. Dynamometer absorption capacity will control engine operation up to 370 kW (500 hp).

An eddy current dynamometer with a process controller regulates engine torque. If desired, the engine speed can be controlled by dynamometer loading. Likewise, a fuel-rack controller and actuator are used to position the fuel mechanism, permitting either speed or load regulation. Speed or load control can be selected from parameters such as torque, speed, dynamometer current, throttle position, or others, for example, fuel rate or exhaust pressure.

Transient response time is a function of engine, dynamometer, and controller reaction when these parameters are operated as a unit. With the present engine and dynamometer configuration, speed and torque step changes of 3 s or less are achieved. Tuning the controllers for a fast dynamic action provides a rapid transient response.

Fuel, stored in two 2.1 m³ (550 gal) underground tanks, is pumped to a 0.1 m³ (35 gal) tank in the engine room for temperature stabilization and daily use. A Flowtron mass flowmeter continuously measures the fuel consumption and accurately responds to the transient demands.



KEY
A Intake manifold pressure system
B Engine and dynamometer
C Emission control unit
D Gas sample
E Dilution tunnel
F Exhaust manifold pressure system
G Particulate and vapor-phase HC samplers
⟶ Flow direction

Figure 2.—Schematic of diesel emission test cell.

Intake Manifold Pressure

Stable and repeatable engine-intake manifold pressure is required to produce reliable experimental results. O_2 concentration and fuel-air ratio are dependent on the intake manifold pressure. Figure 4 is a schematic diagram showing a reversible vortex blower (*A*) capable of modifying pressure by 25 kPa (1/4 atm), either positive or negative. Pressures, temperatures, and relative humidity (*G*) are monitored to calculate the necessary corrections for standard conditions or altitude simulation. The feedback control (*H*) uses a corrected pressure value to position a valve (*B*) that maintains the proper pressure at the engine intake manifold. A plenum (*C*) buffers rapid pressure changes during transient operation. The water-cooled heat exchanger (*D*) regulates air temperature within an acceptable range. To accommodate different engine sizes, manual butterfly valves (*E*) bias the flow for better pressure control. A laminar flow element (*F*) measures the engine intake airflow. Selected manifold pressure is maintained, providing consistency for all engine speeds, at a rate consistent with engine transient operation.

Exhaust Manifold Pressure

As shown in figure 5, the exhaust manifold pressure (*A*) is regulated by two butterfly valves in parallel (*C*). For normal operation, valve adjustments simulate muffler back pressure and maintain a fixed differential pressure at the sample port (*B*). Closing the butterfly valves will increase the exhaust pressure as needed. By using the aspirator (*D*) to decrease the exhaust pressure, operation at altitudes as high as 3.7 km (12,000 ft) can be simulated.

Emission-Control Unit

Many types of emission control units are evaluated in this laboratory and are reported in other parts of this Information Circular. Generally, the unit to be tested is located close to the exhaust manifold, with transducers and controls interfaced with the test cell controller. Test cell space is adequate for testing small catalytic converters, large wall-flow particulate filters, and huge water scrubbers that are used on mining equipment. Smaller units are about 25 cm in both diameter and length, whereas

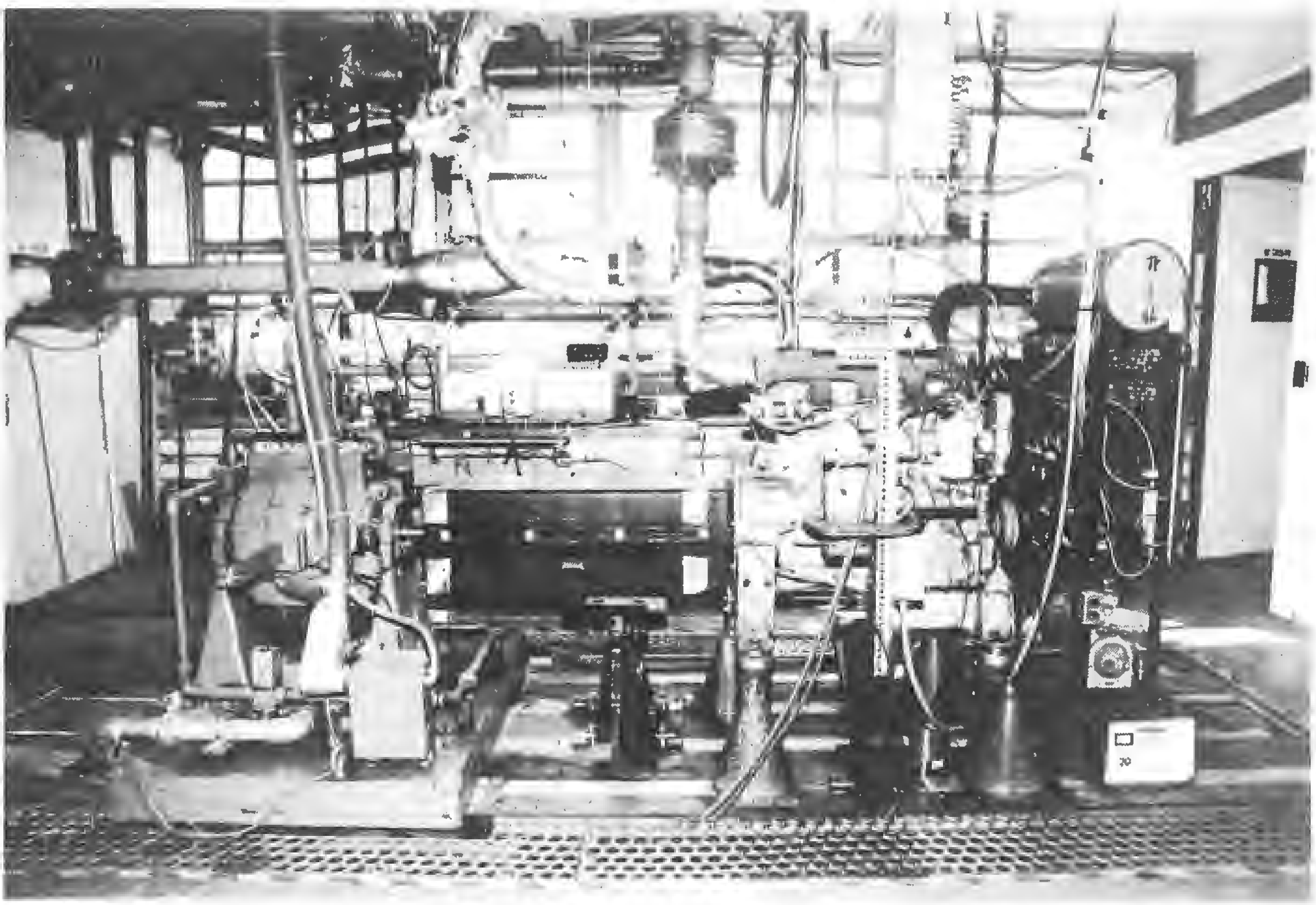
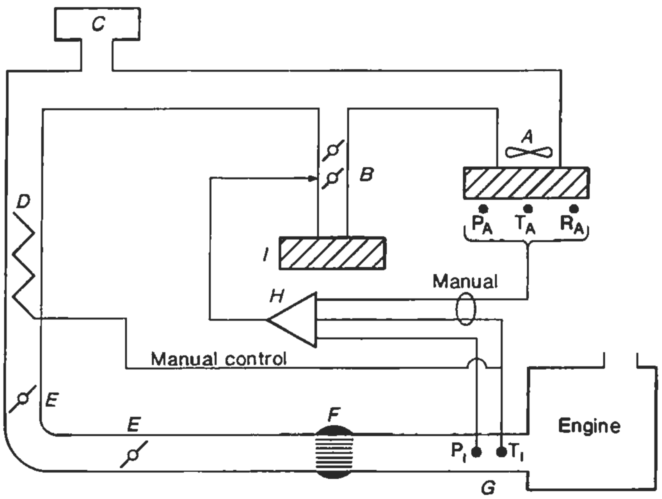


Figure 3.—Engine room of DERL.

the scrubbers are approximately 1 m in each dimension: length, width, and height. The laboratory is versatile enough to accommodate most innovative emission control units.



KEY

A Reversible vortex blower	*H* Feedback control
B Electric driven butterfly valve	*I* Intake air filter
C Plenum	P_A Air pressure
D Water-cooled heat exchanger	T_A Air temperature
E Manual butterfly valve	R_A Air relative humidity
F Laminar flow element	P_I Intake pressure
G Intake condition sensors	T_I Intake temperature

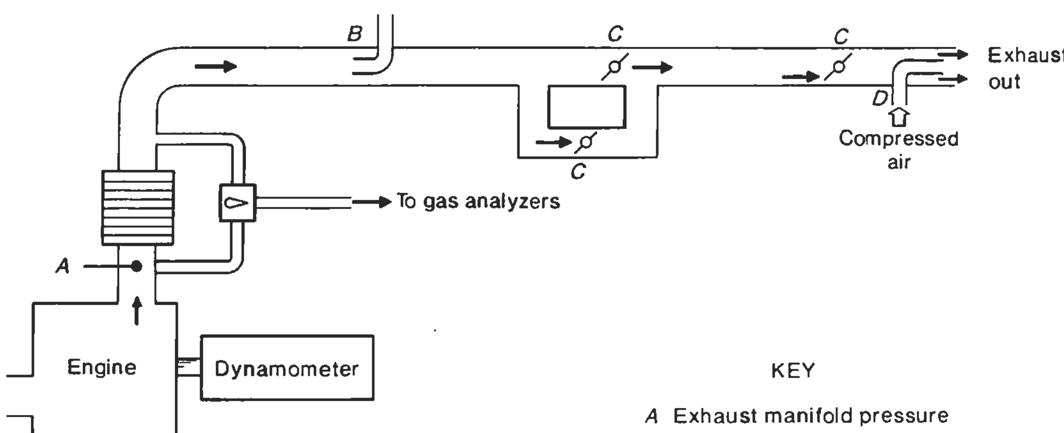
Figure 4.—Schematic of diesel engine intake manifold pressure system.

Gas-Sampling System

The gas-sampling system (fig. 6) transports and conditions the diesel exhaust sample for gas analysis. As depicted, raw exhaust enters the system at the emission control unit and flows out the system at the analyzers. The analyzers, designated as SO_2, NO_x, NO, CO, CO_2, O_2, and HC, then make specific gas measurements.

As shown in figure 6, the diesel exhaust gas is transported via a sampling pump (*D*) through heated lines (*A*), switching valve (*B*), and enclosure (*E*). A high-temperature, stainless steel, positive-displacement-type sampling pump maintains a constant sample flow of approximately 0.4×10^{-3} m^3/s (48 std ft^3/h). The heated lines are constructed of either stainless steel or Teflon fluorocarbon polymer cores that are wound with electrically energized thermal elements and wrapped with insulation. The enclosures, which are electrically heated insulated boxes, and the heated lines are maintained at 200° C using closed-loop control systems. Selection of either the upstream or downstream side of the emission control unit is done by switching the heated valve, which allows symmetrical sample flow through either the inlet or outlet section. After the sample is selected, it must be conditioned for analysis.

The sample exhaust is conditioned through filtration and dehydration as necessary to provide accurate gas analysis. The primary filter (*C*) (fig. 6) is a tubular-glass-microfiber type that removes all suspended solid particles 2 μm and larger. The secondary filters (*H*) (fig. 6), which are sintered stainless steel elements, also provide 2-μm filtration protection for the analyzers. In addition, the HC



KEY

A Exhaust manifold pressure
B Sample port
C Manual butterfly valve
D Aspirator
→ Exhaust flow

Figure 5.—Schematic of diesel engine exhaust manifold pressure system.

analyzer has two internal filters; one is a glass-microfiber-disk type and the other is sintered metal. A refrigerated dryer (*G*) (fig. 6) removes moisture, providing a relatively dry exhaust sample to the CO, CO_2, and O_2 analyzers. A hygroscopic (moisture absorbing), multitube, counterflow-type dryer (*F*) (fig. 6) removes moisture upstream of the SO_2 analyzer.

Dilution Tunnel

DPM is sampled using a partial-flow dilution tunnel system (fig. 7). A positive displacement pump (*I*) draws dilution air from the DERL through an activated carbon bed and a high-efficiency particulate air (HEPA) filter (*A*). Air in the laboratory is at a relatively constant temperature (17° to 25° C), with air conditioners providing additional cooling as needed. Activated carbon removes trace gases such as NO_x, and the HEPA filter is effective in removing 99.9% of the particulate in the airstream. This filtering ensures that background particulate levels are low, precluding any significant contribution to gravimetric measurements of filtered samples. A partial vacuum is formed in the dilution tunnel, and dampers in the exhaust stream maintain a higher (2 kPa) positive exhaust gas pressure.

Exhaust enters the tunnel through an orifice (*D*) (fig. 7), the flow being a function of orifice diameter, exhaust temperature, and pressure difference between the exhaust pipe and tunnel. An air jet valve (*E*) (fig. 7) controls exhaust transfer to the dilution tunnel. Dry filtered air is directed past the orifice and blocks the exhaust sample flow. To collect DPM on the filter media, this airstream is interrupted by solenoid valve action, permitting exhaust flow to the dilution tunnel.

Equipment is currently sized such that the ratio of filtered air to exhaust gas can be selected within the range of 40:1 and 10:1. The dilution ratio is calculated by measuring flows, temperature, and pressure. This ratio is modified as necessary by changing dilution tunnel, exhaust

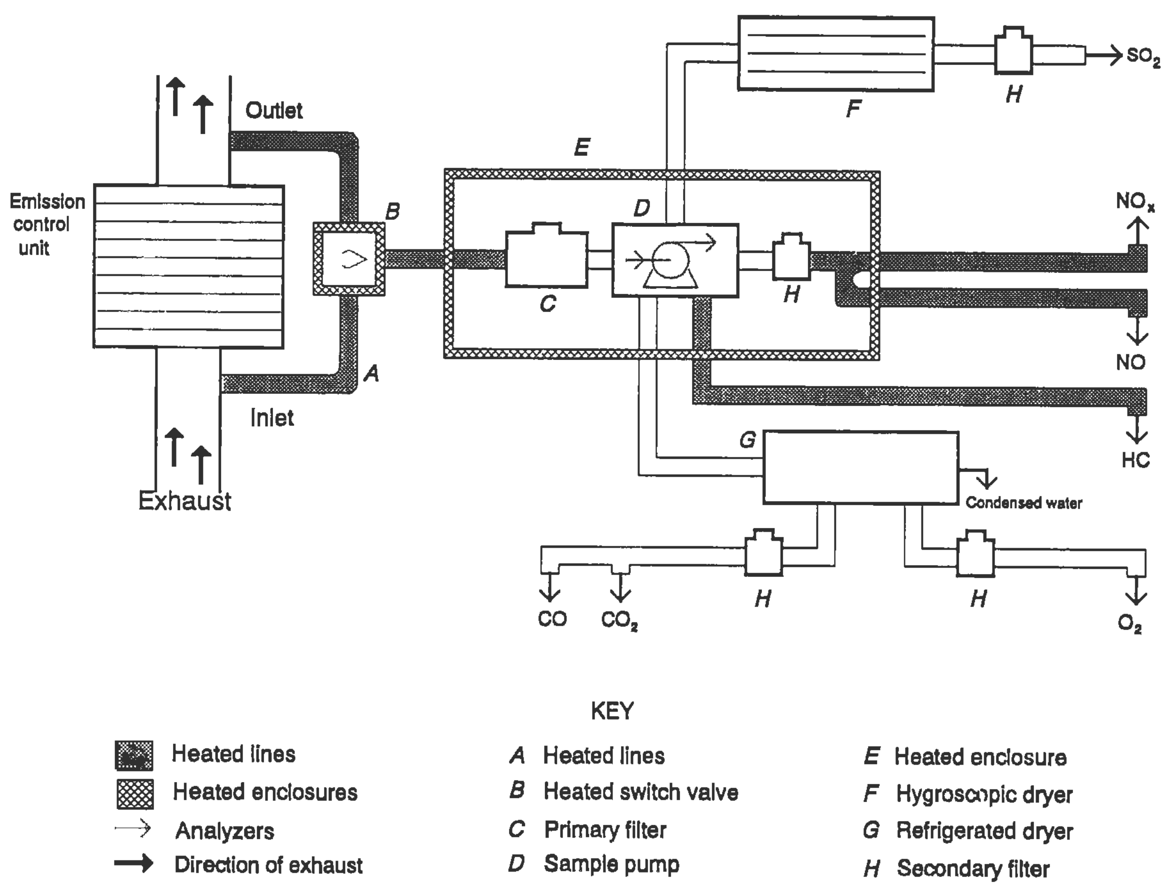


Figure 6.—Exhaust gas-sampling system.

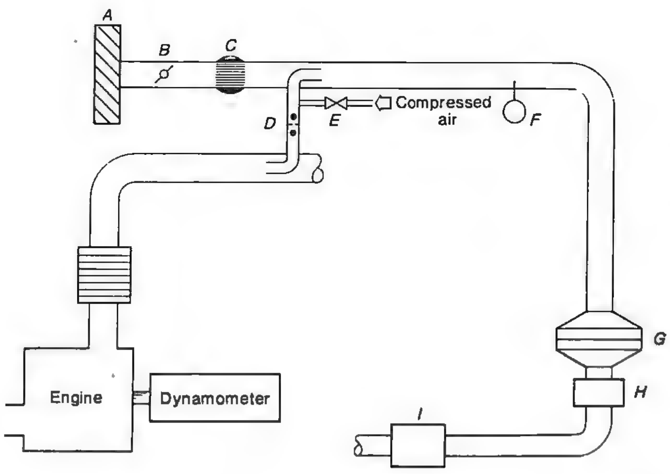


Figure 7.—Schematic of partial-flow dilution tunnel with samplers.

stream, or orifice parameters. DPM concentration or mass production can thus be related to the engine performance or emission control unit efficiency.

Dilution tunnel flow and pressure are determined by using a laminar flow element (*C*) and a pressure transducer (*F*) and controlled by changing pump speed and valve (*B*) settings, both manually adjustable (see fig. 7). Adjusting exhaust pressure or selecting a different size orifice plate will change exhaust sample flow. This flexibility permits adjustment of the dilution ratio and cooling of the exhaust for collecting DPM on a Teflon fluorocarbon polymer-coated glass-fiber-sample filter (*G*) (fig. 7).

Diesel Particulate Matter and Vapor-Phase Sampling System

Figure 8 shows the DPM sampler with a partially inserted sample filter and a vapor-phase sampler. The DPM sampler accommodates a Pallflex fiber filter with a surface area of 0.26 m^2 (20 by 20 in). The vapor-phase sampler containing XAD-2 resin is installed downstream from the DPM sampler. Diluted exhaust passes through these samplers (*G, H*) (fig. 7). Dilution tunnel flow is controlled to compensate for the increasing pressure drop as the sample filter is loaded.

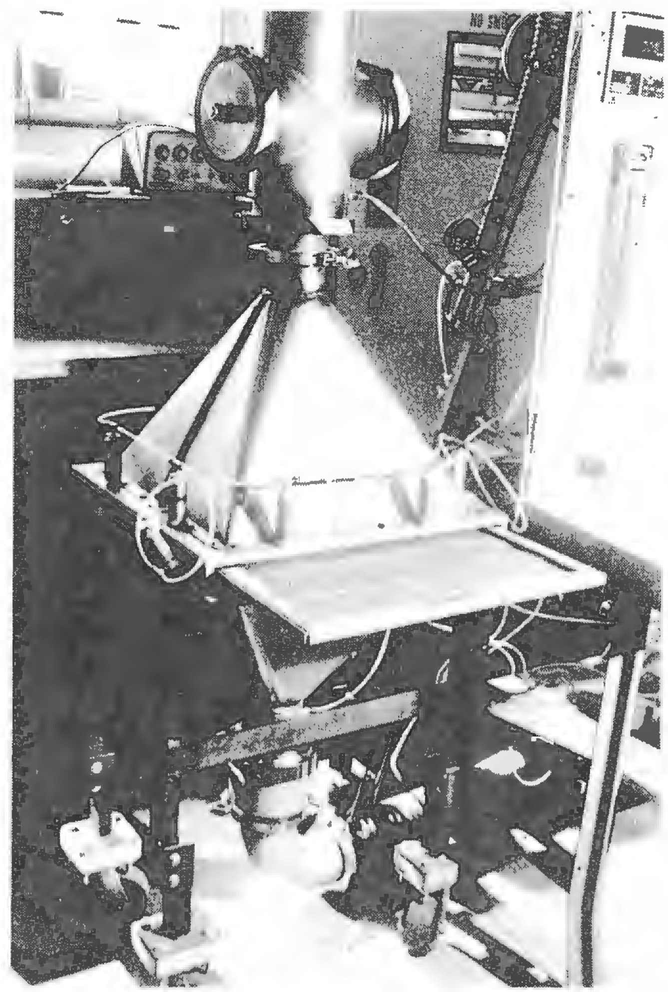


Figure 8.—DPM and vapor-phase samplers. (Filter holder partially exposed.)

TEST CELL CONTROLLER

A Digalog Cellmate II test cell controller provides computer control, real-time data acquisition, and programmed test methods for operation of the laboratory equipment. Computer hardware interfaces to laboratory equipment for measurement and control, while software routines provide programmed tests and convert transducer signals to engineering values.

Control System

The Cellmate II computer has a capacity of 192 analog channels, 96 of which are connected to the test cell sensors and transducers. It also has 32 channels for analog output, some of which are used for controlling the dynamometer and fuel rack. The digital input-output capacity is 64 channels, which are used to monitor limit-control switches and to activate solenoids or other processes that require an on-off action. Each channel is assigned a specified parameter for control, data collection, or display. Three types of data can be displayed, updated, and recorded during the test: (1) measured variables that correspond to input-output channels, (2) system variables such as dates, time of day, operating time, and elapsed time, and (3) calculated variables. Calculated variables are defined as real-time calculations of measured and system variables. An example is engine power, calculated from the measured variables of speed and torque. Displays of all these variables are updated every second. The test cell controller has a software package based on the Forth programming language (*2*) and a subroutine library called Toolbox, consisting of predefined Forth words. Toolbox provides the command language for creating new words and procedures written to control the engine during tests. Forth is a flexible computer language, suitable for instrument control and developing tests for engine operation.

Real-Time Data Acquisition

Data acquisition is the collection and storage of physical or engineering values recorded by the test cell controller. For any experimental trial, information and values are logged to a data base. The ability to record all measurements of interest at a logging rate of 10 times per second is available, although slower rates are usually selected. This data base can be accessed while a test is running. The data base is also networked to an IBM personal computer system and linked to other computers.

Programmed Test Methods

The computer-based test cell controller provides consistent, reproducible, preprogrammed speed and load profiles for experimental tests. Several steady-state tests are available, such as the power rating standard SAE J1349 (*3*), the emission measurement procedure SAE J1003 (*4*), and others representing multistage engine operation specific to research needs. Control programs are available for both transient and ramp tests.

Steady-state tests are conducted by operating the engine at fixed speed and torque stages for periods usually exceeding 5 min, including stabilization and sampling periods. The length of time for a steady-state stage is determined by test or sampling requirements. These tests are used to provide consistent samples for evaluating the performance of an emission control unit.

A transient schedule consists of continuously changing speed and torque conditions with short dwell times. Changes occur at 1 s intervals with dwell times not exceeding 30 s.

Generally, transient schedules are limited to a few minutes. If additional time is needed for sufficient samples or information, these schedules are repeated in a cyclic fashion.

Past investigations have used two transient schedules consisting of 13 stages of limited step changes, 3 s or less each, with one having a stage, or dwell time, of 10 s and the other 30 s. One schedule is shown in figure 9. This laboratory transient schedule attempts to represent the operation of a load-haul-dump vehicle. Variations of these transient programs can be applied to represent full or part load conditions.

Ramp-type schedules change torque at a constant rate over a period of hours. Exhaust temperature is closely related to torque; therefore, a ramp test is useful for indicating effectiveness of control units dependent on temperature, torque, soot accumulation, or fuel-to-air ratio.[7]

All of these schedules, profiles, and programs are recorded, stored, and operated using the test cell controller. This provides consistent, reproducible, and reliable engine operating conditions and ease in modifying or developing schedules.

PROCESS CONTROLLERS

For successful investigations, it is necessary to have stable control of engine speed and torque conditions. This is achieved by using closed-loop process controllers that provide proportional, integral, and derivative action. Process controllers use three measured values: (1) set point, a desired operating condition such as speed; (2) feedback, the actual value of the process being controlled; and (3) control, a signal to activate a control variable. Sensing the difference between feedback and set-point values, the controller provides an output action. This action (for example, positioning the fuel-rack lever to adjust speed) maintains the desired operational control. For diesel engine operation, two controllers are used: one for torque

[7]McClure, B. T., and A. M. Blucher. Laboratory Comparison of Engelhard TX-7DVC (ULTRA) and PTX-10DVC (ULTRA) Oxidation Catalytic Converter Performance. TCRC Internal Rep., Minneapolis, MN, Aug. 17, 1990, p. 9.

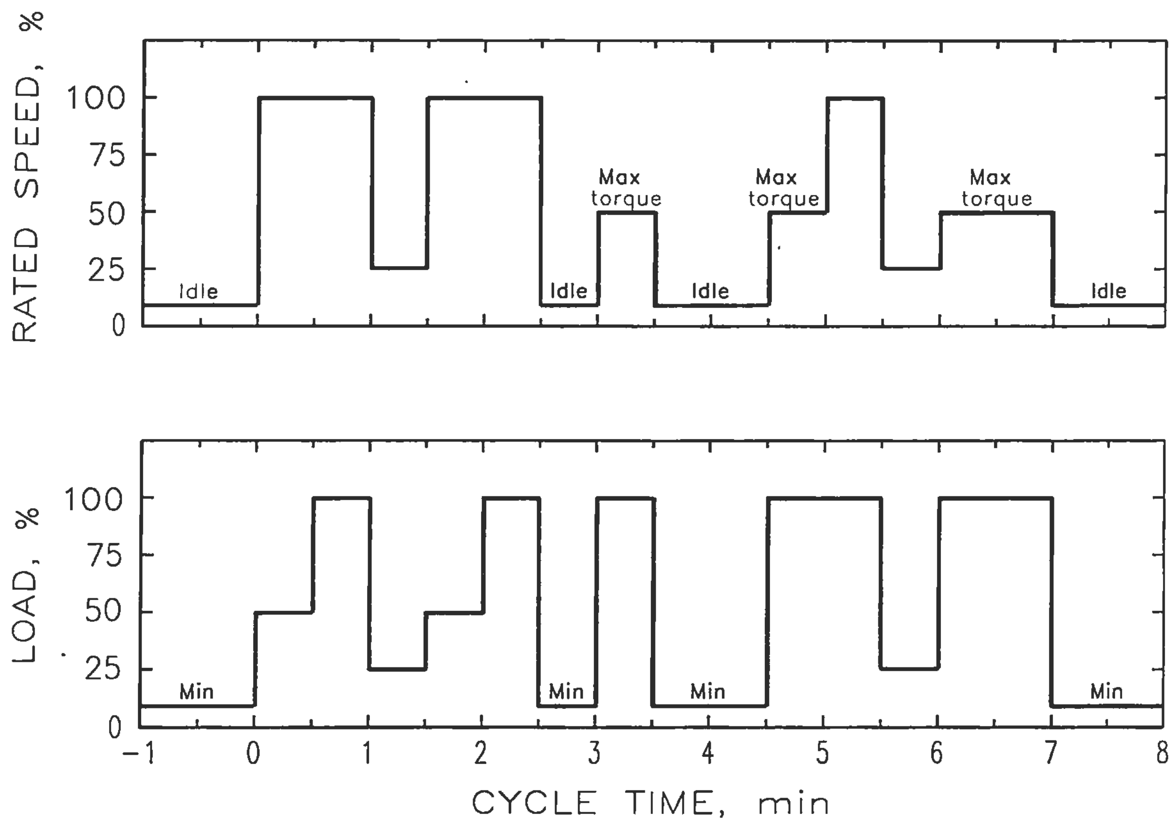


Figure 9.—Example of transient speed and load schedule.

loading and the other for fuel management. A detailed description of process control systems is found elsewhere *(5)*.

Various engineering parameters may be selected for set-point and feedback signals, enabling a variety of control methods. For instance, the dynamometer could control engine speed rather than torque by providing speed set points and feedback to the dynamometer controller. Other parameters, such as fuel rate, fuel-rack position, dynamometer field current, power, and exhaust pressure, or intake airflow, can also be controlled. Process controllers regulate dilution tunnel flow, engine intake manifold pressure, speed, and torque. These control systems are essential to obtain consistent operating conditions on a day-to-day basis.

TRANSDUCERS

The DERL uses a variety of transducers (fig. 10) that provide information from physical parameters; each transducer is selected and matched to a physical, chemical, or mechanical property of interest. These transducer signals are converted to engineering units such as revolutions per minute, pounds (force) per square inch, and newton meters, which are then recorded in a data base for each experimental test. Tables 1 and 2 present a synopsis of some transducers and actuators currently being used.

Table 1.—Synopsis of transducers

Physical parameter	Measurement method	Sensor type	Signal
Gas flow ..	Larminar flow element.	Pressure ...	Analog.
Do......	Orifice plate (pressure drop).	.. do.......	Do.
Pressure ..	Transducer	.. do.......	Do.
Temperature	Seebeck effect ...	Thermo-couple.	Do.
Rotational speed.	Rotating gear	Magnetic pickup.	Electrical pulse to voltage.
Torque (moment).	Dynanometer reaction torque.	Load cell strain gage.	Analog.
Fuel flow ..	Orifice wheatstone bridge.	Pressure ...	Do.
Gases	Chemical analysis.	Detector to voltage.	Do.
Position ...	Potentiometer ...	None	Do.
Opacity ...	Photoelectric	Detector	Do.

Table 2.—Synopsis of actuators

Type	Energy requirement	Function
Solenoid valve	Electrical, ac or dc	Control gas, air, or water.
Solenoid	.. do.	Linear mechanical motion.
Rotary mechanical ..	.. do.	Rotary mechanical motion.
Heater	Electrical, ac	Temperature control.
Power absorber (dynamometer).	Electrical, dc and eddy current.	Torque loading.

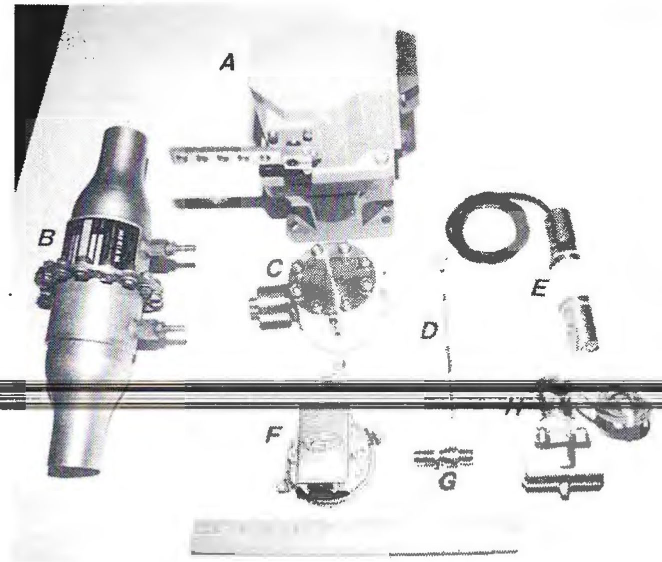


Figure 10.—Variety of transducers and actuators used in DERL. *A*, Rotary actuator; *B*, laminar flow element; *C*, pressure transducer; *D*, thermocouple; *E*, load cell; *F*, pressure switch; *G*, magnetic pickup; *H*, electrical solenoid.

Before each experimental run, the transducers and the data-acquisition equipment are tested for proper operation. Transducers are calibrated using an experience-based criteria or a 6-month interval, whichever comes first. Calibration standards are traceable to the National Institute of Standards and Technology (NIST). Additional information about transducer operation and calibration is available from instrumentation engineering handbooks (*6-8*).

ACTUATORS

Shown in figure 10 are actuators controlled by signals from the test cell controller and used to operate the engine at desired experimental conditions. An eddy current dynamometer is used to absorb engine power and control torque. The engine fuel rack and air plenum dampers are positioned with electromechanical actuators. Electrical solenoids and heaters are used for directing fluids and maintaining specified temperatures. All actuators are matched to the equipment for optimal response and use programmed signals from the test cell controller, providing accurate, repeatable test results. An air-operated aspirator and manually adjusted valves control exhaust pressure.

ANALYSIS

Accurate reliable analysis is necessary for evaluation of experimental investigations. Analyses of gas and DPM comply with government and industry standards (*9-11*), yet research methods can be implemented as well. Many resources are devoted to developing advanced methods for analyzing diesel emissions and experimental data. Methods and procedures for particulate, gas, and data analysis are described in the following section.

PARTICULATE AND VAPOR-PHASE SAMPLE ANALYSIS

By using the sampling system previously described, DPM from diesel exhaust is collected at a temperature below 50° C +2/-5 (*12*) on a Pallflex TX40H120-WW, Teflon fluorocarbon polymer-coated, glass-fiber-sample filter. This material is an optimum filter media suited for collecting DPM (*13*). Sampling times vary from 10 to 75 min. Filter face temperatures are kept below 52° C to minimize artifact formation or chemical change and to comply with standards (*12*).

Sample filters are conditioned overnight at room temperature before weighing. Temperature is maintained at 20° C and humidity at 50%. The balance is calibrated and the filters are weighed twice to ensure a difference no greater than 0.4 mg.

Sample filters are ammoniated (*14*) with ammonium hydroxide for 15 to 24 h after collection. This procedure converts the sulfuric acid to ammonium sulfate and ensures a stable filter mass. After ammoniation, the sample filters are weighed, cut in half, and weighed again. One-half of this filter is analyzed for sulfur by extraction with 1% nitric acid. The quantity of sulfate is determined by using ion chromatography (*15*). The other half of the filter is placed in a vacuum oven where the volatile fraction is determined by vacuum-oven sublimation. Filters are baked in the oven for 15 to 24 h at 200° C and then conditioned to room temperature-humidity for 2 to 3 h prior to reweighing.

In addition to determining the volatile fraction of DPM by vacuum-oven sublimation, some investigations use a vapor-phase sampler (shown in figure 11), which is installed downstream of the sample filter to collect gas-phase HC. The sampler contains 40 g of 20- to 40-mesh XAD-2 resin and is placed between layers of polyurethane foam to collect organic species containing 7 or more carbon atoms (*16*). After sampling, the resin and foam are placed in a glass bottle with a Teflon fluorocarbon polymer-lined cap. The bottles and filters are then wrapped with tinfoil and stored at -20° C. All sample material is then packaged with dry ice and shipped to other laboratories for analysis (*17*). This analysis is conducted to determine Ames activity and polycyclic nuclear-aromatic content.

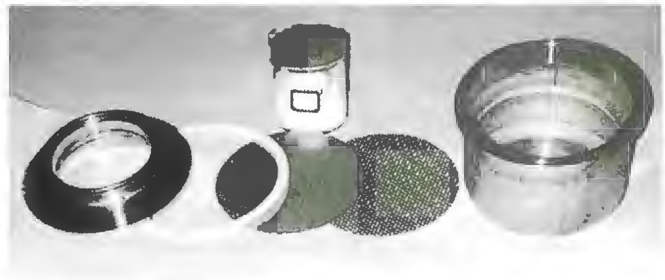


Figure 11.—Disassembled vapor-phase sampler and container of XAD-2 resin.

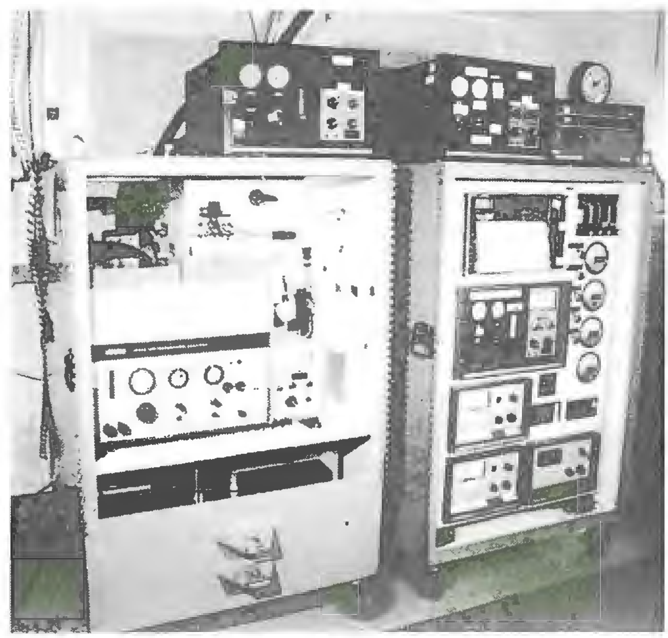


Figure 12.—Exhaust gas analyzers (HC, NO, NO_x, CO, CO_2, O_2, and SO_2).

GAS ANALYSIS

Diesel exhaust gases are sampled from the exhaust stream and measured using analytical instruments specified in Title 40 of the U.S. Code of Federal Regulations (CFR) (*9*). CO_2 and CO concentrations are determined by using nondispersive infrared analyzers. A polarographic sensor is used to analyze for O_2, and total HC is determined by a flame ionization detection method. Two NO_x analyzers, with chemiluminescence detectors, permit simultaneous measurement of both NO and NO_x. NO_2 is assumed to be the difference; i.e., $NO_2 = NO_x - NO$. Although not required by the CFR (*9*), SO_2 is also measured by using a nondispersive analyzer. Beckman analyzers (fig. 12) use established methods of gas analysis. A spectrum-type FT-IR gas analyzer (not shown) is also used to measure exhaust gases of interest, providing additional information for examining exhaust gas chemistry.

DATA ANALYSIS

Experimental information gathered by the test cell controller is merged with gravimetric and chemical analysis into a common data base. Several methods are available for the analysis and use of these acquired data. Information can be transferred to a local minicomputer and shared with others using networks or data links. Data are formatted for use with computer-based spread sheets, such as SuperCalc or Lotus 1-2-3. Most analysis, graphing, and statistical evaluation are done using microcomputers and spread-sheet programs. This provides investigators a great deal of flexibility, with only one data base to be maintained.

SUMMARY

The DERL is used for investigating the most recent scientific and technological methods of diesel exhaust emission control applicable to underground mines. State-of-the-art equipment is used for engine control, emission measurements, and data evaluation. Specialized test methods are implemented using a computer-based test cell controller. The test cell controller manages test control and data acquisition using specialized actuators and transducers. Closed-loop process controllers are used for accurate control of engine parameters.

A diesel engine with a dynamometer power absorber produces emissions for evaluation of control units. Intake and exhaust manifold pressures are controlled to provide consistent engine operating conditions and to simulate effects of reduced pressures at higher altitudes. Numerous types and sizes of emission control units can be evaluated in the laboratory, with provision for the newest methods of exhaust gas analysis. A glass-fiber filter installed in a partial-flow dilution tunnel is used to collect DPM.

Particulate sample analysis is conducted using established gravimetric, vacuum sublimation, and chemical methods. Exhaust gases are analyzed using established methods supplemented by the use of a wide-range FT-IR spectrometer. Measured values of engine operation and emission analysis are acquired and recorded in a computer data base. With this laboratory, the Bureau is positioned to conduct diesel exhaust emission research at the leading edge of science and technology.

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THE EFFECTS OF MAINTENANCE AND TIME-IN-SERVICE ON DIESEL ENGINE EXHAUST EMISSIONS

By Robert W. Waytulonis

ABSTRACT

Research was conducted under a U.S. Department of the Interior, Bureau of Mines contract to determine the effects of maintenance and time-in-service on diesel engine emissions and performance. Data from six Caterpillar 3306 PCNA and seven Deutz F6L 912 W engines from five underground mines are presented; their number of hours in service ranged from 485 to 9000. Also, a laboratory study induced faults in a new diesel engine to determine their effects on emissions. Analysis of the in-service engine data and the induced faults study revealed that harmful pollutants can be controlled to near new engine levels by sustained and proper maintenance. Maintenance activities causing the engine's fuel-air ratio to deviate from the factory setting have an immediate detrimental effect on most pollutants of concern. With proper maintenance, engine component wear affects emissions and performance only after several thousand hours in service.

INTRODUCTION

The increasing use of diesel-powered equipment in underground mines and concern for the health of miners led the Bureau of Mines, U.S. Department of the Interior, to embark on a project to obtain definitive data on the relationships between engine condition, maintenance practices, emissions, and time-in-service. Although it has been recognized for some time that properly adjusted engines and plentiful ventilation were necessary for safe operation of diesel-powered equipment (Grant 1973, Holtz 1960), little information existed to support this precept.

This report is based on data obtained from a study performed by Southwest Research Institute (SwRI) under U.S.B.M. contract H0292009 (Branstetter 1983). The objective of the SwRI study was to quantify typical mine diesel emission levels and relate this information to maintenance and time-in-service. This report discusses underground diesel maintenance, further analyzes the SwRI data on 13 in-service diesel engines, and presents the effects of induced faults on emissions.

DESCRIPTION OF METHODS

The SwRI project was divided into two major segments; the in-mine engine evaluations and a laboratory study of the effects of induced faults on engine emissions. Near identical emission and diagnostic instrumentation was used in both segments.

INSTRUMENTATION

Performance and diagnostic instrumentation were used to evaluate engine condition and measure exhaust emissions. The factors that affect emissions include engine speed, torque, fuel consumption, intake airflow, injection timing, nozzle crack pressure, compression, barometric pressure, and relative humidity. These parameters were measured in the mines and the laboratory using conventional instrumentation and techniques specified by the Environmental Protection Agency (EPA 1982, Fed. Reg. 1981) and described by Branstetter et al. Carbon monoxide (CO) and carbon dioxide (CO_2) were measured using nondispersive infrared (NDIR) analyzers. Nitric oxide (NO) and nitrogen oxides (NO_x) were measured by a heated chemiluminescent analyzer, and hydrocarbons (HC) were measured using a flame ionization detector (FID). During the in-mine studies, a Bosch spot smoke meter was used to measure smoke density. The readout of the Bosch smoke meter or Bosch smoke number (BSN) has a scale of 0 to 10. Although correlations were not made in this study, the exhaust carbon and total particulate mass concentrations correlate well with the BSN (Alkidas 1984). In the laboratory, exhaust particulate measurements were accomplished with an exhaust dilution tunnel.

IN-MINE ENGINE EVALUATIONS

Five mines supplied engines or complete vehicles with varying amounts of accumulated time-in-service to the field research team. During the testing of in-service engines it was difficult to obtain permission from mines to perform the in-depth and complete testing necessary to form quantitative relationships between time-in-service, local maintenance practices, and emissions. Only mines having generally good maintenance programs were willing to allow the testing reported here; therefore, it is assumed that the majority of the engines had received proper maintenance throughout their lives. Whenever possible mine operators supplied engines that had differing numbers of hours-in-service. Such a selection made it possible to attempt a qualitative correlation between engine performance and time. Reference to specific products in the text does not imply endorsement by the Bureau of Mines.

The six Caterpillar 3306 PCNA engines (designated "C") were six-cylinder, water-cooled, indirect-injection, four-cycle, naturally aspirated diesels rated 146 hp (109 kW) at 2200 rpm. The factory setting for fuel injection timing for these engines is 13 crank angle degrees before-top-dead-center (BTDC). These engines were all tested without removing them from the vehicle and were coupled to the dynamometer through the vehicle's torque converter. Full load-peak torque speed could not be attained owing to the torque converter's slip ratio and drive line mechanical losses. The load-speed test points used in the analysis of these engines include only 100 and 50 percent load-rated speed.

The seven Deutz F6L 912 W engines (designated "D") were all six-cylinder, air-cooled, indirect-injection, four-cycle, naturally aspirated diesels rated 84 hp (63 kW) at 2300 rpm. The factory setting for fuel injection timing is 24 degrees BTDC. The Deutz engines were tested apart from the mine vehicles; thus additional test data were obtained at 100% and 50% loads-peak torque speed. The format used to identify the engines in the forthcoming tables and graphs is "C or D - number of hours-in-service." For example, C-5000 designates a Caterpillar engine with 5000 hours-in-service. An in-mine engine test set-up is shown in figure 1.

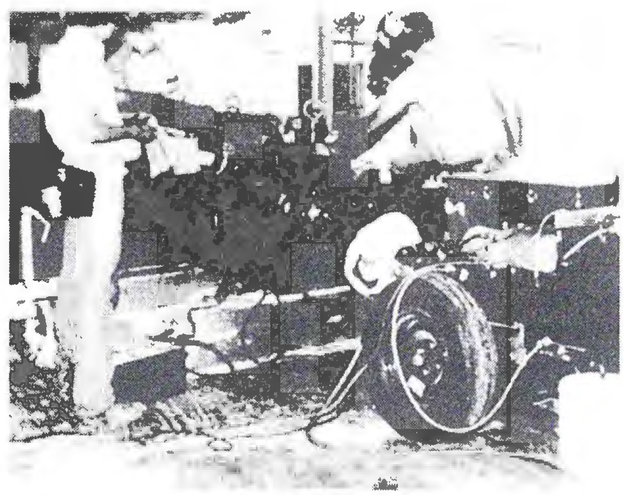

Figure 1.—A typical in-mine test set-up for the evaluation of diesel engines.

LABORATORY STUDY OF INDUCED ENGINE FAULTS

A new Deutz F6L 912 W (D-0) engine was used to determine the effects of maladjustments or faults on the production of HC, CO, NO_x, and particulate matter. After initial tests to acquire the engine baseline data, faults were artificially induced at different levels of severity and the resulting change in emissions were measured. The faults were intake combustion air restriction, exhaust-gas restriction, fuel injection timing adjustment, and overfueling. The first level of severity represents the limits of manufacturer-recommended specifications, and the second level was chosen to be deliberately excessive but within the realm of possibility through improper maintenance; intake restriction = 25 and 50 in water (6 and 12 kPa), exhaust restriction = 3 and 6 in Hg (10 and 20 kPa), and overfueling = 10% and 20% overrated. Fuel injection timing advance had three levels of severity: -4, +4, and +8 crank angle degrees from 24 degrees BTDC. The engine was tested with the individual faults and at the two or three levels of severity. Also, tests were conducted with two faults simultaneously. Finally, all four faults were induced simultaneously. Three baseline tests were performed on the engine during which all adjustments were set as recommended by the manufacturer.

DATA ANALYSIS TECHNIQUE

Data were analyzed according to the protocol developed by Branstetter, using a normalized weighting equation. The mass emission rate for each pollutant was used in the data analysis. The data were reduced by combining load-speed test modes of each engine, for a given pollutant, into one number by weighting the emission value at the load-speed test points. The weighting factors are based on the percentage of time the engine is assumed to be at a load-speed condition during a hypothetical operating cycle. Mass emissions were reduced and the units used in figures 2 through 4 are grams per brake horsepower-hour (gm/bhp-hr). So even though the C and D engine groups have different horsepower ratings, valid comparisons of the two engine groups can be made on a per-horsepower basis.

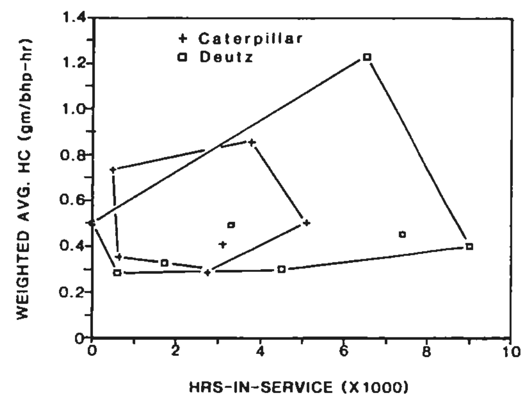

Figure 2.—Weighted average hydrocarbon emissions vs. hours-in-service for the C and D engine groups.

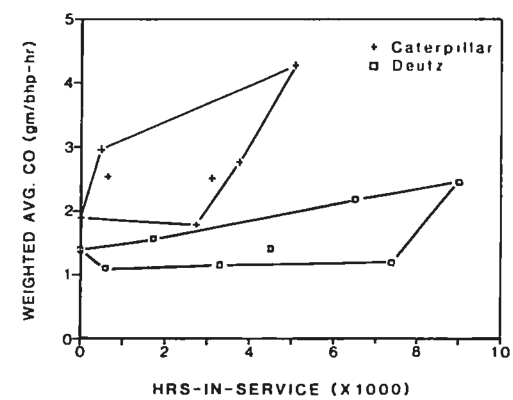

Figure 3.—Weighted average carbon monoxide emissions vs. hours-in-service for the C and D engine groups.

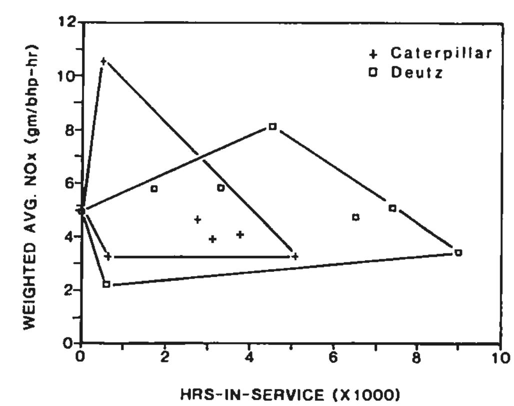

Figure 4.—Weighted average oxides of nitrogen emissions vs. hours-in-service for the C and D engine groups.

UNDERGROUND MINE MAINTENANCE

GENERAL

The objective of diesel engine maintenance is to keep engines in operating condition so that productivity continues and useful life is maximized. Preventive maintenance, periodic repairs, and adjustments are all part of a basic maintenance program. While maintenance cannot guarantee hazard-free operation, it can prolong or restore near-original efficiency of the engine and vehicle (Springer 1975). Lack of basic maintenance decreases equipment availability and useful engine life and can increase engine failures. Underground mine maintenance programs must cope with unique environmental problems not common in other settings. Underground conditions vary but are usually very harsh and hard on equipment. Working areas are no larger than necessary, and often small poorly lighted cutouts serve as shops. Tools may consist of only essential items such as wrenches, a cutting torch, a welder, and large hammers. Some mines have large well-lighted shop areas where more complicated repairs can be undertaken and may even purchase specialized engine diagnostic equipment for preventive maintenance. Nevertheless, the underground mining environment is not conducive to performing diesel engine or any other maintenance activities.

The Mine Safety and Health Administration (MSHA), through certification or approval, assures that new diesel-powered equipment meets specified safety criteria. This includes a minimum ventilation requirement in locations where the diesel unit is to be operated. The ventilation rate is calculated to dilute certain gaseous pollutants to one-half their individual Threshold Limit Values (30 CRF 32, 36, 1984). Once the equipment is put into operation, it is the responsibility of the mine operator to keep it in good condition.

DIESEL ENGINE MAINTENANCE

A brief discussion of the six major systems pertaining to the maintenance of diesel engines follows:

1. Intake air system.—Dust-laden mine air causes intake air filters to become filled with dust, creating a restriction that may exceed the manufacturer's recommended limit. Intake air filters should be replaced when the pressure drop across the filter exceeds the manufacturer's specification, usually about 20 in (5 kPa) of water. Not all air intake system failures can be detected by pressure drop indicators, e.g., a broken intake air duct or punctured filter will not be detected. The best method presently available for detection of these failures is a visual inspection of the air intake system. A failure, if not quickly repaired, will cause rapid engine wear and result in increased emissions and decreased performance.

2. Engine cooling system.—The loss of engine cooling leads to scuffed cylinder walls and piston, cracked heads, and burned valves. These conditions directly affect emission production and output power. A liquid-cooled engine relies on transfer of heat from the coolant to the radiator, and from the radiator to ambient air. Internal coolant passages of the engine and radiator must be kept free of mineral and rust deposits for effective heat transfer. Mine water is generally high in minerals and salts, rendering it unfit for use in engine cooling systems. It is recommended that a premix of a 50% mixture of distilled water and antifreeze be used.

Air-cooled engines reject heat via cooling fins which are an integral part of the engine. During normal operation these fins become coated with oil and dust, which bakes on to form an insulating layer. If this layer is allowed to build on the engine, overheating will result. Periodic steam cleaning will prevent this situation.

3. Diesel fuel handling and quality.—DF 2 diesel fuel should be used whenever ambient temperatures are above the cloud point of the fuel. This is because when compared to DF 1, DF 2 possesses better lubrication properties and tends to extend fuel injection system component life. Additionally, DF 2 has a higher energy content per gallon. Low-sulfur (less than 0.5% by weight) fuel should always be used; the sulfur present in all diesel fuels directly affects the emissions of particulate sulfates and accelerates engine wear. Fuel contamination will also cause accelerated engine wear. It is important to minimize the number of fuel transfers and to store the fuel in tightly sealed containers which are clearly labeled.

4. Fuel injection system.—The adjustment of the fuel injection system has considerable effect on the production of exhaust pollutants. The most critical adjustments are fuel flow rate and fuel injection timing. The engine fuel flow rate is usually set at the factory or at the mine site, and this setting is based on the MSHA horsepower and ventilation rating. The fuel rate remains constant for long periods; however, it can be adjusted to yield higher output horsepower.

Unless manually adjusted, diesel injection timing generally remains constant over long service intervals. Timing could be improperly adjusted at the factory, improperly set by a serviceman, or otherwise altered to yield higher output horsepower. Engine manufacturers usually allow a 1-degree deviation from the recommended setting. Although changes in fuel injection timing and fuel injection rate can increase power output, increases in exhaust pollutants may accompany the power increase. The life of the injection system is greatly affected by the quality of fuel and lubricant. Contamination of the fuel erodes injector nozzle tips and the injection pump plunger and barrel. Like the rotating components of the engine, it is important that the lubrication oil in the injection pump be clean.

5. Lubrication system.—Failure of the lubrication system usually results in catastrophic engine failure. System failures are often caused by a component failure, such as seized bearings, lubricant breakdown or contamination, or engine over-heating. To control these failures it is important to keep the crankcase lubricant free of solid and liquid contamination, and maintain the engine's cooling system. If an engine becomes excessively hot, the oil viscosity is lowered, resulting in loss of lubricity and accelerated engine wear.

6. Exhaust system.—Excessive exhaust-gas restriction can result from either a partially plugged water scrubber or catalytic converter, or a dented exhaust pipe. Diesel engine manufacturers generally consider 2 to 3 in Hg (7 to 10 kPa) to be the acceptable limit. Excessive backpressure results in increases of some pollutants and decreases output power. Periodic inspection and cleaning of exhaust system components will preclude excessive backpressure.

TEST RESULTS OF IN-SERVICE CATERPILLAR AND DEUTZ ENGINES

Table 1 contains diagnostic information and performance data for the 13 in-service engines, the D-0 engine, and partial information for a C-0 engine. The maximum horsepower is that developed by each engine at 100% of its maximum load at rated speed; brake specific fuel consumption (BSFC) in pounds per hour is also given at this condition. Fuel injector nozzle crack pressure, cylinder compression, and fuel injection timing are also listed to describe the internal condition of the engines. To identify possible reasons why emissions and performance vary with maintenance-related activities or time-in-service, the information contained in table 1 must also be examined in conjunction with the induced-faults data in table 2, and the emissions data in figures 2 through 5. Figures 2 through 5 are envelopes which contain all values for the respective engine group. Both engine groups are shown on common axes for visual comparison. Each engine can be identified by the legend and corresponding hours-in-service value. With the information contained in these table and graphs, additional engine analysis can be performed by the reader.

Figure 2 shows the weighted average hydrocarbon (HC) emissions in gm/bhp-hr plotted against hours-in-service for all in-service C and D engines. The HC value for the C-0 engine is unknown. With the exception of C-485, C-3765, and D-6500, all the in-service engine values fall between about 0.28 and 0.50 gm/bhp-hr. Table 1 shows that C-485 had a 4-degree timing advance but otherwise good diagnostic indicators. The advanced timing accounts for these high HC emissions. The compression in C-3765 was slightly low, and the injection timing was not obtained. Low compression can cause inefficient combustion and an increase in HC emissions. Low fuel injector nozzle crack pressure results in a poor fuel spray pattern or dripping, which causes an incomplete mix of fuel and combustion air. D-6500 had very low fuel injector crack pressure in all six nozzles, which resulted in very high HC emissions. These data indicate a gradual increase in HC emissions for the first 4000 to 5000 hours-in-service.

Table 1.—In-service engine diagnostic information

Engine	Max. hp	BSFC (lb/Bhp-hr @ max load/speed)	Nozzle Crack Pressure (psi) Cylinder Number 1	2	3	4	5	6	Compression (psi) Cylinder Number 1	2	3	4	5	6	Injection timing (deg. BTDC)
C-0	146	n/a	400 TO 800 →						no published data →						13
C-485	139.9	0.3873	700	650	600	700	700	600	370	365	370	360	370	360	17
C-634	125.5	0.4231	750	750	750	650	750	800	330	350	375	n/a	350	355	15
C-2740	129.4	0.4066	700	700	700	700	800	750	n/a	295	n/a	300	290	280	n/a
C-3099	151	0.3774	600	700	700	700	600	700	350	360	345	350	355	320	18
C-3765	140.7	0.4052	900	700	800	700	700	700	340	350	345	330	330	325	n/a
C-5071	154.7	0.4085	750	800	800	800	800	800	n/a	n/a	n/a	n/a	385	375	n/a
D-0	83.5	0.4266	1850	1850	1850	1850	1850	1850	362 TO 435 →						24
D-600	78.2	0.4230	1750	1650	1650	1650	1700	1650	440	415	430	430	440	430	18
D-1720	86.8	0.4101	1550	1600	1675	1600	1650	1600	460	455	435	430	430	435	32
D-3300	79.7	0.4152	1400	1600	1500	1600	1500	1400	360	420	395	390	390	355	24
D-4500	77.5	0.4118	1700	1700	1600	1700	1600	1600	410	410	405	410	385	410	29
D-6500	78.7	0.4285	400	400	400	400	360	400	390	400	400	420	365	390	23
D-7375	63.4	0.4543	1600	1625	1600	1650	1700	V. LOW	320	340	360	330	335	330	n/a
D-9000	87.4	0.4141	1750	2100	2100	2000	1800	1800	390	420	450	420	450	440	21

In figure 3, the weighted average carbon monoxide (CO) emissions are plotted against time-in-service. Unlike the HC, NO_x, and Bosch smoke data, the emission envelopes for the C and D engines do not overlap for CO. The C engine group has the higher CO values. Excessive CO emissions result from incomplete combustion. For the C envelopes, data are grouped between about 1.9 and 3 gm/bhp-hr except for C-5071. Diagnostic information for this engine is incomplete; however, low compression or retarded timing will cause CO to increase. CO data for all the D engines fall between about 1.1 and 2.5 gm/bhp-hr. D-9000 is the highest in this engine group, and its slightly retarded timing contributes to a high CO value. In general CO emissions appear to increase slowly with time-in-service for the D engine group; it is difficult to distinguish a trend with time for the C group.

In figure 4, weighted average oxides of nitrogen (NO_x) emissions are plotted against time-in-service. For the C engine group, C-485 lies outside a decreasing trend with time; in the D engine group D-4500 also is an outlier. Both these engines have advanced fuel injection timing, which is the cause of these high NO_x emissions. D-600 has very low NO_x emissions resulting from this engine's retarded timing. Except for these three engines, the values for both engine groups fall between about 3.2 and 6 gm/bhp-hr, with the C group having the lowest values. This is possibly due to the lower combustion temperatures in the water-cooled C group, which tend to lower NO_x. These data indicate a gradual decrease in NO_x emissions with time-in-service, for both engine groups.

Figure 5 is a plot of the Bosch smoke number (BSN) at full load-rated speed vs. time-in-service for the C and D engine groups. BSN is an indication of combustion efficiency and particulate mater emissions. Within the C group, C-2740 had the lowest value at about 1. In table 1 it can be seen that this engine could only reach about 130 hp (97 kW) vs. its 146 hp (109 kW) rating, and this contributes to the low BSN; BSN is generally greater at higher engine loads. C-634 and C-5071 both had high BSN's of about 3. C-634 could only attain about 126 hp (94 kW) and had slightly advanced fuel injection timing, which in combination increased BSN. C-5071 actually exceeded its rated power output by about 9 hp (6 kW), which could account for its high BSN. Within the D engine group, D-1720 had the highest BSN at about 4. A combination of greater-than-rated power output with advanced fuel injection timing was the cause of its high BSN. D-9000 had the lowest value (1.3 BSN) for the D group of engines. This was due to this engine's retarded timing. Additionally, the higher-than-baseline nozzle crack pressures effectively further retard fuel injection timing, and it was these conditions that counteracted the greater-than-rated power output and resulted in a very low BSN. Disregarding these extremes, BSN for both engine groups fell between about 1.6 and 2.2 with a slight increasing trend over time.

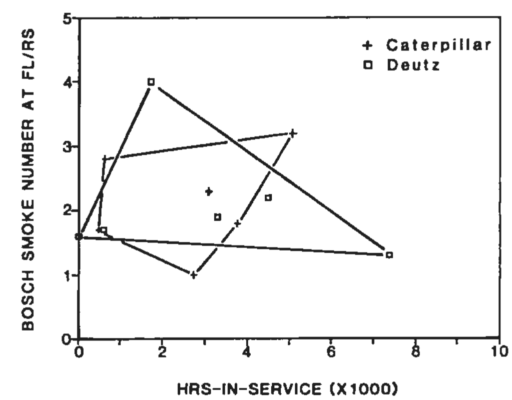

Figure 5.—Bosch smoke number for C and D engine groups at full load-rated speed vs. hours-in-service.

Annual fuel consumption estimates are based on measured average brake specific fuel consumption for each in-service engine and 3456 hours per year operation. The engines are compared on the basis of equal work performed (horsepower-hours) in figures 6 and 7. Figure 6 indicates that a new C engine would consume about 25,000 gal (95 kl)/year of fuel; C-485 is seen to have extremely high fuel consumption at more than 70,000 gal (265 kl)/year. During the testing of this engine a leak in the high pressure fuel line occurred at the 50% load-rated speed test point. This very high estimate assumes that this condition was allowed to continue. C-634 would consume about 20,000 gal (76 kl)/year, slightly less than the C-0 values. Based on the information in table 1, it cannot be determined why this engine was more fuel efficient. C-2740 had slightly higher than baseline fuel consumption at 27,000 gal (102 kl)/year, owing in part to its low cylinder compression. All other C group engines are estimated to consume near-baseline levels of fuel.

The annual fuel consumption estimates in figure 7 for the D engine group vary from about 11,000 to over 18,000 gal/year (42 to 68 kl/year). D-1720 consumes the least fuel of all D engines owing to its advanced injection timing, which enables it to get slightly more horsepower per unit of fuel consumed. Although this engine's output power was high, a penalty of high CO emissions as shown in figure 3 resulted. D-7375 is estimated to consume in excess of 18,000 gal (68 kl)/year owing to its one leaky injector and low cylinder compression. D-6500 is estimated to consume over 15,000 gal (57 kl)/year of fuel owing to very low injector nozzle crack pressures in all six cylinders. All other D group engines would consume about 12,000 to 13,500 gal/year (45 to 51 kl/year).

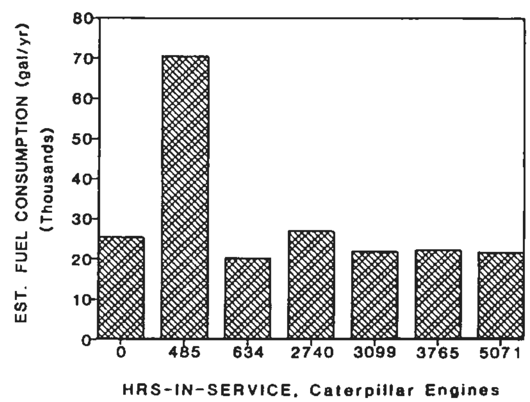

Figure 6.—Estimated annual fuel consumption for the C engine group.

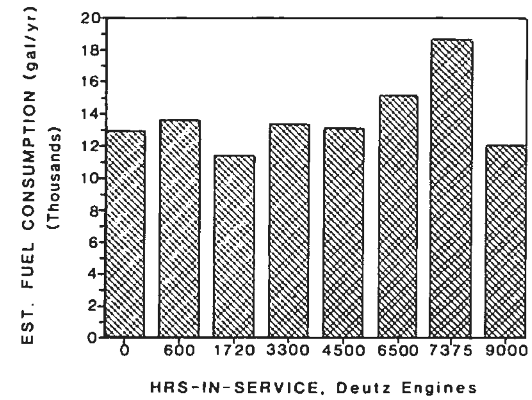

Figure 7.—Estimated annual fuel consumption for the D engine group.

TEST RESULTS OF INDUCED FAULTS ON A NEW DEUTZ F6L 912 W ENGINE

A summary of the induced-faults tests is presented in table 2, which lists the percent deviation from baseline caused by the faults. The weighted baseline values for the gaseous emissions were HC = 0.31, CO = 1.15, NO_x = 3.15 gm/bhp-hr, and steady-state particulate matter at full load-peak torque speed = 569 milligrams per standard cubic meter (mg/scm), compared with 64 mg/scm at full load-rated speed.

The single fault that has the greatest influence on the production of hydrocarbons is retarded timing (+306%) and this is worsened when combined with restriction of intake air (+71% to +443%). Advancing injection timing also increases production of HC but levels off at 4 degrees advance to +107%. Exhaust-gas restriction tends to slightly increase HC by +17% at 3 in Hg (10 kPa) and +2% at 6 in Hg (20 kPa), while intake restriction and/or overfueling causes small decreases.

The test condition producing the highest CO emissions was the combination of intake air restriction and overfueling (+164% to +445%). Producing almost an equal amount of CO (+448%) was the combination of all faults at their most severe settings. Overfueling combined with exhaust restriction (+102% to +326%) followed by overfueling alone (+95% to +247%) produced less of an increase. Overfueling was the common element producing the highest CO. It appears that the advance in the injection timing in the absence of other faults somewhat compensates for overfueling and limits the production of CO.

The single fault most severely affecting production of NO_x is fuel injection timing advancement (+1% to +50%). The greatest increase of NO_x occurred when timing advance and exhaust-gas restriction were combined (+2% to +53%). Retarded injection timing provided the greatest reduction in NO_x (-33%). Severely restricting intake air (-12% to -15%) and overfueling (-24%) both resulted in reduction of NO_x.

When the engine was operated at full load-rated speed, intake air restriction (+25% to +75%) or overfueling (+44% to +45%) had the most effect of single faults on particulate production. The combination of these faults at the most severe test point resulted in a 1038% increase above baseline. Combining all faults also greatly increased particulate production but at about half this condition (+548%). All combination faults except those with timing advance resulted in at least a 100% increase over baseline values.

Particulate values at full load-peak torque speed are somewhat similar to those at full load-rated speed. Of all the fault conditions that increased particulates, overfueling was a common element. The single faults that increased particulates were intake restriction (+44% to 164%) and overfueling (+125% to +173%).

Table 2.—Percent deviation from baseline caused by induced faults in a new Deutz F6L 912 W engine

Fault Description	Degree of Fault	HC	CO	NO_x	Particulates* FL/RS	Particulates* FL/PTS
Intake Air Restriction (in-H20)	25	-28	+8	-15	+25	+44
"	50	-36	+28	-12	+75	+164
Exhaust Restriction (in-Hg)	3	+17	+1	+9	-15	-6
"	6	+2	+6	-3	-8	-11
Timing Advance (24 deg BTDC)	-4	+306	+53	-33	-4	-23
"	+4	+106	+4	+1	+2	-41
"	+8	+107	+12	+50	+29	+30
Overfueling (pct rated)	+10	-28	+95	0	+45	+125
"	+20	-20	+247	-24	+44	+173
Intake Air Restriction & Timing Adv.	25 -4	+71	+25	-27	+7	+150
"	50 -4	+443	+122	-38	+120	+94
Exhaust Restriction & Timing Adv.	3 +4	+59	+11	+2	-13	+5
"	6 +8	-29	+23	+53	+25	+59
Intake Air Restriction & Overfueling	25 +10	-3	+164	-14	+139	+194
"	50 +20	-21	+445	-35	+1038	+366
Overfueling & Timing Adv.	+10 +4	-24	+97	+11	+58	+118
"	+20 +8	-5	+112	+19	+102	+211
Intake & Exhaust Restriction	25 3	0	+8	+3	+8	+45
"	50 6	-38	+72	-8	+153	+91
Exhaust Restriction & Overfueling	3 +10	-33	+102	+6	+77	+368
"	6 +20	-46	+326	-13	+263	+324
Int. & Exh. Restrictions O-fuel & Timing Adv.	25 3 +10 +4	-40	+72	+10	+132	+338
"	50 6 +20 +8	-44	+448	+6	+584	+352

* FL/RS - full load/rated speed
FL/PTS - full load/peak torque speed

In general, engine faults did not result in decreasing particulate matter reduction. Also, it was found that the level of emission caused by a pair of faults occurring individually is not as severe as the level when the same faults are induced simultaneously. For example, if an otherwise properly adjusted engine has an intake air restriction of 50 in of water (13 kPa), particulate emissions increase 75%. If the engine is overfueled and otherwise adjusted properly, particulates increase by 44%. If the two fault conditions are combined, particulate emissions increase by more than 1000% over the baseline value. These maintenance-related faults effectively change the engine's fuel-air ratio, resulting in excessive exhaust pollutant production.

CONCLUSIONS

In the absence of severe faults or maladjustments, exhaust emission quality does not degrade excessively during the initial 4000 hours-in-service. After 4000 to 5000 hours-in-service the engines tests in this project typically developed the following trends: HC increased, CO increased, NO_x decreased, and particulates increased. Two explanations are offered for these qualitative trends. After time, engine component wear becomes significant and affects engine operation and composition of the exhaust. For example, a worn fuel injection system has the effect of retarding fuel injection timing and thus decreasing NO_x emissions. Also, it was observed that older engines are not as carefully maintained as newer engines, and minor faults are more prevalent. However, gradual component wear is believed to be the principal cause of the observed changes in exhaust emissions over time.

Induced faults tests revealed that intake air restriction, fuel injection timing, and overfueling had the greatest effect on emission rates, while certain combinations of faults had synergistic effects. It was observed that when the faults were removed, the engine emission characteristics returned to original levels. The production of HC is most affected by fuel injection timing maladjustments; retardation of the injection timing has the worst effect of any single fault. The combination of timing retardation and combustion air intake restriction promoted the greatest HC emissions. Overfueling the engine was the single fault that had the greatest effect on CO. Any other fault in conjunction with overfueling, with the exception of timing advance, increased the production of CO above the level caused by overfueling alone. The production of NO_x was most affected by injection timing. Retarding the timing decreased NO_x, while advancing the timing by more than 4 degrees substantially increased NO_x. The quantity of particulate matter produced while the engine was operating under full load was most affected by combining intake restriction with overfueling. These engine faults are caused by specific maintenance activities: (1) intake air filter change-out, (2) fuel injection timing adjustment, (3) fuel rate adjustment, (4) fuel injector nozzle cleaning and/or change-out, and (5) exhaust restriction monitoring.

The quantity of an engine combustion products emitted into the mine atmosphere is in direct proportion to the amount of diesel fuel consumed. Proper engine maintenance results in lower fuel consumption and lower concentrations of exhaust pollutants, and this translates into cost savings and improved air quality. Diesel engine manufacturers have refined their product performance to be a balance between exhaust emissions, fuel efficiency, and durability. Any changes induced into a diesel engine that result in a fuel-air ratio deviation from the factory setting or accelerated engine wear will cause emissions, efficiency, and durability to degrade. Diesel engines in service in underground mines can be expected to perform several thousand hours with minimal degradation of exhaust-gas characteristics and performance if properly maintained.

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AN OVERVIEW OF THE EFFECTS OF DIESEL ENGINE MAINTENANCE ON EMISSIONS AND PERFORMANCE

By Robert W. Waytulonis[1]

ABSTRACT

Diesel engines are a source of mine air contamination and can be a safety hazard if misused. Safe and healthful use of diesel-powered equipment depends primarily on proper maintenance of the engine, rapid dilution of the exhaust, adequate ventilation to dilute and remove the exhaust from the mine and to restore oxygen used in the combustion process, and a mine air monitoring program to insure pollutant concentrations are below Federal standards.

The objective of this paper is to outline the diesel engine maintenance practices affecting emissions and performance. This information is based on research sponsored by the Bureau of Mines, which investigated current use patterns of diesels in underground mines and the effects of engine maintenance on exhaust emissions. The paper is organized so that practical maintenance recommendations appear in a form that can be readily applied by a mine operator.

The major findings essential for safe equipment use and long engine life are use indirect injection engines, read and apply the information in the equipment manuals, shut down engines when ventilation is interrupted, use low-sulfur fuel, keep all fluids entering the engine clean, do not overheat engines, do not idle longer than 5 min, do not lug the engine, keep the fuel-to-air ratio within specifications, and shut down engines if black smoke appears in the exhaust.

If the maintenance practices described in this paper are enacted, reduced emissions will result, thus improving the air quality in areas where diesel-powered equipment is used. Additionally, these practices also reduce the chance of accidents occurring because of equipment failure, or fire and explosions, thus mine safety is improved.

INTRODUCTION

Diesel-powered equipment was first introduced into U.S. underground metal and nonmetal mines in 1939 (*1*),[2] and today they are heavily relied upon to move personnel, materials, and ore. Use of diesels in underground coal mines has steadily increased from less than 200 units in 1973 to about 1,200 units in 1985 (*2*). A historical perspective of the Bureau's research on diesels in underground mines is presented in Bureau reports (*3-4*).

Diesel equipment has disadvantages that must be overcome to ensure that the equipment does not present additional hazards in the mine environment. Diesel engines are a fire and explosion hazard (*1, 5-6*) because of their high surface and exhaust temperatures, and the possibility of engine backfires. Additionally, diesel exhaust is a source of noxious gases and particulate matter (*1, 5*), which must be controlled to ensure a healthful work environment.

The increased use of diesels, and the concern for the safety and health of miners, led the Bureau of Mines to sponsor research with the objective of defining current use patterns of equipment, and relationships among engine

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[2]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

conditions, maintenance practices, and emissions (*7*). Additional in-depth data analysis (*8-9*) was undertaken, which further defined the effects of maintenance on exhaust emissions and time in service.

One way to ensure safe operation and reduce emissions is to perform regular engine maintenance. Although it has been recognized for some time that properly adjusted engines and ventilation were necessary for safe operation, the objective of this paper is to outline the diesel engine maintenance practices affecting emissions and performance in a way that is useful to the mine operator.

BACKGROUND

DIESEL ENGINE OPERATION

All diesel engines operate on the compression-ignition principle in which air is compressed and liquid fuel is injected under high pressure in the form of a spray. This mix of fuel and air ignites by the heat of compression, resulting in power output from the engine.

Diesel engines are either naturally aspirated (NA) or turbocharged (TC). In NA engines, air is taken in from the atmosphere without external assistance. The amount of air taken in depends on engine speed. In TC engines, exhaust energy is used to power a turbine air compressor that increases the amount of air inducted per piston stroke. The amount of fuel injected determines the power output.

An engine's fuel-air (F-A) ratio is the mass of fuel consumed divided by the mass of air. For each gallon of fuel, approximately 12,500 gal of air is required. An F-A ratio of about 0.01 occurs at idle; at high power output the ratio is closer to 0.05. The chemically correct F-A ratio is 0.067. This is achieved when the correct amount of fuel is injected to chemically react with all the available oxygen in the combustion chamber. Because of incomplete mixing of the fuel with air, it is impractical to operate at this condition and, therefore, all diesel engines operate fuel lean (or air rich), making it a comparatively low-emission power source.

DIESEL ENGINE EMISSIONS

The majority of the gaseous emissions are composed of oxygen, nitrogen, and water vapor. A small percentage of the total is made up of the products of incomplete combustion, i.e., carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), oxides of nitrogen (NO_x), oxides of sulfur (SO_x), and exhaust particulates (smoke or soot). Although small by comparison to the total exhaust volume, these pollutants are important because of the large amount of exhaust flow and the limited fresh air available for dilution in underground mines. Typically, a 100-hp engine will emit in excess of 1,000 ft^3/min of exhaust at full speed. Measures must be taken to minimize worker exposure to these contaminants.

Diesel exhaust-gas composition is related chiefly to the F-A ratio. There is a range of F-A ratios within which the generation of CO is relatively low (*5, 10*). When any diesel engine is adjusted for maximum power output, the F-A ratio is in the rich range. The volume of CO and objectional gases, particularly NO_x, are affected both by the F-A ratio at which the engine is operated and the design of the combustion chamber.

An important product of incomplete combustion is particulate emissions, which are composed primarily of small carbon particles with absorbed HC's and other gases. Different types of particles are emitted from diesel engines under different modes and operating conditions. About 95 pct, by mass, of the smoke particles are submicrometer in size (*11*). These types of particulate emissions are

1. *White smoke.*—Results when the engine is cold or under low load. Liquid particles appear as white clouds of vapor emitted under cold starting, idling, and low loads. These consist mainly of water vapor, unburned fuel, and a small portion of lubricating oil (*12*). These white clouds disappear as the load is increased and the engine warms.
2. *Black smoke (soot).*—Is a sign of overfueling or a rich F-A ratio. Soot or black smoke is unburned carbon particles emitted as a product of the incomplete combustion process, particularly at maximum loads (*12*).
3. *Otherparticles.*—White and/or blue-black smoke particles result from lubrication oil finding its way into the combustion chamber because of wear or leaks. Typically the oil passes by worn valve guides and piston rings.

REGULATIONS

Title 30 of the Code of Federal Regulations (*13*) contains the health and safety regulations governing diesels in mines. Under part 32 (*14*), CO emissions are regulated to 2,500 ppm in the undiluted exhaust and 3,000 ppm under part 36 (*15*). Once an engine is submitted by a manufacturer to the Mine Safety and Health Administration (MSHA) for certification, the maximum F-A ratio, whereby these CO values are not exceeded, is determined and set. Next, the engine is run throughout its operating range and NO_x, CO_2, and CO are measured. The quantity of air required to dilute each pollutant to less than its threshold limit value (TLV) is calculated to establish the ventilation rate for the engine. NO_x is usually the pollutant that governs the amount of ventilation required. For NA prechamber engines, the worst operating condition for NO_x is usually at part load-peak torque speed. Exhaust particulate emissions, per se, are not regulated; however, these regulations state that equipment should be shut down when "black smoke" appears.

An important determination made during certification testing by the MSHA is the maximum allowable fuel-injection rate needed to avoid excessive generation of CO. The results of engine tests are used to determine maximum fuel injection rate at or below which CO can be controlled by a reasonable ventilation rate and smoke is essentially eliminated. This fuel rate must be adjusted to the altitude at which the engine will be operating (*5*).

DIESEL ENGINE MAINTENANCE

The objective of diesel engine maintenance is to keep engines in good operating condition to maximize productivity and engine life. Once equipment is put into operation, it is the responsibility of the mine operator to keep it in good condition. Preventive maintenance, periodic repairs, and adjustments are all part of a basic maintenance program. Maintenance can prolong or restore near-original efficiency of the engine (*16*).

A brief discussion of the six major systems pertaining to the maintenance of diesel engines used in underground mines follows.

AIR INTAKE SYSTEM

The high compression ratios and close tolerances of diesel engines require that airborne particles be removed from the large volumes of air consumed, in order to prevent abrasion of internal engine surfaces. This requirement demands a well-maintained air intake system.

Dust-laden mine air causes intake air filters to become filled with dust, creating a restriction that may exceed the manufacturer's recommended limit. Intake air filters should be replaced when the pressure drop across the filter exceeds the manufacturer's specification, usually 20 to 25 in H_2O. A dirty intake filter, if not quickly replaced, will result in increased emissions and decreased performance. Loose clamps, small cracks in hose or piping, poorly connected slip joints, or defective seals must be repaired to keep out dirty air.

Installation of intake restriction indicators downstream of the air cleaner is recommended. However, installation should not compromise permissibility features on approved equipment. Equipment operators should carry spare filter elements for replacement when the gauge indicates a saturated filter. Used filter elements should be discarded. Not all air intake system failures can be detected by pressure drop indicators, e.g., a broken intake air duct or punctured filter will not be detected. The best method presently available for detection of these failures is a visual inspection of the air intake system.

Premature engine failures are often traced to dust intake. Dual element air filters and proper service intervals provide an excellent defense.

COOLING SYSTEM

The loss of engine cooling leads to scuffed cylinder walls and pistons, cracked heads, and burned valves. These conditions directly affect emission production and output power. A liquid-cooled engine relies on transfer of heat from the coolant to the radiator, and from the radiator to ambient air. Internal coolant passages of the engine and radiator must be kept free of mineral and rust deposits for effective heat transfer. Mine water is generally high in minerals and salts, rendering it unfit for use in engine cooling systems (*17*). Ideally, a 50-pct mixture of distilled water and antifreeze should be used. Not only necessary for cold weather operation, antifreeze will prevent rust formation and also provide lubrication for the water pump, and increase the boiling temperature of the coolant.

Air-cooled engines reject heat via cooling fins, which are an integral part of the engine. During normal operation these fins become coated with oil and dust, which bakes on to form an insulating layer. If this layer is allowed to build on the engine, overheating will result. Periodic steam or pressure cleaning will delay development of this condition.

Whether the engine is air- or liquid-cooled, the causes of overheating of diesels include the following:

1. Dirt deposits blocking airflow through the radiator or bent cooling fins; damaged fins and shrouds reduce airflow and contribute to overheating.
2. Engine faults, such as retarded fuel injection timing and overfueling. These increase combustion and exhaust-gas temperatures, putting additional heat load on the cooling system.
3. Incorrect coolant solution; a 50-pct antifreeze and distilled water solution is optimum. Also, internal scale build-up caused by use of water with high mineral content reduces cooling system performance.
4. Slipping fan and pump belts, which reduce air and coolant flow.

FUEL QUALITY AND HANDLING

DF 2 (sometimes designated 2-D) diesel fuel should be used whenever ambient temperatures are above the cloud point (approximately 37° F) of the fuel. DF 2 possesses better lubrication properties than DF 1 (1-D) and tends to extend fuel injection system component life. Additionally, DF 2 has a higher energy content per gallon (*18*).

Sulfur content should be as low as possible, preferably less than 0.2 pct by weight. If the sulfur content of the only available fuel is known to be above 0.2 pct, the engine oil should be changed more frequently. The sulfur present in all diesel fuels directly affects the emissions of particulate sulfates and accelerates engine wear (*19*). Much of the sulfur will pass through the engine and reappear as SO_x emissions (*20*). Sulfur in the fuel combines with moisture in the engine to produce sulfuric acid, which is corrosive to parts, bearings, and seals. The quality of fuel delivered to the mine should be controlled by placing specifications on the purchase order.

Fuel contamination causes accelerated engine wear, because of extremely close tolerances, often 0.00008 in, of the injection equipment (*21*). Most fuels hold a small amount of sediment and abrasives in suspension that should be removed. Most engines include one or more filters to protect the injection system from dirty fuel. In addition to routine cleaning or replacement of filters, there should be periodic cleaning or draining of the vehicle fuel tanks. Proper fuel handling can reduce fuel contamination. It is important to minimize the number of fuel transfers and to store the fuel in tightly sealed containers that are clearly labeled.

Water is a common contaminant. It condenses in storage tanks, especially if the tanks are partially full and are at high humidity, or water may be in the delivered fuel. The best method to remove water is to install fuel-water separators on all equipment, minimize fuel transfer points, and keep fuel storage tanks full. There are three places where a fuel filter and water separator would be used in a good fuel handling system: (1) at the outlet of the surface storage tank, (2) at the pump side of the portable fuel trailers, and (3) on the engine.

FUEL INJECTION SYSTEM

The engine fuel flow rate is usually set at the factory or at an authorized service shop, and is based on the MSHA horsepower and ventilation rating. Seals to discourage tampering are installed on the fuel pump because of the critical relationship between F-A ratio and emissions. Operation of any diesel engine at F-A ratios greater than 0.05 produces excessive quantities of CO and particles that requires an impractical ventilation rate (*5*).

The function of the injection nozzles is critical to good fuel economy. Injectors act to mechanically atomize the liquid fuel by forcing it under very high pressure through small holes at a certain time in the combustion cycle. Whatever happens during operation to alter spray pattern, injection timing, or fuel charge, will alter engine performance and emissions. If the nozzles are dirty, improperly adjusted, or worn beyond tolerances, the engine will waste fuel. Very small particles of dirt in the fuel can damage the injectors, and can result in increased CO, HC's and particulate emissions. Carbon buildup on injector tips results in loss of power and requires more fuel to accomplish a given amount of work. Improperly adjusted nozzle opening pressures can affect the spray pattern, resulting in a poor F-A mixture and loss of fuel efficiency. Malfunctioning injectors cause smoking, uneven engine operation, and high CO and HC emissions (*7-9*).

If a fuel injector problem is the suspected cause of excessive smoke, the following items should be inspected: fuel injector and nozzles for leakage, opening pressure, nozzle valve sticking, spray pattern, and correct nozzle part number.

To check injectors, they must be removed and placed in a special test fixture. A simple apparatus can be used to check spray pattern and nozzle opening pressure. More sophisticated bench-test equipment should be used by specially trained technicians to flow-balance and match injector delivery rate, spray pattern, and penetration. It is advisable to inspect injectors on a routine basis, as specified in the engine manual (*22*).

Unless manually adjusted, diesel injection timing generally remains constant over long service intervals. Timing could be improperly adjusted at the factory or by a serviceperson, or otherwise altered to yield higher output horsepower. Engine manufactures usually allow a 1° deviation from the recommended setting.

Induced fault testing has shown that injection timing (advanced or retarded) will affect all emissions (*7-9*). CO will increase whether timing is advanced or retarded from the factory setting, particles will tend to decrease slightly with retarded timing and increase with advance timing, and NO_x increases when timing is advanced and decreases when it's retarded. Once properly set, fuel injection timing does not require frequent adjustment.

LUBRICATION SYSTEM

Failure of the lubrication system usually results in catastrophic engine failure. System failures are often caused by a component failure, such as seized bearings, lubricant breakdown or contamination, or engine overheating. To control these failures it is important to keep the crankcase lubricant at the recommended level, free of solid and liquid contamination, and maintain the engine's cooling system. If an engine becomes excessively hot, the oil viscosity is lowered and oil consumption increases, resulting in loss of lubricity and accelerated engine wear (*23*).

EXHAUST SYSTEM

Excessive exhaust gas restriction or backpressure can result from either a partially plugged water scrubber, flame trap, catalytic converter, or dented exhaust pipe. Engine manufacturers generally consider 2 to 3 in Hg to be the acceptable limit. Excessive backpressure causes increased emission of some pollutants and decreased power output. Periodic inspection and cleaning of the exhaust system components will preclude excessive backpressure.

RECOMMENDATIONS

The following is a list and description of 10 recommendations for safe use of diesel equipment in underground mines:

1. *Use indirect injection (IDI) combustion chamber engines.* The first step a mine operator can take to reduce emissions is to select prechamber or IDI engines, which have lower emissions than direct injection (DI) engines of equivalent power. These engines emit about one-half as much CO and particle emissions as do DI engines, thus requiring less ventilating air.

The DI combustion chamber design is used almost exclusively in over-the-road and other surface vehicles. It has an advantage of slightly less fuel consumption, but has a penalty of higher levels of pollutants in the exhaust.

Figure 1 is a plot of the ventilation requirements for three engines in the 135 to 150-hp range. The Isuzu QD 145 is a DI engine requiring 156 (ft^3/min)/hp. The Deutz F6L 413 and the Caterpillar 3306 PCNA are IDI engines requiring 86 and 103 (ft^3/min)/hp, respectively. These engines have been tested and certified by MSHA for use in underground mines. It is clear that the IDI engines have an important advantage by requiring significantly less ventilation air to dilute their exhaust pollutants to less than the current TLV's.

2. *Read operation and maintenance manuals.* The operator's manuals should be made required reading to learn the correct operation of the vehicle and engine. The engine manual should be followed for service intervals and other vital information. Manufacturers have developed engines to be a balance between performance, durability, and emissions. Deviation from proper servicing methods and intervals will result in degraded performance and emissions, and shortened engine life.

3. *No ventilation, no operation.* If ventilation is interrupted for any reason, all diesel equipment should be shut down until fresh airflow is resumed. If more than one diesel is used in a split of air, 100 pct of the largest ventilation air quantity requirement plus 75 pct of the second largest ventilation requirement, plus 50 pct each of the remaining diesel unit's requirement, determines the total quantity of ventilating air for the diesel equipment.

4. *Use low sulfur fuel.* It is especially important to limit the amount of sulfur in the fuel. Low sulfur content is important for maximum engine life, lubrication, and fuel economy. Also, sulfate emissions are controlled by limiting the amount of sulfur in the fuel.

5. *Keep it clean.* Dirt is very detrimental to engines. Regular checks and maintenance of the machine's air induction system are necessary to peak engine performance. The diesel consumes large volumes of air to function. If the volume of air is restricted or insufficient, the engine will perform poorly and emit large quantities of particulates and other pollutants, which indicate that the fuel is not burning completely. One of the most common causes of excessive and dark smoke is intake air restriction caused by plugged air cleaners. The most effective way to improve engine life is to frequently and correctly service air cleaners.

6. *Keep it cool.* Engine overheating is a frequent cause of premature engine failures. Insure that lubrication oil is the correct viscosity and kept at the recommended level. Keep all heat exchangers free of accumulated dirt and open to circulating air.

7. *No extended idling.* An established tradition of diesel engine operation is idling engines for long periods, which wastes fuel. Fuel consumption is not the only problem; engines at idle tend to overcool with operating temperatures well below ranges recommended by the manufacturers. This results in incomplete combustion, which leads to varnish and sludge formation. Unburned fuel washing down cylinder walls removes the protective film of lubricant and results in accelerated wear (*23*). Once fuel mixes with crankcase oil, dilution further reduces effectiveness of the lubricant. Planning for cold starts and shut down of engines for work breaks is now regarded as much more economical and less damaging to engines than prolonged idling. Engines should be shut down if idle periods are expected to exceed 5 min.

8. *No lugging.* Engine lugging or operating the engine at high load-low speed will significantly increase CO and particle emissions, and increase operating temperatures. Lugging should be avoided in order to operate at the lowest CO and particulate emission range. Operators should shift gears to operate the engine at a higher rotational speed or lessen the engine load, rather than lug the engine. Figure 2 illustrates this by showing typical horsepower curves at 1,200 and 2,000 r/min. If a certain amount of power is required to perform the task at hand (as indicated by the dotted line intersecting the y-axis),

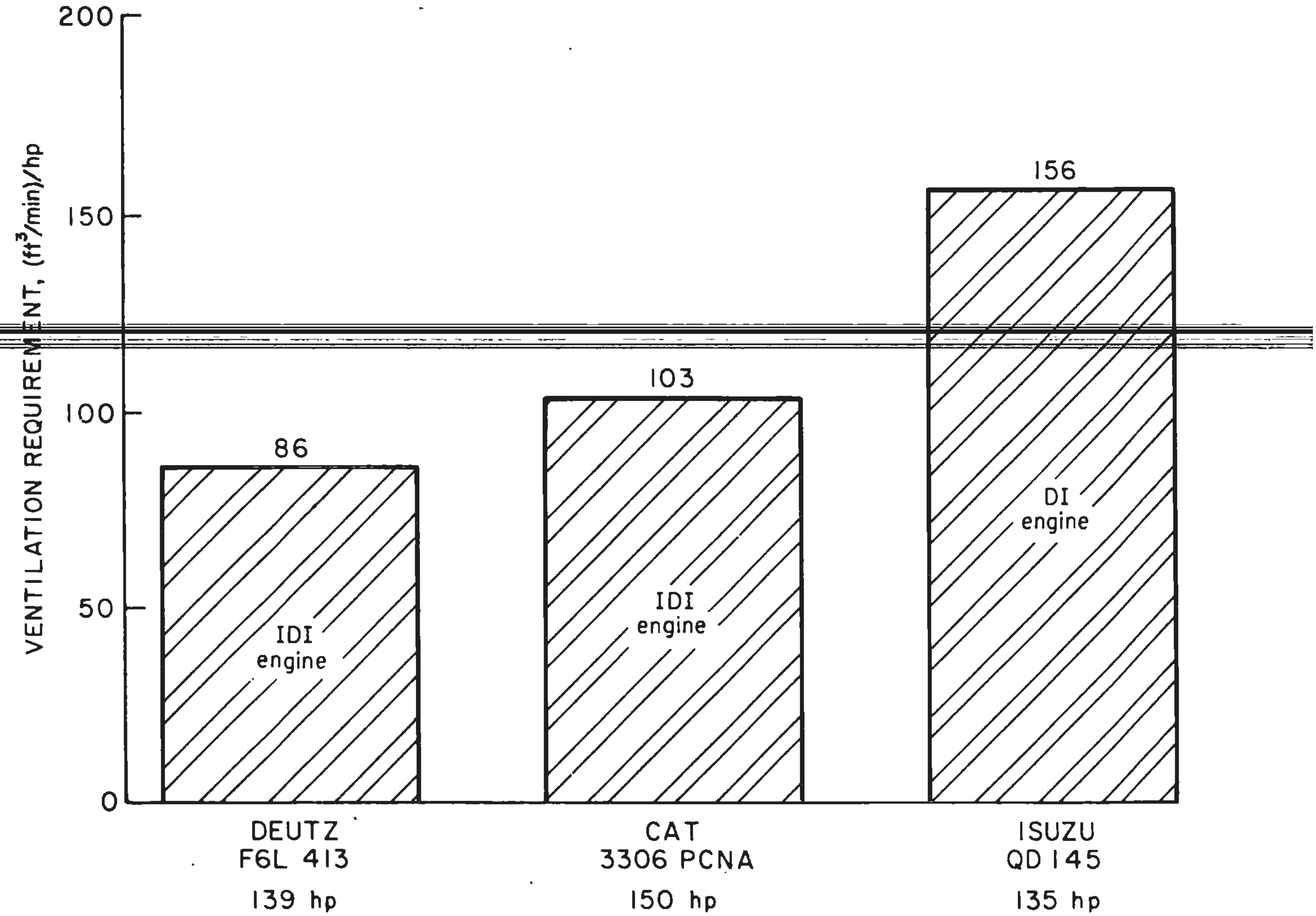

Figure 1.—Ventilation requirements for one direct (DI) and two indirect (IDI) injection engines in the 135- to 150-hp range.

this level of power can be attained at two different F-A ratios. By operating at the lower F-A ratio of 0.032 at 2,000 r/min, CO, particulate, and exhaust-gas temperatures will all be lower than at the corresponding F-A ratio of 0.05 at 1,200 r/min.

9. *No overpowering.* The fuel injection pump governor must be set according to manufacturer's specifications. Engines have a specific engine high idle, full load, and, in some cases, torque converter stall speeds. The governor setting should never be set to exceed these limits. The engine's F-A ratio is set and locked, and should remain that way until adjustment by an authorized person. Derating the engine limits the maximum fuel rate and promotes oxidization of HC's and CO to H_2O, and more complete burning of the fuel.

Fuel system tampering sometimes occurs in an attempt to increase output horsepower. Changing the calibration of the fuel pump or installing larger capacity injectors affects the F-A ratio and results in greater pollutant production and possible engine damage. These changes increase combustion pressures and engine temperatures. The increase in combustion pressure will be felt throughout the entire engine. More stress is placed on liners, rings, pistons, bearings, valves, camshafts, and cam followers. The types of damage that can eventually occur are cracked or burned pistons, scored liners, accelerated bearing wear, broken or sticking valves, and broken rings (7). The damage caused by increased combustion pressures may not be apparent for some time.

Air density decreases with an increase in elevation; therefore the F-A ratio will change as altitude increases. If the engine is to be operated at altitudes above 1,000 ft, the fuel rate must be reduced by 3 pct for each 1,000 ft above 1,000 ft. An engine operating at 7,000-ft elevation, for example, would be limited to consume 18 pct less fuel at full load-rated speed. An engine adjusted for sea-level operation, but operating at 4,000 ft, is overfueled by about 10 pct, and if operating at 7,000 ft, is overfueled by 20 pct.

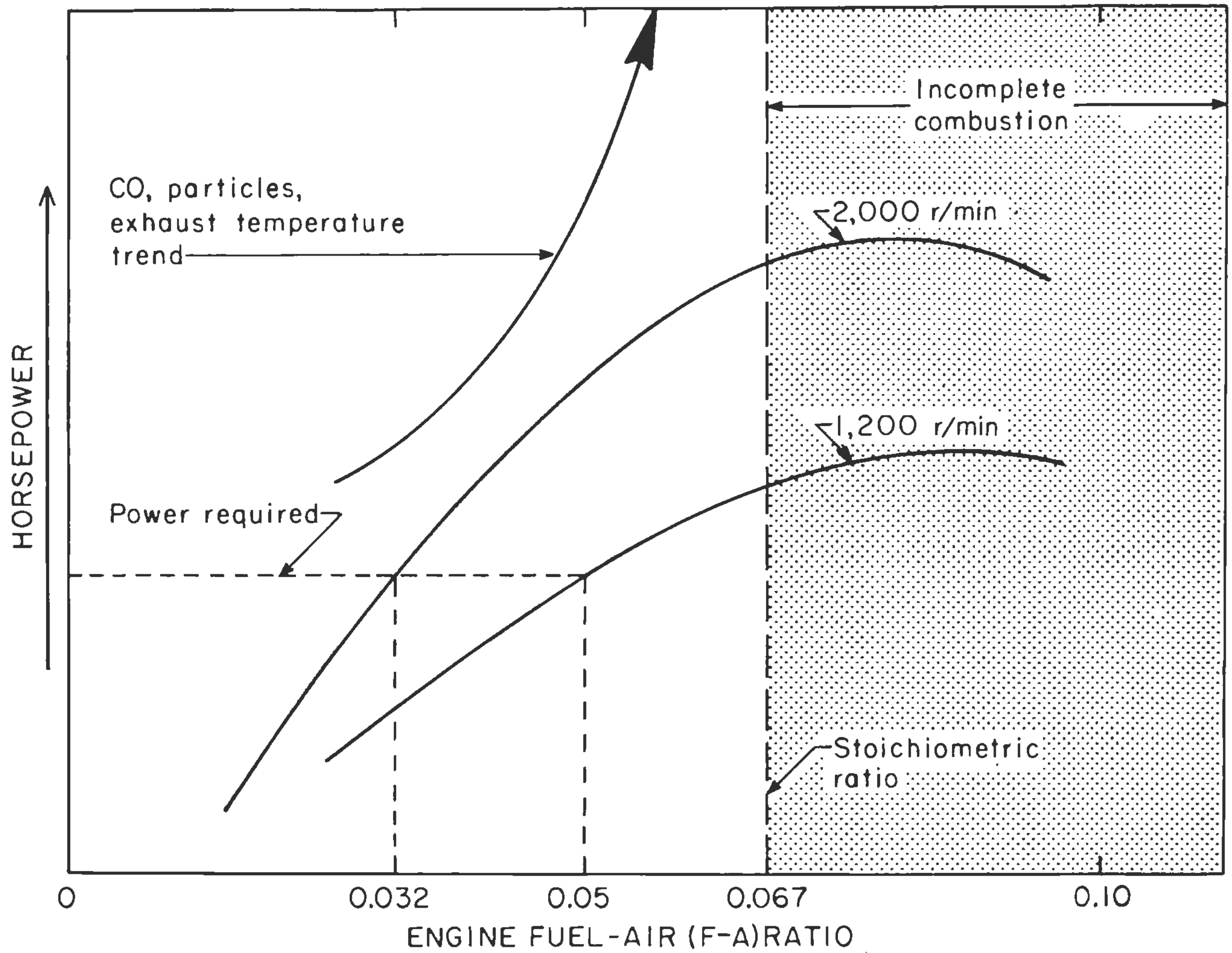

Figure 2.—Typical horsepower curves and corresponding fuel-air ratios for 1,200 and 2,000 r/min.

Only a trained and certified person should set fuel pumps and once set, leave it alone. Failure to derate will greatly increase fuel consumption and exhaust pollutants.

Turbocharged engines can exceed 1,000-ft altitude before deration due to the excessive quantities of air available from the turbocharger. For example, a caterpillar 3306 PCTA engine can operate up to 6,500-ft elevation before deration is required.

10. *Beware of black smoke.* Dark smoke from a diesel engine exhaust is a result of an improper F-A ratio. This is a dangerous condition because of high CO and particles in the exhaust. Equipment emitting black smoke should be shut down and taken to a maintenance area for diagnosis and repair.

Black smoke may indicate incorrect governor setting, air cleaner restrictions, incorrect fuel delivery, improper injection pump timing or cam valve timing, defective injectors or nozzles, poor compression, or incorrect timing advances.

CONCLUSIONS

Exhaust pollutants can be held to very low levels through proper and sustained engine maintenance. A good engine maintenance program will reduce the diesel's burden on the mine ventilation system and help sustain good air quality. Additionally, the added benefit of high equipment availability and good performance with minimum fuel consumption can be realized.

The safe and healthful use of diesel-powered mine equipment can be promoted by adherence to the following four basic guidelines:

1. Use equipment approved by MSHA; this assures that equipment workmanship and materials pertinent to maintaining permissibility, have been scrutinized, and a safe maximum fuel rate and corresponding ventilation rate has been established for the vehicle.

2. Perform proper and timely engine maintenance specified by the manufacturer; this is essential for satisfactory engine life and performance, and minimum fuel consumption and emissions.

3. Assure adequate ventilation; this is necessary for good air quality in areas where diesels are operating, to dilute and remove the exhaust gas, and replenish oxygen.

4. Perform regular air monitoring; contaminants such as CO and total respirable dust must be regularly sampled to determine if air quality is being maintained at acceptable levels.

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CARBON DIOXIDE AS AN INDEX OF DIESEL POLLUTANTS

By J. Harrison Daniel, Jr.[1]

ABSTRACT

The underground use of diesel equipment in hard-rock mines is well established, and the use of the equipment in underground coal mines is increasing. As the number of diesel units and their power ratings increase, concern over the health effects of the exhaust emissions becomes more significant. A monitoring methodology to assess underground air quality in mines using diesel equipment is needed along with the development of emission control technology. The Bureau of Mines has been developing a methodology that provides an assessment of air quality by measuring only ambient carbon dioxide (CO_2) concentrations after the relationships between CO_2 and the other pollutants have been established. The concept involves determining the ratios of the other pollutants to CO_2 under actual equipment operating conditions, using an air quality index to establish a single CO_2 concentration below which other pollutants are considered below harmful levels, and verifying if engine operating conditions have changed such that maintenance is required.

INTRODUCTION

The exhaust pollutants emitted from the combustion process of diesel engines represent a principal concern over the use of the equipment in underground mines. Because of increasing mechanization, underground mining has become less dependent on large, concentrated work forces. Many operations have a few persons working in many different and scattered sections, which makes the mobility of diesel-powered equipment very attractive in mine feasibility and design studies. The versatility of the equipment is also an advantage since a single piece of equipment can be modified to perform the many different functions required of loading and hauling of both workers and supplies.

The issue of proper control of diesel exhaust emissions is complex. The operating mode and condition of the engine, the mine environment, and the equipment operator's habits all influence the concentration and composition of the exhaust emissions. The Mine Safety and Health Administration (MSHA) in April 1986, along with the National Institutes for Occupational Safety and Health (NIOSH) and the Bureau of Mines completed a study of the health and safety implications of the use of diesels in underground coal mines. This interagency study did not find conclusive evidence that indicates that uncontrolled diesel exposure poses no health risk, and states that sensitivity toward this issue and a conservative approach toward control of diesel exhaust exposure is warranted (*1*).[2]

It is not practical to measure all the constituents of diesel exhaust in the underground mining environment. A selective monitoring methodology is therefore required that will accurately assess the overall air quality when diesels are used. The Bureau has been developing a monitoring methodology that requires only the measurement of CO_2 to assess the mine atmosphere. Once the relationship between the other pollutants and CO_2 has been established for the specific equipment and mine conditions, CO_2

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[2]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

becomes a surrogate for the other pollutants. CO_2 remains a reliable indicator of overall air quality as long as the equipment operating conditions and mine ventilation do not significantly change. The monitoring methodology makes use of an air quality index to provide a relative, numerical value to assess air quality. This index combines the individual and combined health effects of the pollutants.

References dealing with underground mining operations have suggested that CO_2 concentrations could allow accurate prediction of the levels of other exhaust contaminants (*2-4*). Other references have described the monitoring methodology used with the air quality index (*5-7*). The feasibility of using the CO_2 monitoring methodology with the air quality index has been demonstrated in three mines in the United States and two in Canada—Homestake gold mine, Lead, SD (*8*), White Pine copper mine, White Pine, MI, and Brushy Creek lead-zinc mine, Vibirnum, MO (*9*), Ojibway salt mine, Windsor, Ontario, Canada (*10*), and Sullivan lead-zinc mine, Kimberley, British Columbia, Canada (*11*).

NEED FOR A MONITORING METHODOLOGY

The policies of various organizations are split concerning the underground use of diesel equipment. This difference is popularly termed the diesel debate. The United Mine Workers of America is opposed to the present use of diesel equipment in underground operations, while the American Mining Congress, an industry association, supports the use of underground diesel equipment (*12-13*). Complicating the issue is the fact that attempts to control only one of the emission pollutants can often result in an unacceptable increase in the concentration of a number of the remaining pollutants. It is necessary to control all the pollutants below harmful concentrations. The operating mode and condition of the engine, the mine environment, and the equipment operator's habits all influence the concentration and composition of the exhaust emissions. The proper control of diesel exhaust emissions is thus a sensitive and complex issue.

Bureau studies in the 1950's concluded that diesels could be operated safely from an air quality perspective, provided the engine is properly maintained and adjusted, the tailpipe exhaust flow is immediately diluted, and adequate positive mechanical ventilation is provided to dilute and remove the exhaust from the mine and to restore oxygen used in the combustion process (*14*). To assure that these conditions are fulfilled and to address the complex operational variables that influence exhaust concentration and composition, a monitoring methodology is needed that will not only assess the worker's atmosphere where diesels are operated, but will also evaluate the mine ventilation and equipment condition.

In April 1986, as a result of a joint diesel task group, MSHA recommended that any requirements concerning air quality should consist of an approach that integrates the control of emissions through mine ventilation practices and periodic sampling of both the workplace and equipment (*1*). It was further recommended that the three components affecting air quality—the emissions, the ventilation, and the sampling strategy—are interrelated and must be considered as a system.

The monitoring methodology is needed even with the development of emission control systems mounted on board the mobile equipment. Emission control systems by themselves do not insure compliance with mine atmosphere regulations because specific uses of the equipment or conditions under which the equipment operates may exceed the design capabilities of the emission control device. The controls that will be developed to reduce contaminant levels may also require periodic maintenance and inspection to ensure that they are functioning properly. It is also likely that these on-board controls will produce a back pressure on the combustion process of the engine, which may adversely affect both performance and emissions.

Finally, it is essential to consider the engine type, the task the equipment performs, and the specific mine conditions under which the equipment operates in selecting emission control alternatives. The degree and the sophistication of the emission controls required for each unit are a function of these parameters. In some sections of underground mines, mine ventilation may be adequate to allow the safe use of properly maintained equipment without emission controls; however, in other sections mine ventilation may not be adequate to allow safe operation, depending on the task and the number of units operating. Each condition must be investigated for proper worker protection. An effective monitoring methodology will determine the degree of control required.

THE MONITORING METHODOLOGY

GENERAL

The monitoring methodology described provides an assessment of air quality when underground diesel equipment is used by measuring only ambient CO_2 concentrations on board the equipment after the relationships between CO_2 and the other pollutants have been determined. It also provides a means to evaluate both the adequacy of mine ventilation to remove exhaust pollutants and the operating condition of the engine. Since it is based on pollutant ratios established under site-specific mine conditions, once it has been established it does not have to be corrected for altitude effects. The methodology has evolved from Bureau in-house research and contract work with Michigan Technological University in Houghton, MI (*2, 15*).

The methodology involves the following three phases: (1) establishing pollutant characteristic curves for specific diesel equipment and ventilation conditions that illustrate the relationship between the concentration of the exhaust pollutants and the concentration of CO_2 measured at the same location and over the same period of time, (2) using an air quality index to establish a single CO_2 concentration below which the other diesel pollutants are considered below harmful levels, and (3) measuring periodically the tailpipe emissions of the engine to verify if engine operating conditions have changed. The concepts involved in the methodology will be developed in the following subsections.

CO_2 AS IN INDICATOR OF OTHER POLLUTANTS

Measurements of CO_2 concentrations can provide a basis for estimating concentrations of the other combustion products from diesel engines—CO, NO, NO_2, SO_2, and particulate matter. The amount of CO_2 produced during the combustion of liquid hydrocarbon fuels, such as diesel oil, is directly related to the amount of fuel burned. The power output and/or loading of the compression ignition (diesel) engine is controlled by the amount of fuel that is directly injected into the cylinders. The power at any given moment is related to that fuel consumption by a nearly constant factor, the brake specific fuel consumption (bsfc) given in pounds per horsepower-hour. The precise metering of the fuel by the fuel injectors, which individually control each cylinder, accounts for the nearly constant bsfc. In addition, the carbon content of the various engine-quality fuels is very constant so that the CO_2 concentrations in the exhaust vary in nearly direct proportion to the engine duty cycle and load. The CO_2 concentrations are also less affected than those of the other pollutants by improper adjustment of the fuel system, combustion chamber design, and imperfections in fuel injection nozzles.

CO_2 is present in the exhaust gases in the highest concentration of any of the pollutants; therefore, making it easier to detect and measure that many of the gases. Table 1 shows the combustion products of diesel fuel on a volumetric basis (*16*). The combustion products shown are for complete combustion of the fuel with the chemically correct ratio of air to fuel to completely oxidize all the fuel. The threshold limit value (TLV) of CO_2 is 0.5 pct, or 5,000 ppm by volume. This value is 2,500 times the TLV for SO_2, 1,667 times the TLV for NO_2, 200 times the TLV for NO, and 100 times the TLV for CO_2 as shown in table 2 (*17*).

Table 1.—Products of combustion of diesel fuel, volumetric basis, percent

Complete combustion products:	
Nitrogen (N_2)	73
Carbon dioxide (CO_2) plus oxygen	13
Water (H_2O)	13
Incomplete combustion products (pollutants):	
Hydrocarbons (HC)	<1
Carbon monoxide (CO)	<1
Nitric oxide (NO)	<1
Nitrogen dioxide (NO_2)	<1
Carbon (C) or smoke	<1
Sulfur dioxide (SO_2)	<1
Total	100

Table 2.—1986-87 ACGIH TLV's for selected substances

		TWA[1]	STEL[2]
CO	ppm	50	400
CO_2	pct	0.5	3.0
NO	ppm	25	NAp
NO_2	ppm	3	5
SO_2	ppm	2	5
Dust, mg/m³:			
Coal		[3]2	NAp
Metal-nonmetal		[4]10	NAp

NAp Not applicable.
STEL Short-term-exposure limit.
TWA Time-weighted average.
[1]8- or 10-h shift.
[2]Ceiling limit that is not to be exceeded. Excursions above the TWA up to the STEL are allowed for up to 15 min as long as there is at least 1 h between such excursions.
[3]Respirable size; if >5 pct quartz, the standard is (10 divided by percent of respirable quartz).
[4]Total dust; if >1 pct quartz, the standard is set for the respirable fraction instead and is [10 divided by (percent respirable quartz plus 2)].

There is no TLV specifically for diesel particulates, although the diesel particulate is collected in the 10-mm nylon cyclone respirable dust sampler, which is used to monitor respirable dust on a full-shift (8-h) gravimetric or mass basis. This cyclone sampler, which collects respirable-sized particles without regard to the source of the particles or dust, is used by MSHA to enforce Federal dust standards. The diesel particulate is thus included with the respirable dust TLV or standard. Regulations (*18*) also cite that "abnormal smoke production should be sufficient reason for removing a locomotive from service until this condition has been corrected."

CO_2 is the only stable and nonreactive pollutant in the exhaust that is unaffected to any appreciable extent by time, emission control devices, or engine wear. Typically, CO_2, SO_2, and NO_x (NO and NO_2) accompany CO_2 as combustion products. The production of CO and NO_x can be markedly suppressed, but for a given amount of fuel burned, the production of CO_2 cannot be reduced.

Accuracy of air quality measurements is dependent upon the zero stability and resolution of the instruments, the other airborne contaminants that interfere with the detection principle of the instruments, as well as the purity of the gases used to calibrate the instruments. Because of these impacts on accuracy of measurements, the use of CO_2 measurements to estimate the concentrations of the other gaseous pollutants may give greater accuracy and reliability than direct underground measurements of the concentrations of the other pollutants. This conclusion can be attributed principally to both the difficulties of measuring the very low concentrations (as low as 1 ppm) of the other pollutants in the very humid, dusty, confined, and often hot underground mine environment, and the lack of availability of accurate, portable, commercial instrumentation for these measurements. However, portable and accurate commercial instrumentation to measure CO_2 concentrations in the underground mine environment is available. These portable instruments can be calibrated outside the mine and are not required for continuous, extended operation in the mine environment.

POLLUTANT CHARACTERISTIC CURVES

Pollutant characteristic curves are plots of the individual time-weighted average (TWA) concentrations of diesel pollutants versus the corresponding CO_2 concentrations found at the same location and measured over the same period of time. These plots illustrate the relationship between the concentration of the exhaust pollutants and the concentration of CO_2. There is a separate plot for each pollutant—CO, NO, NO_2, SO_2, and particulate matter. These curves are determined for each piece of diesel equipment and are used to estimate the exhaust pollutant concentrations. After the curves have been established, the exhaust pollutants can be estimated by measuring only the ambient CO_2 levels on board the equipment and reading the pollutant concentration from the curves. A representative curve is shown in figure 1. The operating points shown are TWA measurements of the pollutant measured on board the piece of diesel equipment versus the CO_2 values. The dashed, horizontal line represents a TLV below which the pollutant must be kept. A corresponding limiting CO_2 level above which the pollutant exceeds its TLV is read from the x-axis.

Dilution of each exhaust gas pollutant concentration with fresh air is equal for all pollutants and thus does not alter the ratio of the concentration of the pollutants to each other or to the CO_2 concentration. This ratio of pollutant concentration to the CO_2 concentration is the slope of the curves; hence, the curves ideally represent straight lines that pass through the origin. It is possible that the fuel-air combustion process over a wide range of CO_2 values, that is different fuel rates, will not approximate a straight-line plot. However, over the range of CO_2 values of concern, the mass of CO_2 produced by the fuel-injected, compression-ignited diesel cycle is expected to be directly related to the mass of fuel burned.

The numerical value of the slope is a function of the type of engine and its condition, the exhaust emission control devices, the duty cycle of the engine, the operator's habits, and the mine environment. All these interrelating variables affect the quality of exhaust emissions so that the curves must be determined from actual underground conditions. These curves, once established, will be altered by changes in engine condition. Thus, the periodic assessment of the engine tailpipe emissions to ensure that the

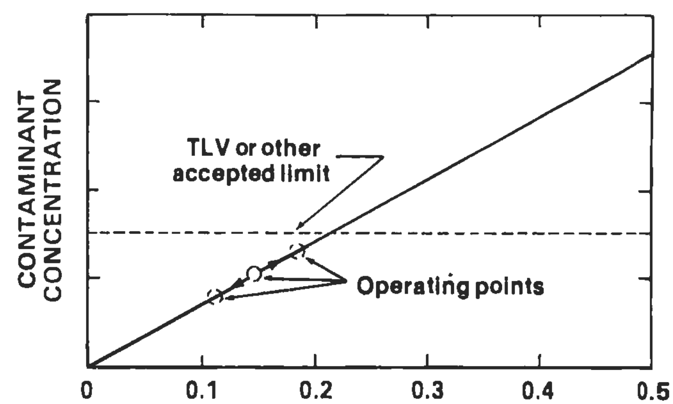

Figure 1.—Pollutant characteristic curve.

engine has not degraded becomes an essential part of the methodology.

If more than one diesel unit is operating in a single ventilation split, a cumulative pollutant characteristic curve can be established for that split, which includes the contribution of all the exhaust pollutants from all units. A fixed-point monitoring position characteristic of the overall air quality of the split can then be used for monitoring purposes.

AIR QUALITY INDEX TO DETERMINE CO_2 CONTROL LEVEL

An air quality index (AQI) is required to establish a single CO_2 concentration at which the other diesel pollutants are considered below harmful levels. Such an index is necessary to combine the effects of the pollutants into a single number that is used to assess air quality. The index selected is the only one known to have been developed that incorporates the additive effects of the pollutants when found in combination. It was defined in 1978, by Ian W. French and Associates, Ontario, Canada, as a means of quantitatively evaluating underground hard-rock mine atmospheres (*19*). It involves the measurement of five exhaust pollutants, CO, NO, SO_2, NO_2, and respirable combustible dust (RCD), on a TWA basis. This RCD term is an estimate of diesel particulate (carbon-based particles) in hard-rock mines that do not contain carbon in the host rock. The values of the pollutants measured underground are used to calculate a numerical value for the AQI using the following formula:

$$AQI = (CO)/50 + (NO)/25 + (RCD)/2 + 1.5[(SO_2)/3 + (RCD)/2] + 1.2[(NO_2)/5 + (RCD)/2],$$

where the concentration of RCD is expressed in milligrams per cubic meter and all other concentrations are expressed in parts per million. If the concentration of SO_2 or NO_2 is zero, the appropriate bracketed term is omitted. This original 1978 version of the AQI uses the TLV's that were in effect at the time.

In summing the five terms of the equation, the AQI accounts for possible interactions and synergistic effects between the various exhaust components. The value contained in the denominator of each exhaust gas term is the TLV for that exhaust component adopted by the ACGIH in 1978. The TLV for RCD is the value for respirable dust in underground coal mines containing less than 5 pct quartz in the host rock.

French and Associates indicate that an AQI value between 3.0 and 4.0 poses a moderate threat to health, which could be alleviated by personnel protective measures such as respirators or filters. A value in excess of 4.0 indicates a health hazard level and the need for increased ventilation or pollutant source controls to bring the value back to less than 3.0. It is further recommended that these values need to be lowered in mines where the host rock contains over 20 pct quartz, and that an additional term be added to the equation in the case of very dusty mines.

The AQI and values suggested are recommendations based on extensive review of available published data on mine atmospheric contaminant concentrations along with an assessment of scientific and medical knowledge of health effects of the contaminants at the time. This medical knowledge is incomplete with the investigations done to date. In developing the AQI, French and Associates had assumed the public health attitude and approach that it is prudent to reduce all exposures to as low a level as possible, at least until valid scientific data are available upon which more precise limits of exposure can be based.

In 1984, this AQI was modified by French and Associates into a two-part index to resolve criticisms from some health researchers and to include findings from continual review of the world literature relating to the carcinogenicity, mutagenicity, and toxicity of diesel emissions (*20*). The two principal criticisms of the AQI were (1) that the ACGIH recommends that the additive approach for toxic compounds only be used when the components exert their toxicity by similar mechanisms—mainly, the respirable dust and gaseous terms might be considered separately, and (2) that the synergism factors 1.5 and 1.2 for SO_2 and NO_2, respectively, were not supported by scientific evidence. It is now suggested that two independent equations, one for the gases and one for the respirable dust and SO_2 and NO_2 components be used as follows:

$$AQI(gas) = (CO)/TLV \text{ for CO} + (NO)/TLV \text{ for NO} + (NO_2)/TLV \text{ for } NO_2.$$

The AQI(gas) should not exceed 1, and no individual component should exceed its TLV, and

$$AQI(particulate) = (RCD)/TLV \text{ for RCD} + [(SO_2)/TLV \text{ for } SO_2 + (RCD)/TLV \text{ for RCD}] + [(NO_2)/TLV \text{ for } NO_2 + (RCD)/TLV \text{ for RCD}].$$

It is recommended that the AQI(particulate) value should not exceed 2.0, and no single component should exceed its TLV, as dictated by current ACGIH values. If the concentration of SO_2 or NO_2 is zero, the appropriate bracketed term is omitted. These terms are included to address the synergistic effects of the SO_2 and NO_2 with RCD.

An AQI summary graph of all the pollutants showing the contribution of each pollutant to the AQI is obtained from the characteristic curves and the AQI formula. Values are plotted versus CO_2 concentration. A representative graph is shown in figure 2. The plot labeled Total in figure 2 combines the individual pollutant contributions to the AQI and is the summary plot. From this total plot, underground air quality can be assessed from the TWA measurements of CO_2 taken on board the diesel equipment with a portable instrument. Figure 2 shows that a CO_2 concentration of 0.09 yields an air quality of 3, which indicates the upper CO_2 level for safe operation in this representative example.

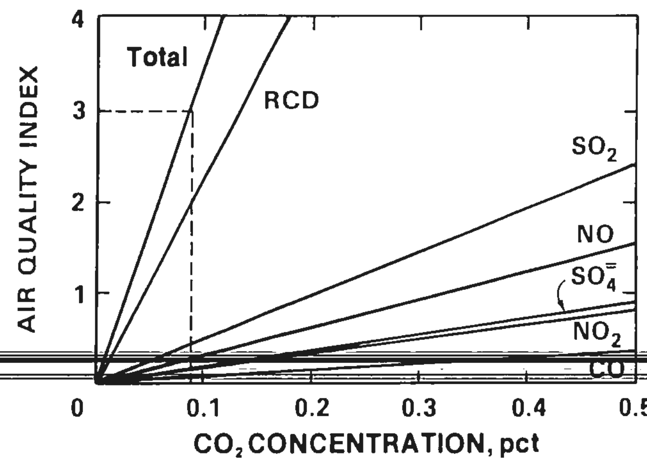

Figure 2.—AQI and contributing characteristic curves.

INDUSTRY USE OF THE METHODOLOGY

For the methodology to be useful to the mining industry, the following conditions are required: (1) it must be reduced to a procedure that mining personnel can implement without continual assistance of personnel trained in complicated instrumentation and analysis techniques, (2) agencies responsible for establishing health standards must approve the AQI and its limiting values, and (3) a method that can be implemented by mine workers to assess engine condition in the underground environment must be developed.

Establishing the pollutant characteristic curves involves specialized and expensive instrumentation, as well as trained personnel to collect and analyze the data. It cannot be done by present mining staffs, but must be accomplished by consultants or service organizations. However, the CO_2 monitoring required to assess air quality after the characteristic curves have been established can be performed by mining personnel with little additional training required.

To evaluate quantitatively the health aspects indicated in the AQI, field investigations are necessary under mine conditions that have a record of the health effects from diesel engine operation. Such epidemiological health effects evaluations at occupational exposure levels would take perhaps 20 to 30 yr to prove any possible adverse health effects on humans. The Canadian Department of Energy, Mines and Resources (CANMET) has examined the AQI concept with the findings of a number of animal diesel-exposure studies. CANMET researchers found that the limits associated with the one-part AQI expression compared very favorably with the health effects observed during two extensive animal studies conducted by General Motors Research Laboratories and by Lovelace Biomedical and Environmental Research Institute (*21*). The studies showed that the animals did not experience adverse health effects at exposure levels below the AQI limit, and did experience adverse health effects at levels greater than the limit. In comparing the one-part AQI with the two-part AQI, CANMET researchers showed a correlation coefficient of 0.953 between the two AQI expressions in testing eight diesel engines. The Bureau of Mines and Michigan Technological University in the United States, as well as CANMET, have been using the AQI concept to compare the relative effectiveness of exhaust control concepts (*22*).

Changing engine conditions due to wear, maladjustments, and improper maintenance will alter the slope of the pollutant characteristic curves so that actual engine pollutant correlations with CO_2 will no longer be representative of the curves established at the original operating conditions. A simple tailpipe exhaust analysis method is necessary to indicate changes in engine condition so that the engine may be restored to its operating condition under which the characteristic curves were established. Because of the widely varying and harsh conditions under which diesels are operated in underground mines, a typical time period for scheduled maintenance is impossible to predict, thus requiring this exhaust analysis. This time period will be determined for each specific case of diesel use and may only involve periodic measurement of the CO_2 level at the tailpipe of the engine. Portable instruments exist for this type of evaluation.

Finally, the cost effectiveness of the methodology depends greatly on the time interval over which the on-board CO_2 measurements need to be taken to assure a healthy environment. This time interval may be thousands of hours if both mine and engine conditions remain constant. This interval will have to be determined as the methodology is evaluated.

CONCLUSIONS

With the attractiveness of considering the use of highly mobile diesel equipment during the planning phase of designing a profitable mine and the continuing research into both exhaust controls and health effects of diesel particulates, the diesel debate is expected to continue. The monitoring methodology described in this paper is being developed as a means to assure the safe use of diesels underground from an air quality standpoint. Phases of it may seem rigorous from an industry perspective, but the complexities will be reduced as it continues to be developed and demonstrated. It is important to note that the methodology is more applicable to mines that operate a number of active diesel sections on a single ventilation split. In mines that employ a single diesel vehicle per split and where the air volume is adequate, the methodology may not be necessary. This is particularly true if the mine is operating under more stringent dust standards, which are applicable when respirable-sized silica or quartz particles are present in the mine air. The methodology described will provide a means to determine the degree of exhaust controls required.

The Bureau is developing an alternative methodology to assess mine air quality in mines using diesel equipment in addition to the concept of monitoring CO_2. This alternative methodology is based on monitoring only the diesel particulate present in the mine atmosphere. The concept is based on the fact that the diesel particulates are predominantly less than 1 μm in aerodynamic diameter; hence, represent the most severe health hazard of the combustion products since they can be inhaled and retained in the lungs. Their small size also allows them to be selectively differentiated from other dusts such as coal, rock, and mineral dusts present in the mine atmosphere. This is particularly important in coal operations where it is important to know whether the carbon-based, respirable-size dust aerosols are diesel combustion products or coal particles so that effective dust control technology can be implemented. This concept of monitoring diesel particulates is described in a paper of Information Circular 9141.

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GLOSSARY

Absorption.—Process whereby gas molecules become dissolved in a liquid.

Adsorption.—Transfer of gas or vapor molecules from the surrounding gas to a liquid or solid surface.

Aerodynamic (equivalent) diameter.—Diameter of a unit-density sphere having the same gravitational settling velocity as the particle in question.

Aerosol.—Assembly of liquid or solid particles suspended in a gaseous medium long enough to be observed and measured, generally about 0.001 to 100 μm in size.

Air monitoring.—Sampling and analysis of air to determine the quantity of pollutants present.

Ambient air.—Surrounding air.

Area sample.—Sample taken in a fixed location assumed to be representative of the area being investigated.

Bimodal size distribution.—Particle size distribution with two distinct maxima.

Breathing zone sample.—Sample taken as close as possible to the point at which the subject inhales air; represents a subject's inhaled air.

Cascade impactor.—Device that uses a series of impaction stages with decreasing particle cut size so that particles can be separated into relatively narrow intervals of aerodynamic diameter; used for measuring aerodynamic size distribution of an aerosol.

Coarse particle mode.—Largest particle mode (>2 μm) in atmospheric particle size distributions, consisting primarily of particles generated by mechanical processes.

Cutoff particle diameter.—Diameter of a particle size distribution for which 50 pct of the particles are removed by the device or stage and 50 pct pass through; also called effective cutoff diameter.

Diesel exhaust aerosol.—Generally referring to the composite particle emitted in diesel exhaust and found in an air suspension.

Diesel particulate matter.—Generally referring to the composite particle produced by diesel exhaust; used in reference to deposits of diesel aerosol, generally on filters used to remove particles from the exhaust gas stream, or filter used to sample diesel aerosol in the mine environment.

Diesel soot.—Deposit of diesel particulate matter on a surface.

Dust.—Solid particles formed by mechanical breakage of a parent material; generally consists of particles of irregular shape, larger than about 0.5 μm.

Emission.—Material being discharged into the atmosphere.

Fibrous filter.—Filter consisting of a mat of individual fibers.

Filter.—Porous membrane or mat of fibers used to collect particles from the air.

Fine particle.—Particle less than about 1 μm in size, consisting of particles in the nuclei and accumulation modes; term used in describing atmospheric aerosols.

Geometric mean.—Refers to a size parameter on a logarithmic size scale where a given ratio of two sizes appears as the same linear distance.

Geometric standard deviation.—Measure of dispersion in a lognormal distribution (always >1).

Impactor.—Device in which aerosol particles with sufficiently high inertia in a deflected airstream are impacted onto a surface.

Mean size.—Average of all sizes, i.e., the sum of all sizes divided by the number of particles.

Median size.—Size with an equal number of particles above and below this value.

Nuclei mode.—Smallest mode in atmospheric particle size distributions, formed by condensation of atmospheric gases or emissions from hot processes, typically containing particles <0.1 μm in size.

Particle.—Small, discrete object; it may be chemically homogenous or contain a variety of chemical species; it may consist of solid or liquid materials or both.

Particle size distribution.—Relationship expressing the quantity of a particle property (mass, surface, or volume concentration) associated with particles in a given size range.

Particulate.—A particle; this term is also used to indicate that the material in question has particle-like characteristics.

Permissible.—As applied to mobile diesel-powered transportation equipment, it means that the complex assembly (mining machine) conforms to all requirements of 30 CFR 36.

Permissible exposure limit.—Allowable concentration of pollutant that may cause harm to humans if exceeded.

Personal sampler.—Device attached to a person in order to sample air in the immediate vicinity.

Preclassifier.—Device that removes particles ahead of an aerosol sensor, usually in a manner similar to the particle removal occurring ahead of the respiratory region of interest.

Ramp.—As applied to engine testing, a gradual increase of engine load with accompanying increases in exhaust temperatures.

Regeneration.—Concerns particulate filters; the process of burning collected particulated matter, thereby reducing the engine exhaust back pressure.

Removal efficiency.—The efficiency of removal of a material from exhaust; i.e., one minus the quotient of the amount of material after removal and the amount of material before removal.

Respirable fraction.—Fraction of aerosol that can reach the gas exchange region of the human respiratory system.

Revertant.—A measure of mutagenicity in bacterial bioassays.

Smoke.—Solid or liquid aerosol; the result of incomplete combustion or condensation or a supersaturated vapor.

Steady state.—An engine operating condition; constant speed and load, maintained long enough so that temperatures, pressure, and emission rates do not change appreciably.

Sulfate.—Any material containing SO_4, usually accompanied by water; in this work, it is sulfuric acid.

Transient.—A sequence of speed and load used to test an engine.

Water-bath exhaust conditioner.—A safety device designed to promote contact between exhaust gas and water for cooling, spark trapping, and flame arresting; commonly called a water scrubber.

ABBREVIATIONS AND ACRONYMS USED IN THIS REPORT

ACGIH	American Conference of Governmental Industrial Hygienists
Cat	Caterpillar, Inc.
CDPF	catalyzed diesel particulate filter
CFR	U.S. Code of Federal Regulations
C_m	mass concentration, mg/m^3
CMB	chemical mass balance
DCI	Donaldson Company Inc.
DDC	Detroit Diesel Corp.
DDEF	disposable diesel exhaust filter
DEA	diesel exhaust aerosol
DERL	diesel emission research laboratory
d_p	aerodynamic diameter of particle or aerosol
DPF	diesel particulate filter
DPM	diesel particulate matter
ECM	electronic-control module
EPA	U.S. Environmental Protection Agency
$E_{50\ pct}$	50-pct collection efficiency point
GMTC-RD	Generic Minerals Technology Center for Respirable Dust
hC	Hydrocarbon
hC-FID	Hydrocarbons as detected by flame ionization
HEPA	high-efficiency particulate air (filter)
IARC	International Agency for Research on Cancer
IC	Information Circular
INAA	instrumental neutron activation analysis
LHD	load-haul-dump
MMD	mass mean diameter
M-NM	metal and nonmetal
MOUDI	microorifice, uniform-deposit impactor
MRE	Mine Research Establishment
MSA	Mine Safety Appliances Co.
MSHA	U.S. Mine Safety and Health Administration
MTU	Michigan Technological University
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
OCC	oxidation catalytic converter
OSHA	U.S. Occupational Safety and Health Administration
PAH	polynuclear or polycyclic aromatic hydrocarbon
PDEAS	personal diesel exhaust aerosol sampler
PEL	permissible exposure limit
PI	particulate index
PSL	polystyrene latex
PT	peak torque
r^2	correlation coefficient
REL	recommended exposure limit
RFC-DPF	regenerable fiber coil diesel particulate filter
SE	standard error
SOF	soluble organic fraction of diesel particulate matter
STEL	short-term exposure limit
TCRC	Twin Cities Research Center

TLV	threshold limit value
VORG	volatile organic portion of diesel particulate matter
X^2	chi-square
$\Delta c_m/\Delta \log (d_p)$	finite element of mass concentration size distribution, mg/m^3
σ_g	geometric standard deviation