



00032029

**A mining research contract report  
JUNE 15, 1985**

# **MONITORING AND CONTROL OF MINE AIR DIESEL POLLUTANTS: SUMMARY OF MICHIGAN TECHNOLOGICAL UNIVERSITY RESEARCH**

## **OFR 86-43**

**Contract J0199125  
Michigan Technological University**



**BUREAU OF MINES  
UNITED STATES DEPARTMENT OF THE INTERIOR**

OFR  
86-43

#### DISCLAIMER

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of the Interior Department's Bureau of Mines or of the U.S. Government.

50777-107

<b>REPORT DOCUMENTATION PAGE</b>	<b>1. REPORT NO.</b>	<b>2.</b>	<b>3. Recipient's Accession No.</b>
<b>4. Title and Subtitle</b> Monitoring and Control of Mine Air Diesel Pollu- tants: Summary of Michigan Technological University Research			<b>5. Report Date</b> June 15, 1985
<b>7. Author(s)</b> J.H. Johnson and D.H. Carlson			<b>6.</b>
<b>9. Performing Organization Name and Address</b> Michigan Technological University Departments of Mechanical Engineering-Engineering Mechanics & Institute of Mineral Research Houghton, Michigan 49931			<b>8. Performing Organization Rept. No.</b>
<b>12. Sponsoring Organization Name and Address</b> Office of Asst. Director - Mining U.S. Bureau of Mines Department of the Interior Washington, D.C. 20241			<b>10. Project/Task/Work Unit No.</b>
			<b>11. Contract(C) or Grant(G) No.</b> (C) J0199125 (G)
<b>15. Supplementary Notes</b> Short summary of work covered in reports PB80-207541, PB82-148388 and other reports and papers reference herein.			<b>13. Type of Report &amp; Period Covered</b> Final Report Sept, 1979-June 1985
			<b>14.</b>
<b>16. Abstract (Limit 200 words)</b> The report references reports and publications from 1975 to the present related to diesel underground mine air quality research undertaken by Michigan Technological University. Research results obtained on this contract are summarized in 5 different sections as follows: Section 1 - Development of a Systematic Approach to Monitoring, Data Analysis, and Interpretation for Diesel Mine Air Quality Control, Section 2 - Experimental Evaluation of LHD On-Board Air Quality Control Systems, Section 3 - Development of a Portable Self-Contained LHD Tailpipe Emissions Measurement Apparatus for NO <sub>2</sub> , NO, CO, CO <sub>2</sub> , and Particulate Matter, Section 4 - Quantitative Analysis of Diesel and Coal Particulate Matter by Laser Raman Spectroscopy and Section 5 - Development and Application to Detector Tubes of a Laboratory Method to Assess Accuracy of Occupational Diesel Pollutant Concentration Measurements.			
<b>17. Document Analysis a. Descriptors</b> Mine Ventilation, Mining, Diesels, Monitoring, Measuring Instruments, Exhaust Gases  <b>b. Identifiers/Open-Ended Terms</b> Diesel exhaust, underground mine air monitoring and control, tailpipe measurements, auxiliary ventilation, fans on-board, underground air quality monitoring, diesel exhaust measurement instrumentation, dead-end drifts, mine air quality assessment, mine air quality data. <b>c. COSATI Field/Group</b>			
<b>18. Availability Statement</b> Release unlimited		<b>19. Security Class (This Report)</b> Unclassified	<b>21. No. of Pages</b>
		<b>20. Security Class (This Page)</b> Unclassified	<b>22. Price</b>

(See ANSI-Z39.18)

See Instructions on Reverse

OPTIONAL FORM 272 (4-77)  
(Formerly NTIS-35)  
Department of Commerce

## FOREWORD

This report was prepared by Michigan Technological University, Departments of Mechanical Engineering and Engineering Mechanics and the Institute of Mineral Research, Houghton, Michigan under USEM Contract Number J0199125. The contract was initiated under the Coal Mine Health and Safety Program and the Metal and Nonmetal Health and Safety Research Program. It was administered under the technical direction of Dr. George H. Schnakenberg, Jr. acting as the Technical Project Officer. Mr. A.G. Young was the contract administrator for the Bureau of Mines.

This report is a short summary of the work completed as part of this contract during the period 1979 - 1985 and covered in various reports and publications referenced here. This report was submitted by the authors on June 15, 1985.

The authors express their sincere appreciation to all who have had a part in this large research effort which represents the efforts of a number of researchers from various organizations as can be seen from the various reports and publications referenced.

## TABLE OF CONTENTS

	<u>Page</u>
List of Figures.....	6
INTRODUCTION.....	8
Objective.....	8
Scope.....	8
Definition of the Problem.....	9
Background Research at Michigan Technological University.....	12
SECTION 1: DEVELOPMENT OF SYSTEMATIC APPROACH TO MONITORING, DATA ANALYSIS, AND INTERPRETATION FOR DIESEL MINE AIR QUALITY CONTROL.....	14
SECTION 2: EVALUATION OF LHD ON-BOARD AIR QUALITY CONTROL SYSTEMS.....	19
SECTION 3: DEVELOPMENT OF A PORTABLE SELF-CONTAINED LHD TAILPIPE EMISSIONS MEASUREMENT APPARATUS FOR NO <sub>2</sub> , NO, CO, CO <sub>2</sub> , AND PARTICULATE MATTER.....	31
SECTION 4: QUANTITATIVE ANALYSIS OF DIESEL AND COAL PARTICULATE MATTER BY LASER RAMAN SPECTROSCOPY.....	36
SECTION 5: DEVELOPMENT AND APPLICATION TO DETECTOR TUBES OF A LABORATORY METHOD TO ASSESS ACCURACY OF OCCUPATIONAL DIESEL POLLUTANT CONCENTRATION MEASUREMENTS.....	41
REFERENCES.....	44

## LIST OF FIGURES

## INTRODUCTION

<u>Figure</u>		<u>Page</u>
1	Illustration depicting mine air quality as the product of a manufacturing process.	10

## SECTION 1

<u>Figure</u>		<u>Page</u>
2	Volume of dilution air, CFM/BHP vs diesel-produced CO <sub>2</sub> concentration of diluted air.	15
3	Illustrative diesel pollutant characteristic curve.	17

## SECTION 2

<u>Figure</u>		<u>Page</u>
4	MAQL in schematic form.	20
5	Illustration of mine air quality laboratory showing mine layout.	21
6	Sketch showing approximate mounting scheme for modified exhaust system.	22
7	Schematic showing fan and exhaust pipe location on Wagner ST5A scoop tram LHD used in MAQL experimentation.	23
8	Photograph of Engelhard PTX monolithic catalyst.	25
9	Photograph of Oxy-Cat pelletized catalytic converter.	25
10	Photograph of USBM PRC 15 x 15 x 20-inch fiberglass particulate trap.	26
11	Photograph of untreated exhaust outlet muffler.	26
12	Wagner ST5D Load Haul Dump Vehicle as Modified by Wagner based on findings from USBM sponsored Research at MTU.	29

## SECTION 3

<u>Figure</u>		<u>Page</u>
13	Illustrative schematic of emissions measurement apparatus for sampling gaseous pollutants in undiluted exhaust.	32
14	Sketch depicting the main elements of EMA-2.	34

## SECTION 4

<u>Figure</u>		<u>Page</u>
15	Schematic Diagram of Raman Instrumentation Used to Collect High Precision Coal/Diesel Particulate Spectra.	37
16	Filter spinning assembly.	38
17	Comparison of analog and signal-averaged Raman spectra of coal and diesel particulate.	39

## SECTION 5

<u>Figure</u>		<u>Page</u>
18	Top view of test cell and instrumentation for detector tube tests.	42

## INTRODUCTION

### Objective

This report briefly summarizes the results of research carried out over the past 6 years which have been covered in a number of reports and publications referenced here. The overall objective of this research has been to develop monitoring and control approaches to provide assurance of satisfactory worker air quality in underground mining operations which use diesel equipment.

### Scope

The research has been divided into a number of different tasks. This report breaks the discussion of these tasks into 5 separate sections as follows:

Section 1 discusses the development of an overall systematic approach to monitoring, data analysis and interpretation by which to evaluate the effectiveness of engineering approaches to air quality control in production underground mines that use diesel-powered equipment. This overall full scale production monitoring effort provides the basis for determining the limiting pollutant or air quality index including the CO<sub>2</sub> concentration limit to be used for quality assurance on a daily basis.

Section 2 discusses the evaluation of a number of diesel LHD on-board air quality control systems by testing them on a Wagner ST5D Scoop Tram while loading and hauling ore in an underground mine laboratory simulation of the usual production situation. This effort provides the basic information needed to predict the effects various newly-developed emissions and ventilation control systems will have on the mine air quality.

Section 3 discusses the development of two portable self-contained apparatus and procedures by which to measure tailpipe NO<sub>2</sub>, NO, CO, CO<sub>2</sub> and particulate emissions from a diesel-powered LHD vehicle. The development of a tailpipe measurement apparatus provides the means by which to monitor the slopes of the tailpipe characteristic curves so as to provide the assurance that only ambient fixed point CO<sub>2</sub> concentration measurements (rather than all pollutants) are needed on a daily basis.

Section 4 discusses the development of a laser Raman spectroscopy-based method by which to measure the relative quantities of coal and diesel particulate on a filter containing particulate samples from the air of a coal mine that uses diesel-powered equipment. This measurement is necessary to determine the relative contributions of coal and diesel to the total particulate concentrations to know which source to control.

Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding and does not imply endorsement by the Bureau of Mines.

Section 5 discusses the evaluation of a number of detector tubes for CO, CO<sub>2</sub>, NO, NO<sub>2</sub>, and SO<sub>2</sub> by comparing them with portable instruments calibrated with NBS-traceable gases. This work was carried out to determine the precision and accuracy of this most common method of measurement and to develop a methodology for comparing various portable instruments to laboratory instrument measurements.

#### Definition of the Problem

The above-mentioned study areas each contribute to the overall objective of providing satisfactory worker air quality. Their contributions can be better understood by considering the overall system as follows (1). Figure 1 is an illustration that depicts the mine air quality as the "product" of a "manufacturing process." The "process" which is the diesel loading and hauling operation has various parameters that affect the air quality "product."

First the raw materials -- engine fuel and ventilation air -- are very important to the air quality product. There are numerous fuel parameters that have an important effect on the relative concentrations of the various pollutants in the diesel emissions. Many of these properties are fixed by the engine/manufacturer and the petroleum industry specifications while others vary considerably from one fuel source to the next. Among the variable properties, the fuel sulfur content is perhaps most notable. Variations in the fuel sulfur content have a marked effect on the engine SO<sub>2</sub> emissions concentrations in terms of their effect on air quality. Two properties that have been shown to affect the particulate emissions are the aromatic content and the 90% point temperature on the volatility curve. Furthermore, engine settings and operating conditions which affect the air/fuel ratio have an important effect on the way the fuel is burned which in turn affects the relative quantities of the various types of particulate matter and gaseous combustion products.

Both the quality and quantity of the ventilation air affect the air quality product. The ventilation air quality is affected by upstream operations that increase its pollutant concentrations such as upstream use of diesels and direct-firing of propane to warm the air in the winter months, both of which add a number of combustion pollutants. Also, recirculation of exhaust from diesel mine areas due to poorly planned ventilation techniques has an important effect. Such recirculation often results in false assumptions about the quantity of fresh air reaching a diesel operation since what is measured may possibly be air that a fan is causing to flow around a pillar in a complete loop due to improper placement of fans which direct air to the workplace. Decisions about where to place fans are often difficult due to the ever-changing character of mines near the face. For this reason, air flow rates in conjunction with air quality measurements are essential for controlling and maintaining mine air quality.

In our "manufacturing process" analogy, the diesel loading and hauling operation is the "process." In a load-haul-dump operation, the diesel engine load and speed vary from one part of the load-haul-dump cycle to the next and these variations affect both the composition and the volume

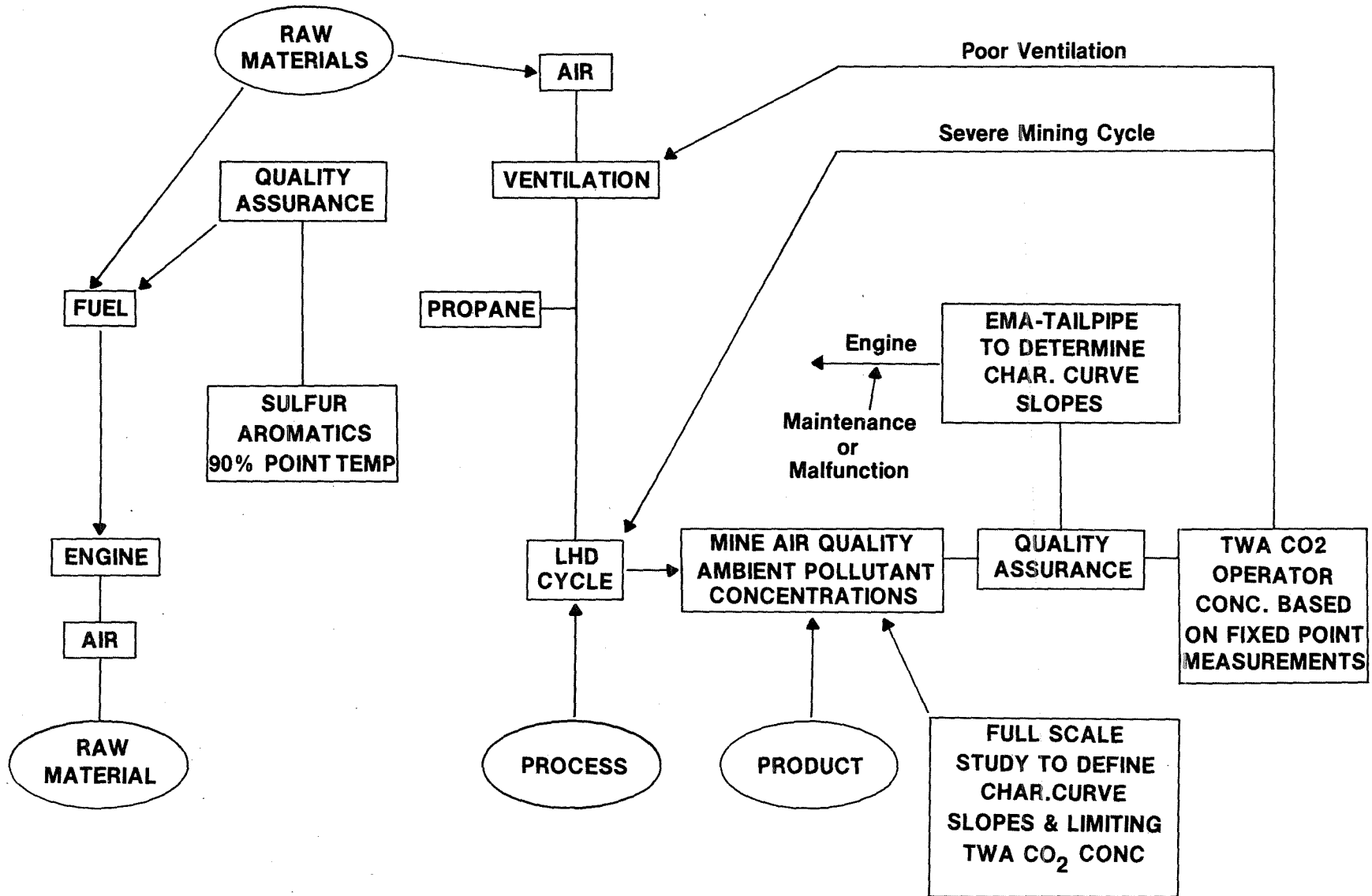


Figure 1. Illustration depicting mine air quality as the product of a manufacturing process.

flowrate of exhaust emitted. Time weighted average operator exposure to these pollutants depends largely upon the fractions of the total time spent in poorly-ventilated or well-ventilated areas and upon the quantities of the various pollutants emitted in these areas.

Diesel exhaust contains a variety of substances too numerous to list each of which affect air quality, the "product" in our analogy. Those of primary concern and to which we have given the most attention have been particulate matter, NO<sub>2</sub>, SO<sub>2</sub> and sulfate, NO, and CO. One way to look at the quality of a manufactured product is to consider its individual features (specific pollutant concentrations). Another way is to consider its overall features (combined concentrations of the various pollutants of concern). Looking at the combined concentrations is convenient, but requires using an index of air quality that is based on known harmful effects of combining individual pollutants -- information that is very difficult to obtain.

The final part of our "manufacturing process" analogy is quality assurance -- making sure that the product is satisfactory for the intended user. Quality assurance involves product testing to assure compliance to the standards. In most any manufacturing process, a substandard product can be improved in various ways. If we are unable to determine the reason(s) for product defects we may decide to increase the level of an expensive raw material that we are sure will improve quality. Thus, in the control of mine air quality we could vary a number of items as follows: begin using a more expensive low sulfur fuel, increase the main ventilation air flow, further derate the diesel engine, slow down the loading and hauling operation, add auxiliary ventilation, overhaul the engine or change to a more expensive engine, or change the mine plan. Any one of the above may improve air quality to where it complies with the standards. However, if we are able to determine the cause we can eliminate the problem in the cheapest way possible.

Determining the cause relates to the methodology discussed in Section 1. As illustrated in Figure 1 this involves a full scale study of the mine air quality to determine the quantities of the various pollutants emitted by the diesel engine in the worst case operation(s). The tailpipe emissions measurement apparatus is then used as often as needed (approximately once every 500 to 1000 hrs) to assure that the diesel engine tailpipe characteristic curve slopes have not changed excessively and mine air CO<sub>2</sub> measurements are made daily at fixed point locations and time-weighted average (TWA) operator exposure levels are calculated to provide assurance of adequate ventilation to meet the CO<sub>2</sub> control limit determined in the full scale study.

The question that presents itself is how to perform the tests and analyze and interpret the results to maximize the utility of the information in determining what process adjustments are needed. Obtaining an answer to this question is the objective of the research discussed under Section 1. Before discussing the present research, however, it is important to point out our earlier work covered in references 2-40 which helps form the basis for the present study.

## Background Research at Michigan Technological University

The earlier research began in 1974 with short term grab sample pollutant measurements near diesel equipment in the White Pine Mine using 'then-state-of-the-art' instruments as discussed in reference 2. Simultaneously a portable trailer-based mine air monitoring laboratory for monitoring CO, CO<sub>2</sub>, NO, NO<sub>2</sub> and real time particulate matter concentrations was designed by MTU researchers (3, 4) and built by Bendix.

Throughout the 1975-1976 time period and thereafter a number of more basic particulate matter studies were conducted in the MTU diesel engineering laboratory laying the foundation for the particulate measurement and control work discussed in Section 2 and the Emissions Measurement Apparatus work covered in Section 3. Reference 5 is one of the first studies conducted using the 'then-new' MTU diesel exhaust dilution tunnel.

The mine project continued by using the facilities developed under the MSHA contract to perform research under new sponsorship by the U.S. Bureau of Mines. Much of our early work in the evaluation and use of portable instruments, the development of measurement techniques and studies in the White Pine (copper) and Brushy Creek (lead) mines is covered in the 1977 report to the Bureau of Mines (6) and in reference 7.

Reference 8 discusses, among other things, the desirable features and specifications in dilution tunnel design and compares other tunnels to the MTU tunnel. Reference 9 discusses further particulate characterization work in the MTU tunnel.

Reference 10 discusses a great deal of work involving the evaluation of mine vehicle on-board prototype ambient air CO<sub>2</sub> instruments developed by Bureau of Mines contractors. Included in reference 10 are our air quality measurements in the Colorado Westmoreland Orchard Valley (coal) Mine. Reference 10 also discusses the evaluation of a number of instruments and describes the Mine Air Monitoring Laboratory (MAML - part of the Mine Air Quality Laboratory (MAQL)).

Reference 11 discusses further basic particulate matter characterization research while reference 12 summarizes the most useful findings from our earlier portable instrument evaluations and the development of measurement techniques for production underground mines.

Reference 13 discusses the basic research and development work in instrumenting the Wagner ST5D LHD used in all our Mine Air Quality Laboratory studies to date. Reference 14 discusses the statistical analysis of production mine air quality measurement data using various statistical frequency distributions. References 15 and 16 discuss the continued basic particulate matter research effort. References 17, 18, and 19 summarize in some detail the production mine instrument evaluation and air quality data that had been collected and analyzed to that time.

Reference 20 discusses some of the first data obtained in the mine air quality laboratory. This reference also includes the results of the first attempts at tailpipe measurements with the original emissions measurement

apparatus on raw exhaust from a Caterpillar 3208 naturally aspirated direct-injection diesel engine connected to the dynamometer in the MTU engine laboratory.

Reference 21 discusses a mathematical dispersion model developed to help predict the concentrations that would be found in a dead-end drift from which a diesel-powered LHD was loading and hauling. Reference 22 is a shortened version of reference 17. Reference 23 discusses further development of on-board instrumentation for the Wagner ST5D LHD used in the Mine Air Quality Laboratory and the development of a simplified mathematical model for predicting concentrations in dead-end drifts from a diesel LHD while loading and hauling. Reference 24 discusses the use of the dispersion model to predict and compare the pollutant concentrations for three ventilation configurations in a downsloping dead-end drift. Reference 25 is a shortened version of reference 18. Reference 26 discusses more of the basic particulate matter research while reference 27 discusses more work with the dispersion model.

Reference 28 summarizes the most important developments in the various basic and mine research tasks undertaken by MTU to that time. Reference 29 is another shortened version of reference 17 with some additions. This paper discusses in detail a number of instruments and measurement techniques for air quality monitoring in a production underground mine. Reference 30 discusses, among other things, the use of a diesel exhaust catalytic converter and results from a biological activity test to determine its effects on the mutagenicity of diesel particulate. Reference 31 gives more details on the material covered in reference 30.

Reference 32 discusses further developments on the dispersion model. Reference 33 further advances the dispersion model predictive work discussed in reference 24.

References 34 and 35 discuss the development of a computer model by which to predict solid and adsorbed hydrocarbon particulate concentrations in dilute diesel particulate emissions. References 36 and 37 discuss laboratory studies on close-coupled exhaust port catalysts and a porous ceramic particulate trap.

The work discussed in references 38-57 will be discussed when appropriate in the following sections.

SECTION 1  
DEVELOPMENT OF SYSTEMATIC APPROACH TO  
MONITORING, DATA ANALYSIS, AND INTERPRETATION  
FOR DIESEL MINE AIR QUALITY CONTROL

References 38 and 39 contain the first published mention of the newly developed approach to mine air quality monitoring. Reference 40 discusses the first application in a production underground mine and references 41, 42, and 43 discuss the second application. References 44 and 45 discuss research verifying the basic concepts, reference 46 discusses the instruments used, references 47 and 48 discuss two applications in Canadian Mines, reference 49 discusses recent improvements in the application of the concepts and reference 50 applies the concepts to measurements made earlier in the Brushy Creek and White Pine Mines.

The new approach is based on the following basic premises:

1. Because the volume of diesel-produced CO<sub>2</sub> can be calculated from the quantity of fuel burned, the CO<sub>2</sub> concentration can therefore be calculated from the quantity of fuel burned and the volume of dilution ventilation air. Furthermore, since the quantity of fuel burned is an estimate of the brake horsepower of diesel power consumed, the diesel-produced mine air CO<sub>2</sub> concentration can be used to estimate the CFM of ventilation air per brake horsepower (CFM/BHP) of diesel-produced power. The following formula may be used to calculate the CFM/BHP from the CO<sub>2</sub> concentration:

$$\frac{\text{CFM}}{\text{BHP}} = \frac{45.18 \times \text{BSFC}}{\text{Diesel-produced CO}_2, \% \text{ by Vol.}*} \quad (\text{Eq. 1})$$

BSFC = Average brake specific fuel consumption, lb/BHP-hr (can vary, .45 lb/BHP-hr is a fairly typical value)

CFM = Volume flow rate of dilution air, CFM

BHP = Brake horsepower produced, BHP

Figure 2 is an illustrative plot of the CFM/BHP versus the diesel-produced CO<sub>2</sub> concentration.

Thus the mine air CO<sub>2</sub> concentration corrected by subtracting the background CO<sub>2</sub> concentration is a measure of the volume of dilution ventilation air per unit of diesel output power.

2. The concentrations of diesel exhaust pollutants in the mine air are proportional to the diesel-produced CO<sub>2</sub> concentration. Thus, for example,

\* The diesel-produced CO<sub>2</sub> concentration is found by measuring the CO<sub>2</sub> concentrations upstream and downstream of the diesel and by subtracting the upstream from the downstream concentration.

## MEASUREMENT OF CO<sub>2</sub> CONTROLS CFM/BHP

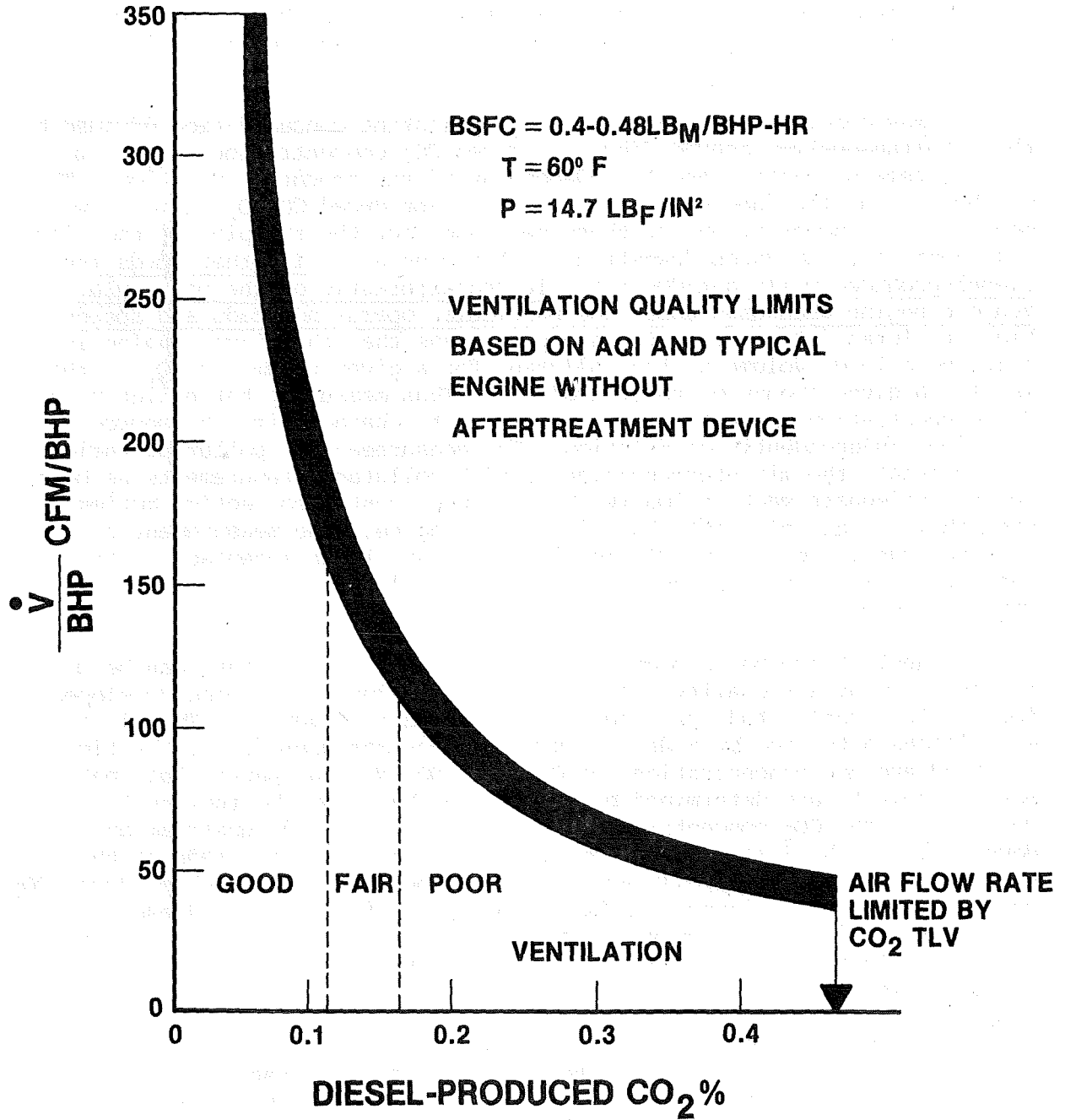


Figure 2. Volume of dilution air, CFM/BHP vs diesel-produced CO<sub>2</sub> concentration of diluted air.

if the diesel-produced CO<sub>2</sub> concentration is reduced to 1/2 its original value by halving the quantity produced or by doubling the volume of dilution air, the concentration of all other pollutants would be expected to be reduced to 1/2 their original values.

The importance of this premise is that it is possible to make sense out of diesel mine air pollutant concentration measurements by measuring the pollutant and CO<sub>2</sub> concentrations simultaneously.

We may conclude that the ratio of a pollutant concentration divided by the simultaneously-measured diesel-produced CO<sub>2</sub> concentration should, within limits, remain constant and is independent of the amount of dilution. Thus we should find the same value for the diesel-produced CO/CO<sub>2</sub> ratio if we measure the concentrations of these two gases out the tailpipe of the diesel mine vehicle or 50 yards downstream in the mine air. In other words the diesel-produced pollutant/CO<sub>2</sub> ratio is characteristic of the particular vehicle engine when used under the particular operating loads and speeds. A high 'pollutant/CO<sub>2</sub>' ratio, for example, means that the diesel engine is emitting a large volume of the pollutant for a given volume of CO<sub>2</sub> -- that is, for a given amount of power produced. Thus measuring the pollutant and CO<sub>2</sub> concentrations simultaneously allows us to characterize the source emissions independently of dilution. The measurement of pollutant ratios also prevents the misinterpretation of high pollutant measurements as being due to inadequate ventilation (with subsequent costly corrective action) when they are actually attributable to the engine. The measurement of simultaneously high CO and CO<sub>2</sub> levels, which are in an acceptable ratio characteristic of the engine, is indicative of low dilution and of a ventilation problem.

To apply these basic premises in making measurements that can be used to control mine air quality, the following procedures have been developed for the full scale study previously referred to in Figure 1. The air in a mine is characterized by 5 days of simultaneous measurements of the time-weighted-average concentrations of CO<sub>2</sub>, CO, NO, NO<sub>2</sub> and particulate matter. SO<sub>2</sub> and sulfate are determined by calculation based on the fuel sulfur content and the CO<sub>2</sub> concentration. Measurements are made upstream and downstream of the diesel operation of concern and plots are made of the various diesel-produced pollutant concentrations vs. the diesel-produced CO<sub>2</sub> concentration as in Figure 3. These plots are referred to as diesel pollutant characteristic curves. The slope of such a plot represents an average pollutant/CO<sub>2</sub> ratio and is characteristic of the particular diesel operation (mining cycle and engine).

Other useful information can be presented on the plot. The regulated limit for the pollutant (TLV or assumed limit) may be shown as a horizontal line on the plot. The point of intersection of the characteristic curve with this limit gives the CO<sub>2</sub> concentration below which the pollutant concentration will remain below its selected limit. Thus, when such a plot has been developed for each pollutant of concern, we can identify the limiting CO<sub>2</sub> concentration which can control all pollutants so they comply with the limits. Thus if we control the ventilation air flow (CFM) and (or) the diesel power output (BHP) such that the CO<sub>2</sub> concentration remains below the control level (i.e. a sufficiently high CFM/BHP), all the pollutants

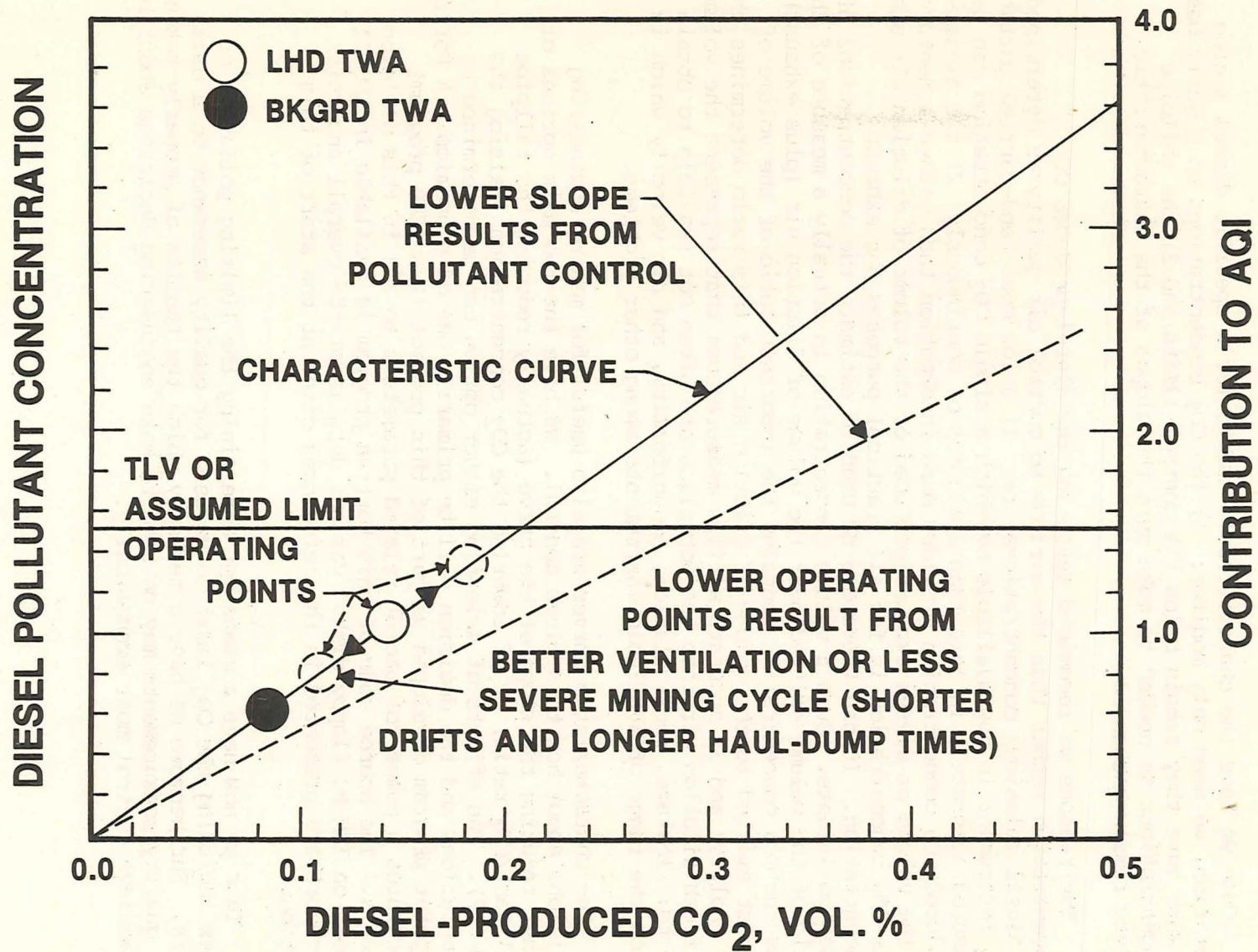


Figure 3. Illustrative diesel pollutant characteristic curve.

should remain below their respective limits if the slopes of the characteristic curves have not changed.

Once we have the characteristic curves for a specific diesel mining operation, we need only monitor: 1) the CO<sub>2</sub> concentrations on a daily basis to make sure they remain below the control limits and 2) the tailpipe concentrations as needed to make sure the slopes of the characteristic curves remain unchanged.

The reasons we recommend measuring the diesel-produced CO<sub>2</sub> concentration rather than the airflow to control air quality as determined by diesel emissions concentrations are: 1) a low cost hand-carried portable CO<sub>2</sub> instrument is now available by which a single CO<sub>2</sub> concentration can be measured accurately in less than 2 minutes or continuously; 2) the diesel-produced CO<sub>2</sub> concentration provides more information than either a measure of the volume of diesel exhaust produced or the volume of dilution air since this CO<sub>2</sub> concentration is for all practical purposes the exhaust concentration. It can therefore be used to estimate the concentrations of other pollutants. Such a volume concentration is actually a measure of the ratio of the volume emitted over the volume of dilution air (plus exhaust). Thus the CO<sub>2</sub> concentration contains the important ratio of the volume of exhaust emitted to the volume of dilution air and this ratio determines the air quality; and 3) accurate airflow measurements that represent the volume of fresh dilution air into the workplace are often not feasible to obtain due to: leakage, recirculation, nonuniformity, and air velocity which is below the range of available instruments among other problems.

The characteristic curves are also useful for making engineering decisions about how to achieve control. We have the two main options of either reducing the slope of the curve (actually reducing the tailpipe pollutant/CO<sub>2</sub> ratio) or of lowering the CO<sub>2</sub> concentration (raising the CFM/BHP). The effects of selecting either option can be determined by calculations and the decision will be primarily one of economics. A Fortran computer program developed as part of this project (the PEAP program) calculates a number of useful related parameters to aid in this decision process. The source code of this Fortran program is available in ASC II format on IBM-PC floppy disk. Various details of the overall analysis procedure are presented in the references cited at the start of this section.

Thus we now have a means for determining the limiting pollutant or index including the CO<sub>2</sub> limit to be used for quality assurance on a daily basis. Furthermore we have a means by which the results of properly taken air quality measurements may be used to make engineering decisions about how to achieve control most economically.

## SECTION 2

EVALUATION OF LHD ON-BOARD  
AIR QUALITY CONTROL SYSTEMS

The Mine Air Quality Laboratory (MAQL) which was developed in the earlier contracts was used to evaluate and compare a number of LHD on-board air quality control systems by testing them on a Wagner ST5D Scoop Tram in a simulated mine load-haul-dump operation. This work is covered in references 50, 51, 52, 53, 54, 55, and 56. Figure 4 is a schematic showing the various components making up the MAQL. Figure 5 illustrates the mine test set-up with the Mine Air Monitoring Laboratory (MAML), the LHD, and the drift monitoring set-up.

References 51 and 56 discuss tests involving the comparison of two Olin Energy Systems Model 200 Fume Dilutors with the standard side-to-the-floor and modified rearward LHD exhaust systems. A stationary jet fan located at the first crosscut and a fan with vent tubing were also tested. Dead end heading lengths of 100, 150 and 200 feet were used in the tests. The tests were run using a modified load-haul-dump cycle which improved repeatability. The modified rearward exhaust system is illustrated in Figure 6.

Both the modified rearward exhaust system and the Fume Dilutors were found to reduce the LHD on-board diesel-produced CO<sub>2</sub> concentrations by about 50% while mucking ore from a 150-ft long drift. The stationary jet fan reduced the CO<sub>2</sub> concentration in the 100-ft drift, but reductions were not significant in longer drifts. Vent tubing reduced concentrations 11% at 150 ft and 62% at 200 ft. It was concluded that, all things considered, the modified rearward exhaust system was the most desirable and most economical system.

Another set of tests evaluating on-board drift ventilation systems was run in the MAQL in which the modified rearward system and an on-board fan system were compared to the standard side-to-the-floor exhaust system on the Wagner ST5D LHD (50). The fan system mounting locations are illustrated in Figure 7. Variations of the hydraulically-powered fan system tested included inlet tubing to cause the fans to draw air from a remote point near the bucket end of the LHD and a diffuser to mix the exhaust with the fan air immediately as it exited the fan and to slow down the velocity of the jet.

Fan variations tested included angle and speed, as well as the addition of inlet tubing and (or) exhaust diffusers. All the variations tested affected fan performance in reducing drift concentrations, but none made the fans significantly better than the modified system.

Overall the modified rearward exhaust system without fans provided the greatest reduction in gaseous pollutant concentrations.

The effect of the length of time that the vehicle stayed out of the drift (haul distance) was investigated and it was found that time increases

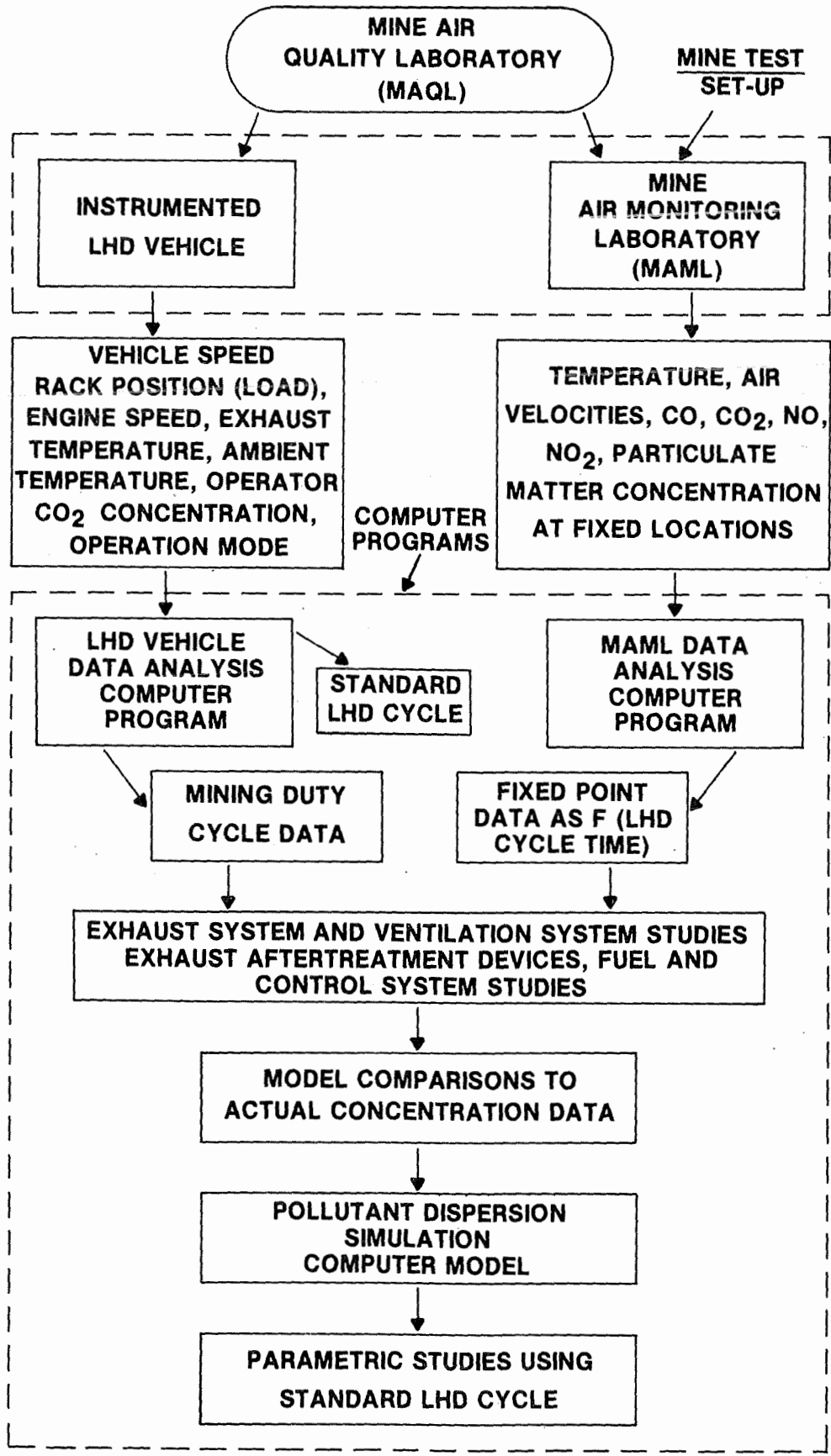


Figure 4. MAQL in schematic form. (52)

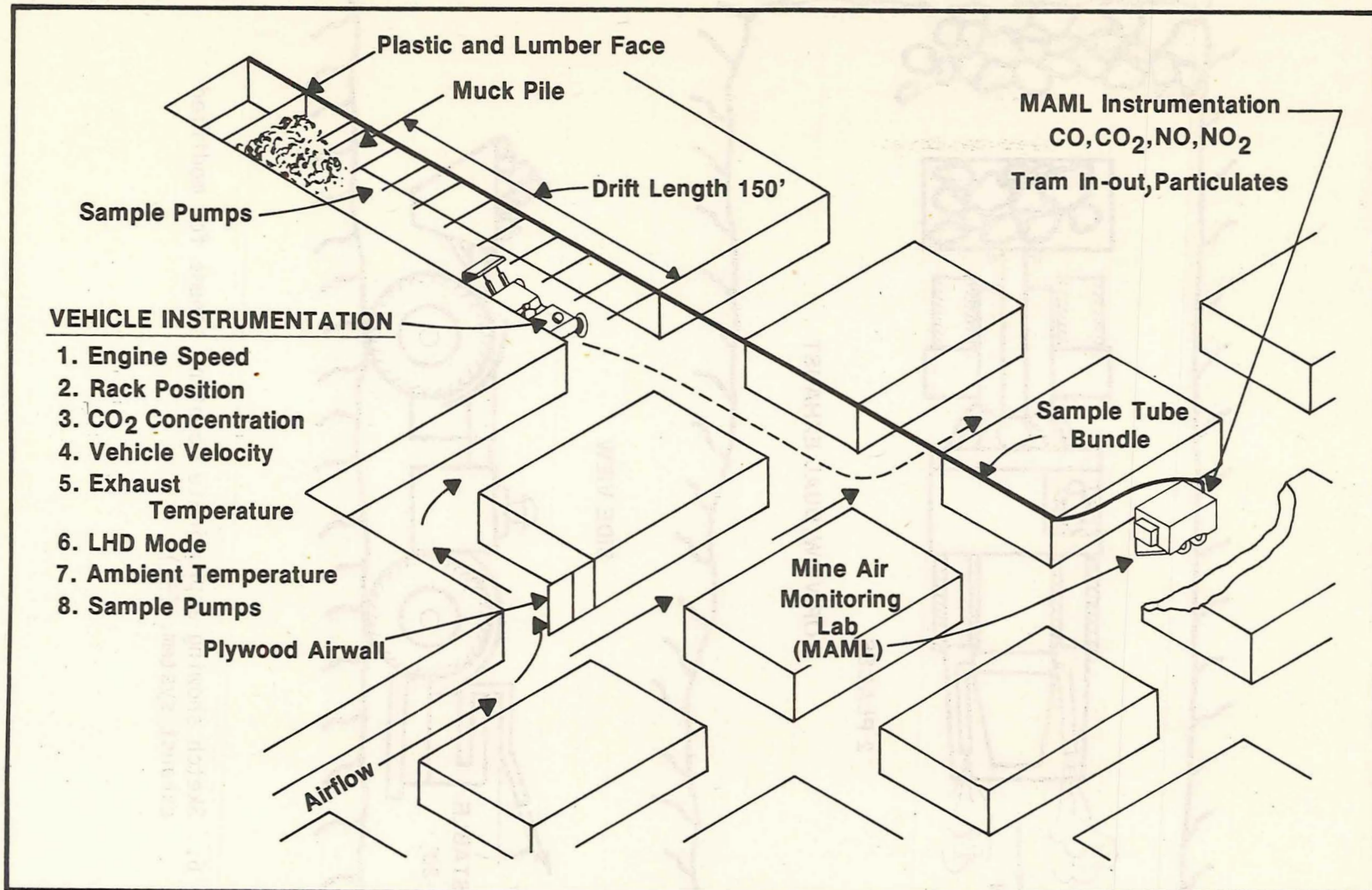


Figure 5. Illustration of mine air quality laboratory showing mine layout

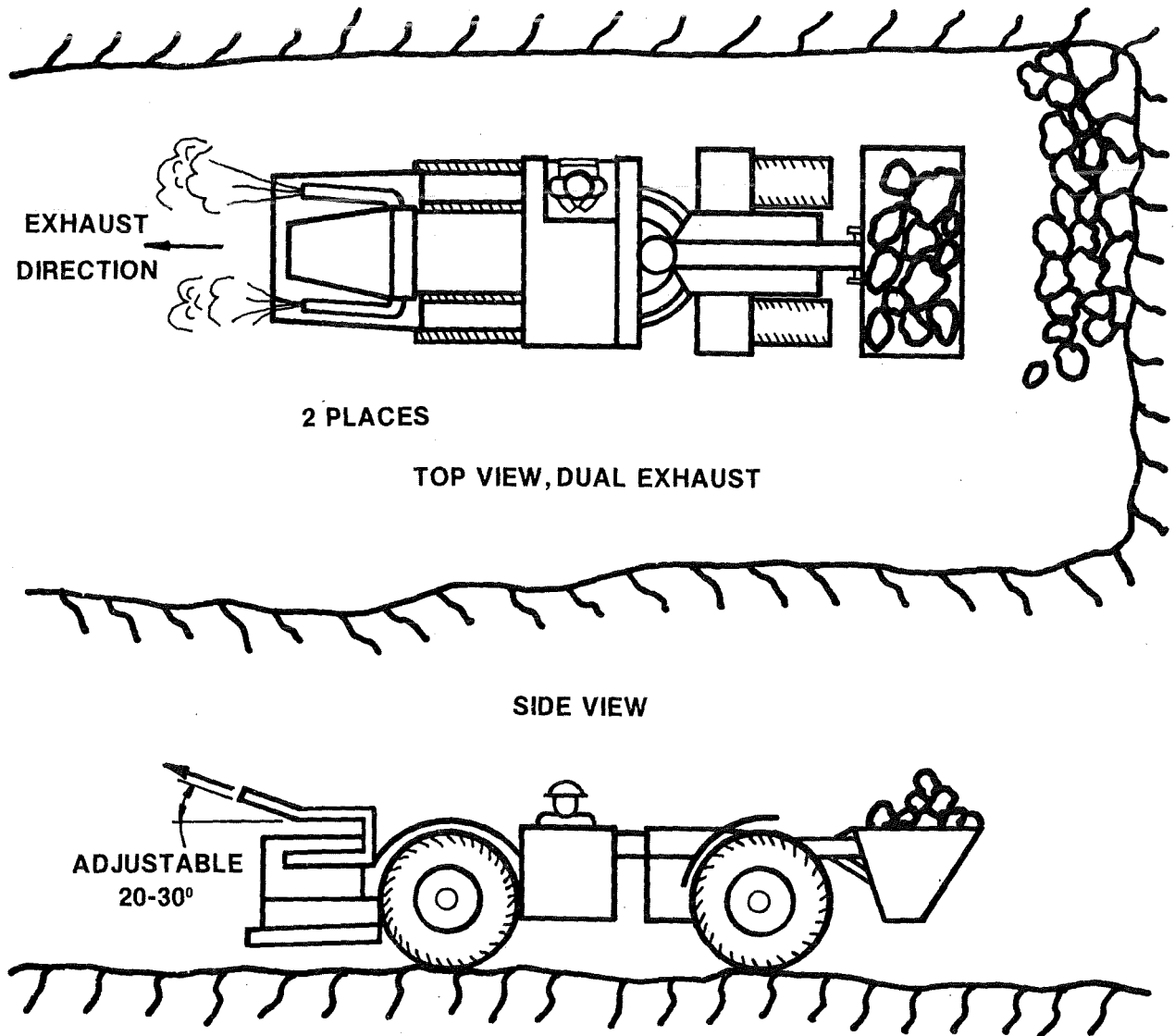


Figure 6. Sketch showing approximate mounting scheme for modified exhaust system. (56)

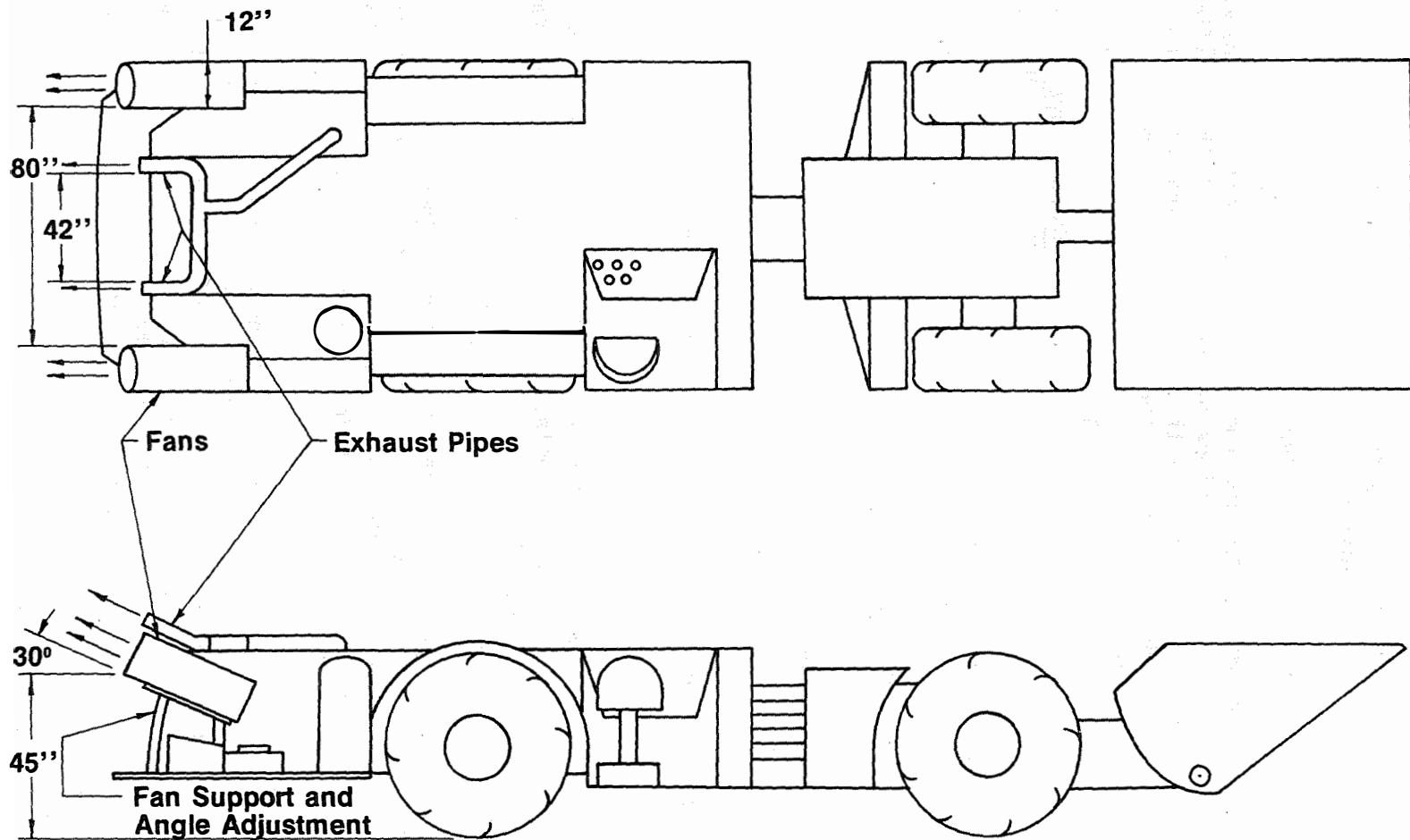


Figure 7. Schematic showing fan and exhaust pipe location on Wagner ST5A scoop tram LHD used in MAQL experimentation. (50)

from 30 to 120 seconds resulted in a drift CO<sub>2</sub> concentration reduction of about 19%.

It was concluded that the modified exhaust system is still the preferred one from the viewpoint of reducing operator pollutant exposure, not to mention its overall simplicity and low cost of installation with no expected operating cost increase over the standard system..

Limited noise data comparing the standard and modified exhaust systems (56) indicate substantial reductions are realized with the modified system. The measurements which were made with the backpressure restricted to 34 inches of water to simulate some of the control devices being tested at that time are tabulated below:

	Noise level, dbA	
	<u>Std.</u>	<u>Mod.</u>
50 ft from vehicle as it passed by	100	95
50 ft behind vehicle while mucking	101	90
10 ft away from side of vehicle	103	102

Mufflers were not used at the time of the measurements.

References 53, 54, and 55 describe in detail the research performed in the MAQL to test the effects of fuels, catalysts, and a filter trap on drift pollutant concentrations. Figures 8 through 11 show the four systems tested on the Wagner ST5D LHD.

Three of these exhaust systems were aftertreatment devices; in the 4th the exhaust was passed through a muffler only. All systems directed the exhaust rearward and toward the roof -- the configuration which had been found earlier to provide the lowest dead-end heading pollutant concentrations.

The aftertreatment devices were a PTX monolithic catalyst, an Oxy-Cat pelletized catalyst, and a stainless steel-fiberglass mesh particulate filter supplied by the Bureau of Mines Pittsburgh Research Center. The various exhaust systems were evaluated in a 150 ft drift to determine their effects on the concentrations of the pollutants CO, CO<sub>2</sub>, NO, NO<sub>2</sub>, total particulate matter, soluble organic particulate matter, sulfate particulate matter, and solid particulate matter.

It was concluded that:

- 1) The particulate filter reduces in-heading total respirable particulate matter (TRPM) concentrations up to 51% for no. 1 fuel

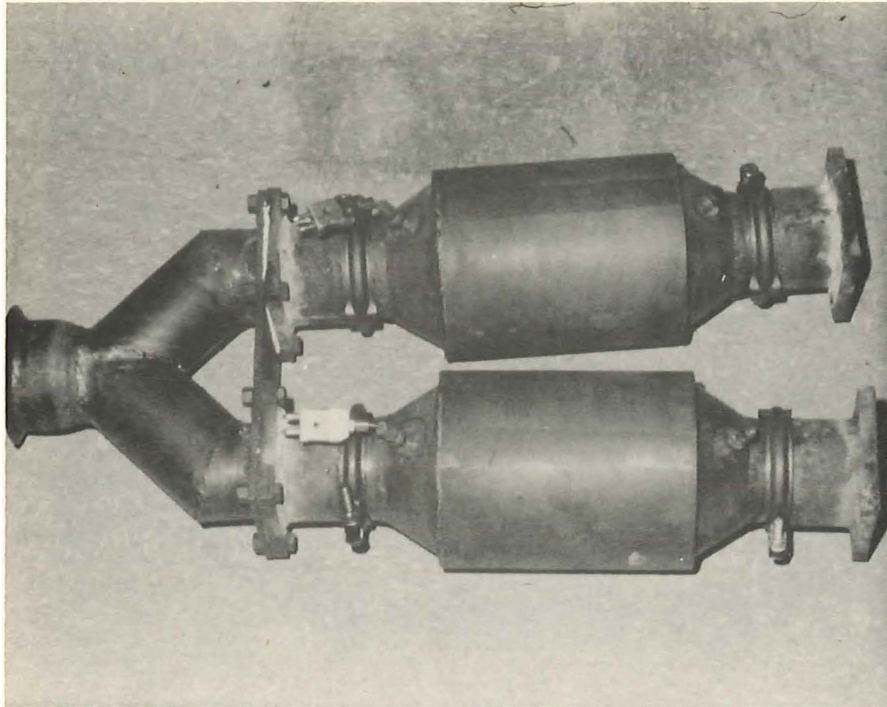


Figure 8. Photograph of Engelhard PTX monolithic catalyst. (55)

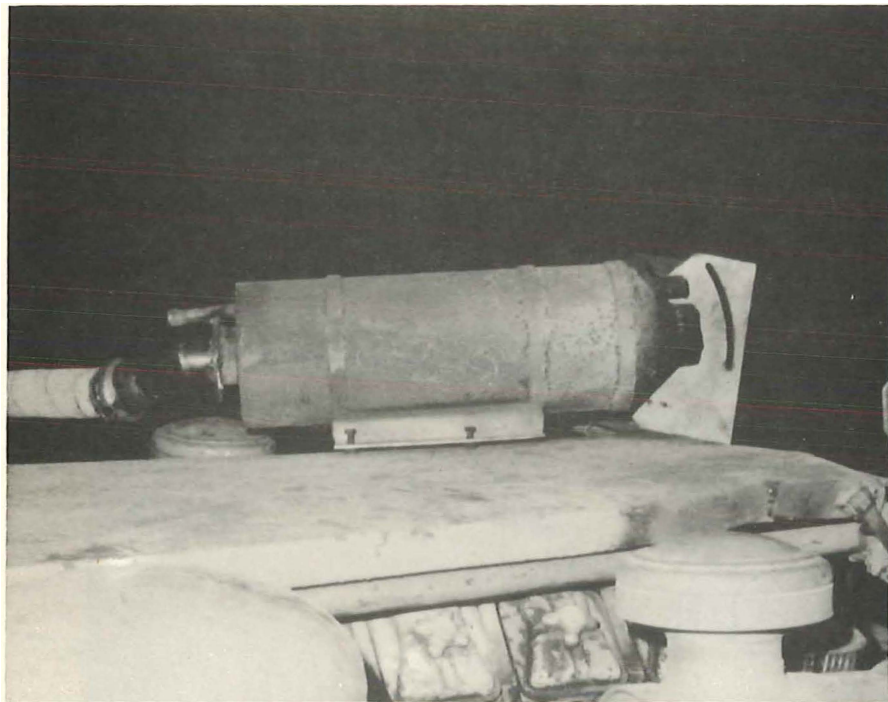


Figure 9. Photograph of Oxy-Cat pelletized catalytic converter. (55)

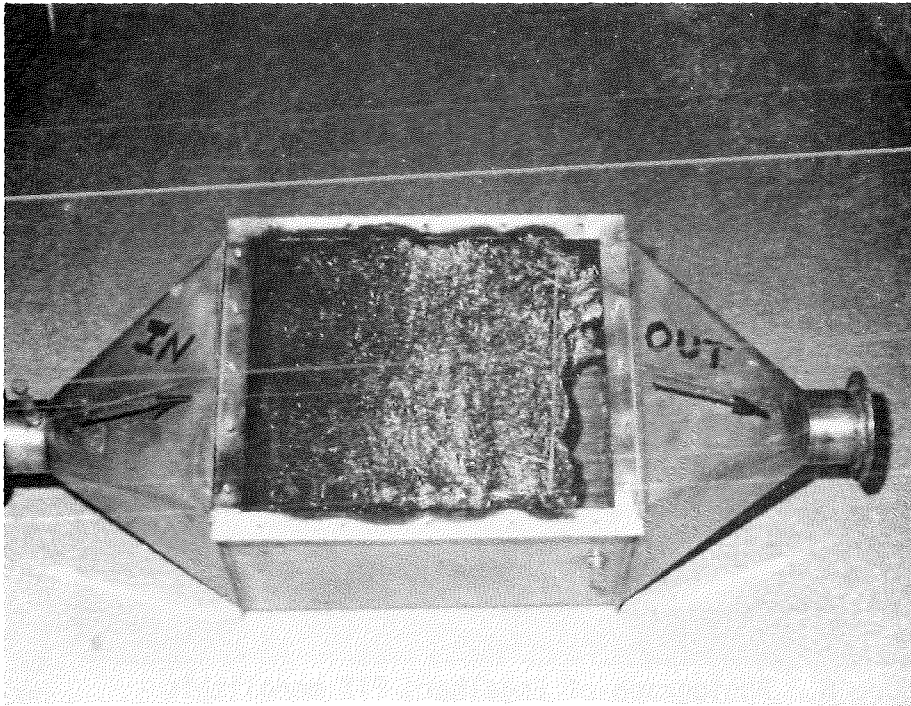


Figure 10. Photograph of USBM PRC 15 x 15 x 20-inch fiberglass particulate trap. (55)

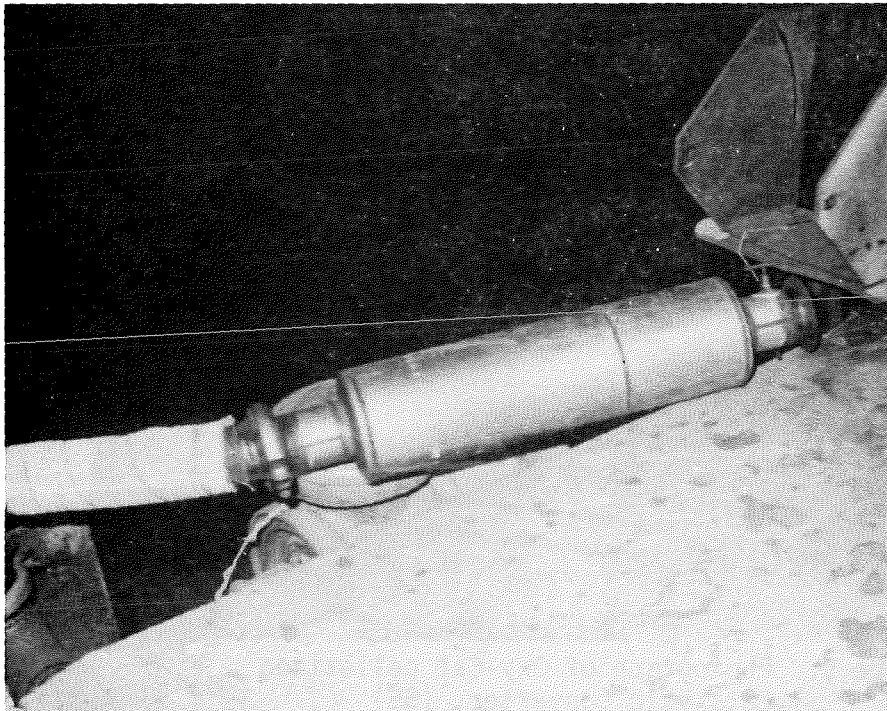


Figure 11. Photograph of untreated exhaust outlet muffler. (55)

(from 1.96 mg/m<sup>3</sup> for untreated exhaust to 0.97 mg/m<sup>3</sup> for the filter) and up to 44% for no. 2 fuel (from 1.90 mg/m<sup>3</sup> for untreated exhaust to 1.06 mg/m<sup>3</sup> for the filter), without significantly changing the gaseous pollutant concentrations.

- 2) The PTX monolithic catalyst reduces in-heading CO concentrations by up to 82% for no. 1 fuel (from 3.5 ppm for untreated exhaust to 0.6 ppm for the monolithic catalyst) and by 86% for no. 2 fuel (from 3.8 ppm for the filter trap to 0.6 ppm for the monolithic catalyst). However, NO<sub>2</sub> concentrations are increased by up to 750% (from 0.2 ppm for untreated exhaust to 1.7 ppm for the monolithic catalyst) and SO<sub>4</sub> by up to 140% for no. 1 fuel (from 0.13 mg/m<sup>3</sup> for untreated exhaust to 0.31 mg/m<sup>3</sup> for the monolithic catalyst) and by up to 455% for no. 2 fuel (from 0.11 mg/m<sup>3</sup> for untreated exhaust to 0.61 mg/m<sup>3</sup> for the monolithic catalyst). The PTX monolithic catalyst also increased TRPM by up to 24% for no. 1 fuel (from 1.86 mg/m<sup>3</sup> for untreated exhaust to 2.31 mg/m<sup>3</sup> for the monolithic catalyst) and 46% for no. 2 fuel (from 1.63 mg/m<sup>3</sup> for untreated exhaust to 2.39 mg/m<sup>3</sup> for the monolithic catalyst). The soluble organic fraction (SOF) concentrations were reduced as much as 30% for both no. 1 and no. 2 fuel (from 0.95 mg/m<sup>3</sup> for untreated exhaust to 0.66 mg/m<sup>3</sup> for the monolithic catalyst).
- 3) Gaseous pollutants were not affected by the Oxy-Cat catalyst tested. However, this catalyst was an unregenerated used one, the history of which was unknown. This pelletized catalyst was associated with large increases in particulate matter emissions which may have resulted from trapping of particulate in the out-of-drift idling of the MTU load-haul-dump cycle and release of particulate in the in-drift running in and out operations.

The successful reductions in mine dead-end heading pollutant concentrations due to relocating the exhaust system outlet were impressive. From further considerations of the basic principles it was concluded that the effect of directing the exhaust upward and to the rear of the LHD vehicle rather than downward and to the side could be improved by coupling this modification to other changes. The additional suggested changes involved relocating the engine air intake ports so that engine air would be taken in near the mine floor where the more dense cool fresh air tends to gravitate and shrouding the engine compartment so that engine cooling air would be taken in from a position near the floor and exhausted rearward and toward the mine roof along with the hot tailpipe emissions. These changes, it was hoped, would assist the natural tendency in the dead end drift in which dense cool fresh air enters the drift at lower elevations and lower density hot exhaust exits the drift near the roof. Furthermore, the changes should result in improved engine cooling -- use of cooler air from near the drift floor for both engine intake and cooling air and also shrouding the engine compartment to confine the cooling air so that it must contact external engine parts.

These considerations resulted in a cooperative effort among MTU, White Pine Copper Co., and Wagner Equipment Co. to do a complete modification of the above-mentioned systems on a single LHD vehicle. As a result White Pine

Copper loaned one of their ST5D LHDs to Wagner to perform the MTU-suggested modifications. The changes have been made and MTU hopes to test the effects on a future Bureau of Mines research contract.

Figure 12 presents a labeled photograph of the LHD vehicle as modified by Wagner showing the various items that were changed.

The rearward exhaust system tailpipes protrude from the space between the hood and engine compartment covers. Unmodified pipes blow the exhaust out the side near the front of the running board on the side of the vehicle opposite the operator (behind right rear wheel if bucket end is considered to be the front end). The modified vehicle pipes protrude only slightly producing the desired enhancement of exhaust vs. fresh air stratification without the potential for damage which would occur with longer pipes coming into contact with the roof during loading and hauling operations.

The removable engine enclosure covers provide access to the engine for service. Cooling air is taken into the engine compartment through a circular hole under the cooling air shroud which is the same diameter as the cooling fan. The air intake shroud causes the air to be taken in from a location nearer the floor, thereby minimizing the possibility for the hot tailpipe emissions becoming mixed with the engine cooling air.

Engine combustion air is taken in at the relatively low position shown also for the reason that the hot exhaust does not mix with it. The warmed cooling air is exhausted through the openings between the hood and engine covers where its buoyancy would be expected to further enhance the stratification of tailpipe emissions.

The Wagner-modified ST5D was tested by Wagner (Wagner report ST-4A-01-A dated 1/23/83) and found to have engine pressures significantly below the Deutz limits as follows:

Engine pressures at high idle (2385 RPM) in inches of H<sub>2</sub>O

	Modified Wagner ST5D		Deutz limit, left or right
	<u>Left</u>	<u>Right</u>	
Exhaust back pressure	11.9	9.9	29.5
Intake air vacuum	9.6	7.0	19.7

Noise levels are listed in the same Wagner report at the converter stall speed of 2272 RPM. These were reduced 2-5 dbA (depending upon measurement position) by addition of the ventilation enclosures (engine covers) on the modified vehicle.

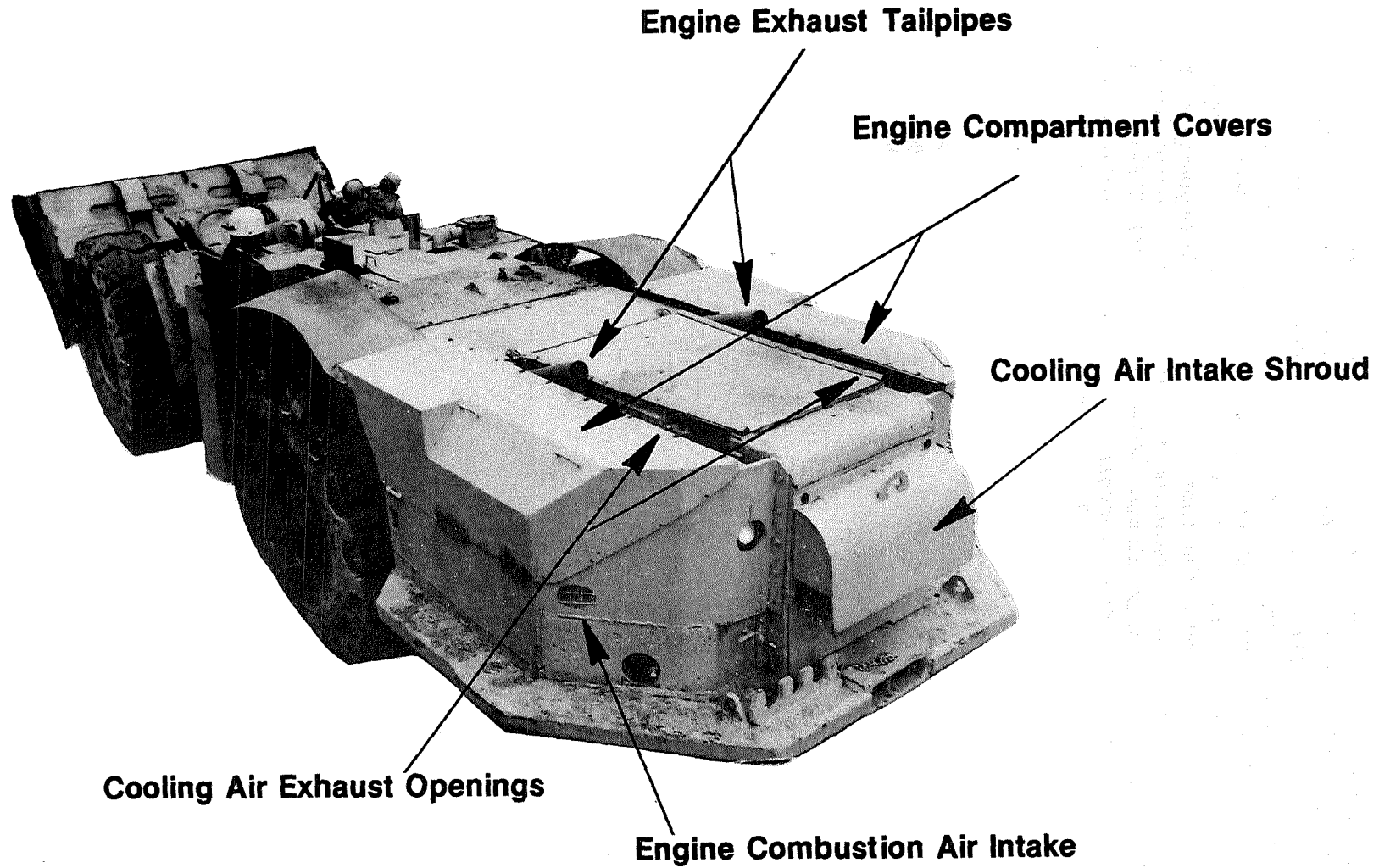


Figure 12. Wagner ST5D Load Haul Dump Vehicle as Modified by Wagner based on findings from USBM sponsored Research at MTU.

In summary, the studies under this contract in the Mine Air Quality Laboratory have provided the basic information needed to predict the effects on mine air quality of a number of LHD-vehicle on-board drift ventilation systems and exhaust aftertreatment devices. Furthermore these studies have shown that the modified rearward exhaust system is as good a means to improve drift ventilation as any of the on-board drift ventilation control systems. The results also indicated that the research prototype particulate trap showed promise as a means of reducing the particulate concentration by control at the source and that catalysts, while reducing the already low CO concentrations, may result in large increases in other toxic pollutants so that their overall effect would be to degrade rather than improve mine air quality.

## SECTION 3

DEVELOPMENT OF A PORTABLE SELF-CONTAINED  
LHD TAILPIPE EMISSIONS MEASUREMENT APPARATUS  
FOR NO<sub>2</sub>, NO, CO, CO<sub>2</sub> AND PARTICULATE MATTER

Efforts to develop a portable apparatus to measure the concentrations of NO<sub>2</sub>, NO, CO, CO<sub>2</sub> and particulate matter in the tailpipe emissions of a diesel-powered LHD had been started in the previous Bureau of Mines contract. The first tailpipe apparatus we developed (EMA-1, which is illustrated schematically in Figure 13) had been tested in the MTU diesel engine laboratory and these results are reported in reference 20.

Procedures were developed in the present contract for using the apparatus in the mine. The procedures which require only a few minutes removal of the vehicle from service, were tested both with laboratory instruments and engines at the Bureau of Mines and the Mine Safety and Health Administration (MSHA) facilities in Bruceton, Pa and with LHD vehicles in two underground mines. The apparatus consisted of the following:

1. For smoke opacity: A Celesco 101B portable diesel exhaust smoke opacity meter and adaptors to interface the meter with the LHD vehicle exhaust outlet and
2. For gaseous pollutants: A particulate conditioning apparatus consisting of a particulate matter filter and exhaust cooling probe assembly, moisture removal ice bath condenser, pump, and metering valves to control the relative volumes of conditioned exhaust collected in two bags. One bag contained pure dry nitrogen which diluted the exhaust so that the concentrations of NO<sub>2</sub>, NO, CO, and CO<sub>2</sub> were in the proper range for measurement by TLV-range instruments. The empty bag was used to collect undiluted exhaust for measurement of the CO<sub>2</sub> concentration. The undiluted CO<sub>2</sub> concentration was used along with the diluted CO<sub>2</sub> concentration to determine the dilution ratio. This ratio was then used to calculate the undiluted exhaust concentrations of CO, NO, and NO<sub>2</sub> from the concentrations measured in the diluted sample.
3. For engine speed determination: A Pioneer model DT-36 digital photo-tachometer with remote reading capability.

From laboratory comparisons to reference instruments it was estimated that NO, CO, and CO<sub>2</sub> accuracies within +25% could be attained by the Emissions Measurement Apparatus (EMA). NO<sub>2</sub> accuracies attainable, were believed to be within +50%.

When duplicate tests on a single White Pine Mine LHD were made on the same day, measured concentrations ranged about the mean to a maximum of 41% of the mean for NO<sub>2</sub>, to 5.0% for NO, to 15% for CO, and to 3.1% for CO<sub>2</sub>. For repeat tests on the same Brushy Creek Mine LHD made on the same day, NO<sub>2</sub>

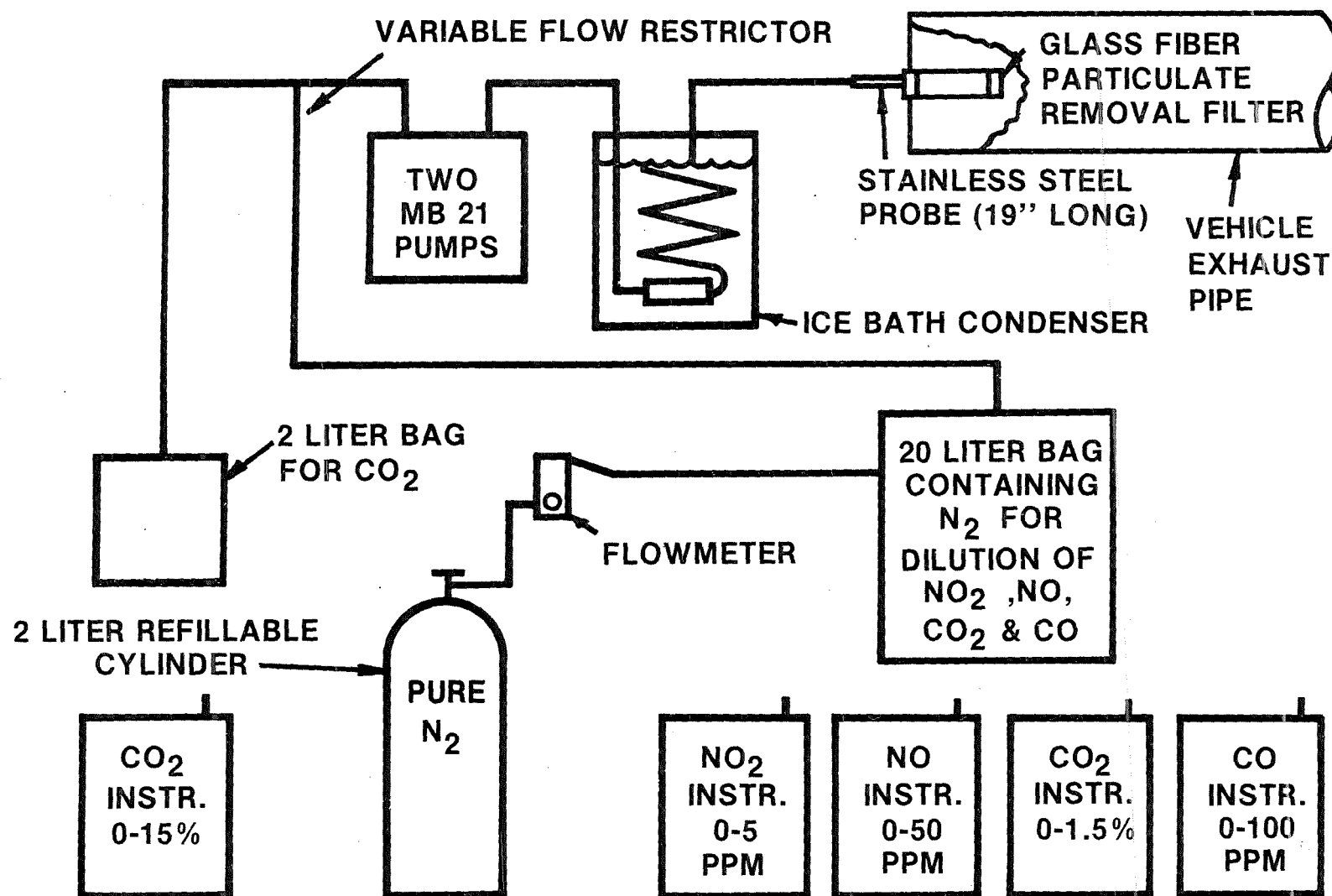


Figure 13. Illustrative schematic of emissions measurement apparatus for sampling gaseous pollutants in undiluted exhaust. (20)

values ranged about the mean value to a maximum of 36% of the mean, NO to 5.9%, CO to 11% and CO<sub>2</sub> to 3.1%.

A number of recommended improvements had been suggested for EMA-1 as follows (55):

1. Eliminate the ice bath by continuous dilution.
2. Eliminate the raw exhaust CO<sub>2</sub> sample bag. In EMA-1, the raw exhaust CO<sub>2</sub> measurement was used to calculate the volumetric dilution ratio. The nonspecific thermal-conductivity-based Cobra CO<sub>2</sub> instrument and the effect on overall accuracy of combining raw and dilute exhaust measurement errors in the calculation of raw exhaust concentrations were a cause of concern with EMA-1.
3. Minimize the cost and complexity of the apparatus.
4. Incorporate particulate matter gravimetric sampling which would simulate as closely as possible the quantities of mass (adjusted for dilution ratio) in the mine ambient air. EMA-1 employed smoke opacity measurements by the Celesco 101B Smokemeter. The main concern with the smoke opacity measurements was that they measure only solid carbon particulate and significant amounts of soluble organic particulate may not be sensed.

A second generation Emissions Measurement Apparatus (EMA-2) illustrated in Figure 14 was designed, developed and tested and is discussed in detail in reference 50. The EMA-2 design is based on overcoming the above EMA-1 concerns by continuously diluting the raw exhaust before it cools enough to result in significant condensation of moisture and hydrocarbons. The diluted sample, after some residence time in a mini-dilution tunnel, is passed through a preweighed filter that collects the particulate matter, while the filtered gases are then collected in a bag for analysis of the concentrations of the gaseous pollutant species.

The EMA-2 performs the following: 1) samples a measureable quantity of hot raw diesel exhaust from the tailpipe of a mine vehicle, 2) dynamically dilutes the sample with an accurately-controlled volume of dilution gas, 3) provides residence time in a mini-dilution tunnel before passing the diluted and cooled gas volume through a 2 1/2-in diameter filter to collect the particulate, and, 4) collects a portion of the diluted exhaust in a bag for immediate analysis of the gaseous pollutant concentrations by direct-reading instruments.

The sampling and particulate collection apparatus contains no battery or AC-powered components such as pumps, heaters, coolers, or other such complex components and is therefore easy to use in a production underground mine with very little (1 hr.) setup time. It consists simply of a cylinder of dilution gas connected to the motive nozzle of a jet ejector with sonic nozzles on both the suction and motive inlets followed by a mini dilution tunnel, a 2 1/2-in diameter filter disk/holder setup, and finally a Calibrated Instruments 5-layer gas collection bag.

The exhaust is sampled by a short probe on the ejector suction inlet and is mixed with the motive gas which dilutes and cools it simultaneously

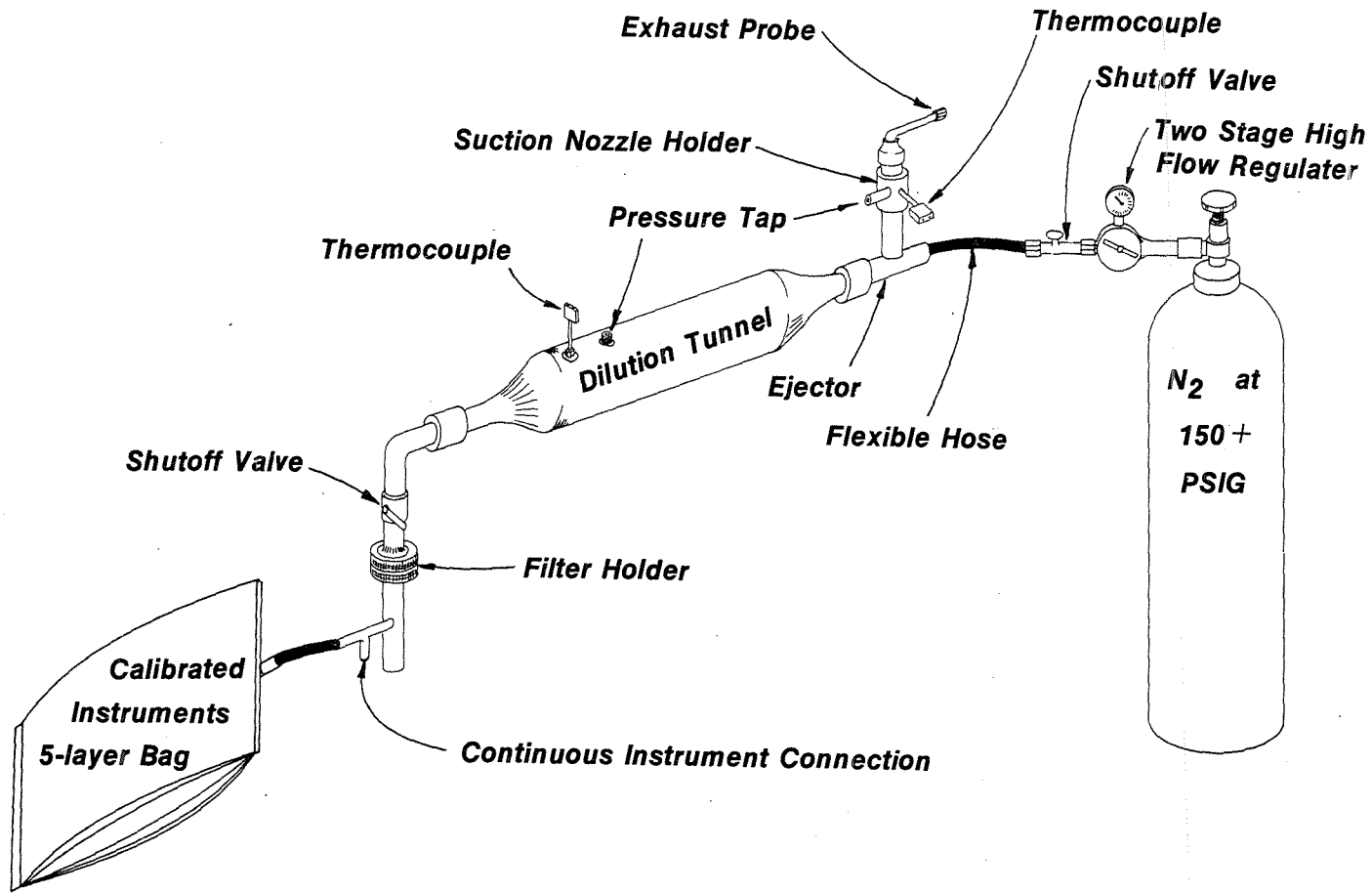


Figure 14. Sketch depicting the main elements of EMA-2 (50)

in the ejector, thus alleviating the water condensation that would otherwise take place as a result of cooling the undiluted exhaust. The mini-tunnel simply provides mixing and residence time for the particulate-formation processes of adsorption and condensation, the filter collects the particulate for gravimetric analysis, and the bag collects the dilute gas for measurement of the concentrations of NO<sub>2</sub>, NO, CO, and CO<sub>2</sub>.

The apparatus was tested on both calibration gases and hot raw diesel exhaust. The results show that it is an accurate, practical raw exhaust sampling and dilution apparatus which can provide dilute exhaust samples, the concentrations of which can be measured by direct-reading instruments that are used to measure diesel pollutant concentrations in the ranges found in the mine ambient air. On the other hand, particulate matter concentrations as measured by the apparatus developed were below and ranged from 37 to 89% of those measured in the MTU dilution tunnel. The particulate matter concentration differences are not fully understood to date and more work is needed.

In conclusion, EMA-2 is a simple, practical raw exhaust dilution apparatus which works extremely well for gaseous pollutants. We believe that a limited additional development/experimental effort will prove that the apparatus is also a satisfactory means to accurately measure tailpipe particulate matter concentrations. As mentioned earlier, this tailpipe measurement apparatus fits into the overall quality assurance methodology as a means to assure that the tailpipe characteristic curve slopes do not change beyond acceptable limits.

## SECTION 4

QUANTITATIVE ANALYSIS OF DIESEL AND  
COAL PARTICULATE MATTER BY  
LASER RAMAN SPECTROSCOPY

A method to quantitatively measure the relative amounts of coal and diesel particulate on an air-sampling filter was developed using laser Raman spectroscopy (54). The measurements are made on "as-received" filters, requiring no special sample preparation or handling which might otherwise change the sample. A spinning sample prevents sample heating in the laser beam, and signal-averaged spectra are collected to obtain the required precision. Measurements on standards of "known" 'diesel particulate/coal' content have demonstrated the validity of the technique. A variety of coal-only and diesel particulate-only samples were characterized spectroscopically as a function of several experimental spectral and system variables, including coal rank and form as well as diesel engine operating conditions.

Figure 15 shows the various components of the system used to collect the coal/diesel particulate spectra. Figure 16 shows the filter spinning assembly and Figure 17 compares analog (top) and signal-averaged (bottom) Raman spectra for coal (left) and diesel (right).

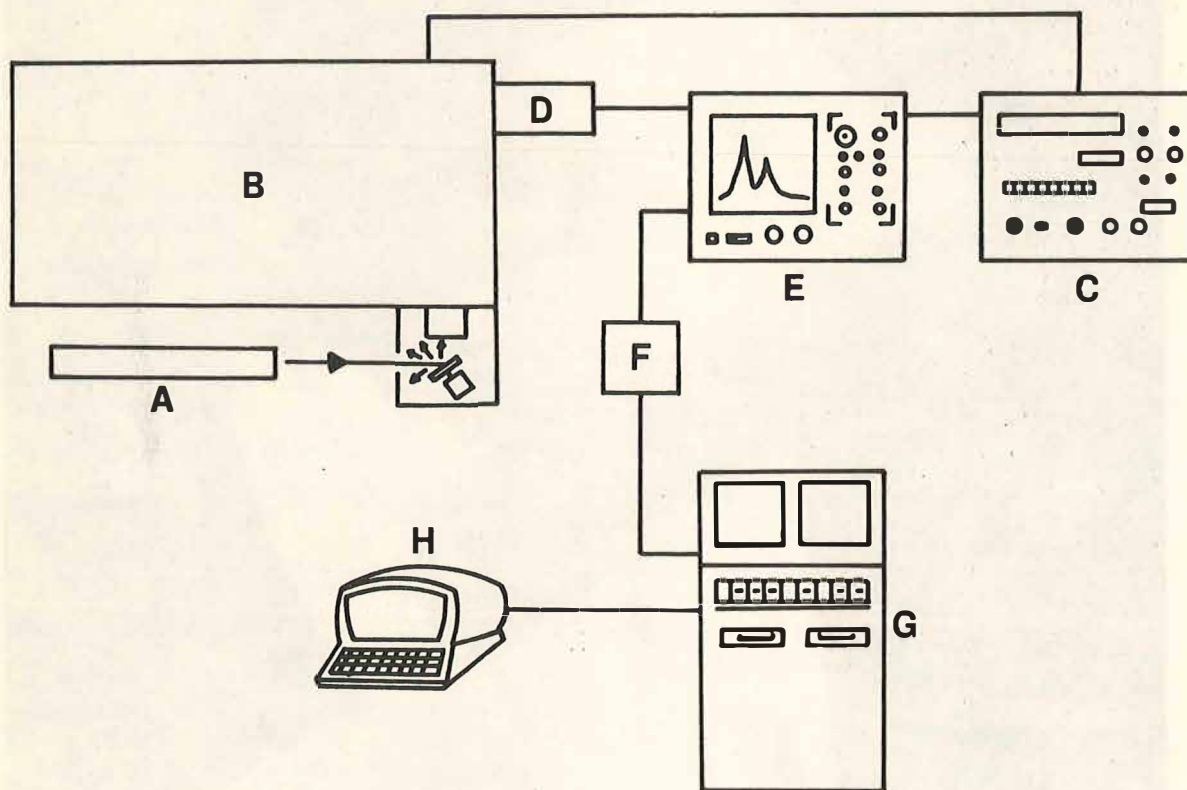
The study results demonstrated that it is possible to measure the amount of diesel particulate in a mixture of coal and diesel particulate, as would be found on filters collected in a coal mine in which diesel engines were used. This was confirmed using samples of known composition in the range below 55% diesel particulate, with better than +6% accuracy.

The Raman intensity was linearly proportional to composition, holding extrinsic alignment variables constant; however, the Raman spectroscopic technique did not lend itself to measurement of absolute intensities. To avoid alignment problems and to maximize precision, the intensity ratio technique was applied. The mathematical form of the composition/intensity ratio relation was derived, and experimental results confirmed that this relation was obeyed. Using this functional relationship, it was possible to extract quantitative composition information from only three empirical intensity ratios,  $r$ ,  $r'$ , and one  $R$  (known).

The minimum empirical data needed for calibration includes the spectra of two pure components and a means of ascertaining the relative intensities of these two spectra. In general, this information is obtainable from a known mixture spectrum or a synthetic 50/50 mixture spectrum. From the results it was clear that the preferred calibration method was to have two or more known standard mixtures. It was not possible to generate such standard mixtures in the study.

A method was also proposed to generate a mixture spectrum synthetically by spinning two filter halves (one-half from each pure component). This

Figure 15. Schematic Diagram of Raman Instrumentation Used to Collect High Precision Coal/Diesel Particulate Spectra (55)



- A. Argon ion laser, Coherent, Inc., 3210 Porter Dr., P.O. Box 1032, Palo Alto, CA 94304;
- B. Ramanor HG.2S four slit double monochromator, Instruments S. A., Inc., 173 Essex Ave., Metuchen, N.J. 08840;
- C. Scan controls for monochromator (B);
- D. Photon counting electronics, Model 1140 Quantum Photometer, Princeton Applied Research, P.O. Box 2565, Princeton, N.J. 08540;  
Hamamatsu photomultiplier tube #R928P, Hamamatsu TV Co., Ltd., 1126 Ichino-cho, Hamamatsu City, Shizuoka-Pref., Japan;  
cooled in Model TE-177-RF cryostat, Products for Research, Inc., 78 Holten St., Danvers, MA 01923;
- E. NS-570A Digital Signal Analyzer, Tracor Northern, Inc., 2551 W. Beltline Highway, Middleton, WI 53562;
- F. Interface (by Tracor Northern, E);
- G. Minicomputer, Nova 3/12, Data General Corp., Inc., Southboro, MA 01772;
- H. Terminal (by Data General, G)

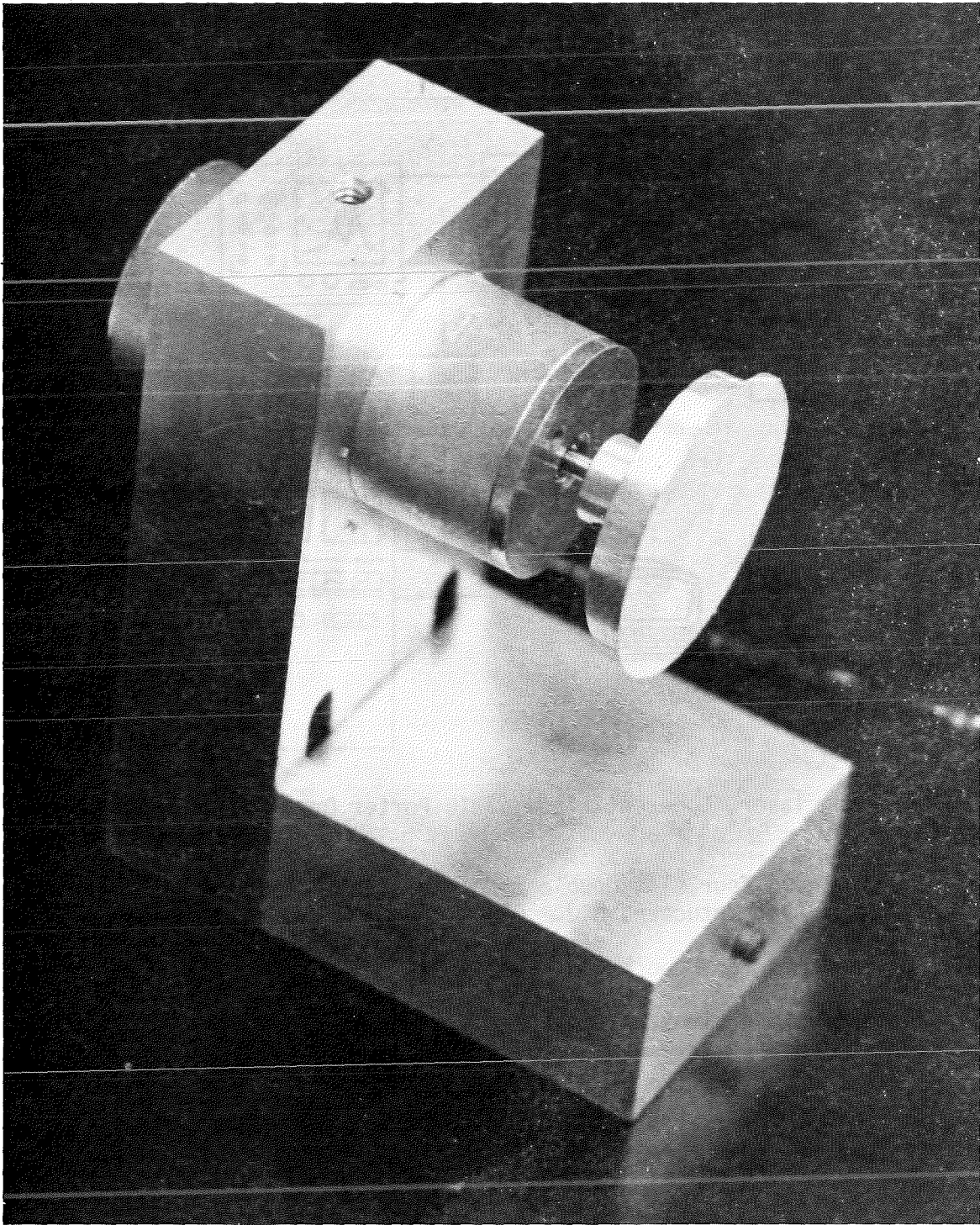


Figure 16. Filter spinning assembly. The diameter of the aluminum filter holder is 3.65 cm. The motor is 24 v DC, # 3A1003-1, from TRW Globe, Inc., 2275 Stanley Ave., Dayton, OH 45404. (55)

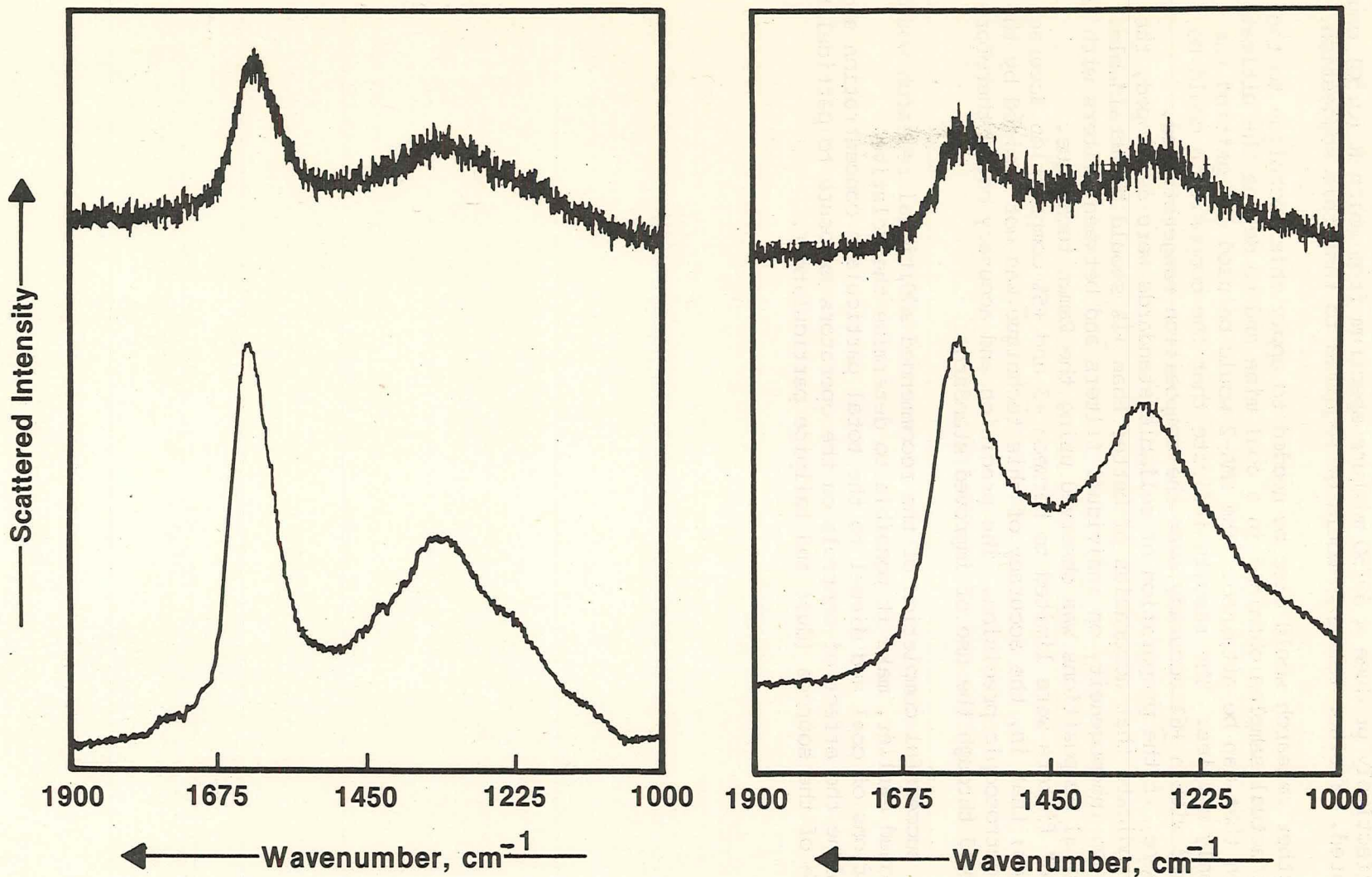


Figure 17. Comparison of analog (top) and signal-averaged (bottom) Raman spectra of coal (left) and diesel particulate (right). These are the spectra of chunk coal #3 and diesel particulate filter #D3.1. The number of multiple scans for the signal-averaged spectra is 20 and 40 for the coal and diesel particulate, respectively (at  $1 \text{ cm}^{-1}/\text{address}$ ). The scan rate was  $200 \text{ cm}^{-1}/\text{minute}$ . (55)

would effectively produce a 50/50 mixture spectrum from which R (0.50) could be measured. Further research would be required to test this suggestion.

Further research would also be needed to apply this technique to the study of actual samples obtained in a coal mine and to define the ultimate precision that can be attained. The EMA-2 would be used for getting the diesel-only samples. The results indicate that the composition could be determined within  $\pm 6\%$  accuracy over the composition range studied. Furthermore, if the preparation of reliable standards were developed, the results indicate that accuracies of better than  $\pm 1\%$  should be attainable. Composition inhomogeneity on individual filters and between filters with the same nominal compositions was observed using the Raman technique. "Standard" filters were limited to between  $\pm 3$  and  $\pm 5\%$  composition accuracy themselves; that is, the accuracy of this technique was not limited by the Raman spectroscopic precision. The precision and accuracy could therefore be improved through the use of improved standards.

The successful completion of the recommended additional research would, as mentioned earlier, make it possible to determine the relative contributions of coal and diesel to the total particulate concentration and to determine the effect of controls on the operators exposure to particulate from each of the sources (dust and tailpipe particulates).

## SECTION 5

DEVELOPMENT AND APPLICATION TO DETECTOR  
TUBES OF A LABORATORY METHOD TO ASSESS  
ACCURACY OF OCCUPATIONAL DIESEL POLLUTANT  
CONCENTRATION MEASUREMENTS

A laboratory method was developed by which to determine the accuracy of techniques for measurement of airborne pollutant concentrations in diluted diesel exhaust (56, 57). The method involves dilution of the raw exhaust from a diesel engine operated at various controlled speeds and loads and sampling the exhaust-air mixture in a manner designed to simulate sampling in air surrounding diesel equipment operated in confined spaces such as in an underground mine. The method developed was applied to National Draeger, Inc. detector tubes for CO, CO<sub>2</sub>, NO, NO<sub>2</sub>, and SO<sub>2</sub>. This included recalibration of the detector tubes with certified gases which had been checked alongside NBS Standard Reference Gases. Detector tube diesel exhaust measurements were compared with simultaneous measurements by portable instruments which earlier tests had indicated were specific for the pollutant of concern. The differences between detector tube and instrument readings were assumed to be made up of detector tube calibration and interference errors. The calibration errors were subtracted from the total error to obtain the interference error.

Figure 18 depicts schematically the test cell and instrumentation for the detector tube tests. The procedure was found to be capable of identifying the existence of significant detector tube measurement errors as shown in Table 1.

From the application of the procedure developed for assessing the effects of diesel exhaust interferences in small samples of detector tubes for CO, CO<sub>2</sub>, NO, NO<sub>2</sub>, and SO<sub>2</sub> in the TLV it was concluded that:

1. Observer bias in determining the position of the end-of-stain is a relatively small source of error, an error which increases with decreasing clarity of the end of stain.
2. Calibration errors ranging from 3 to 55% are much larger than those due to observer bias ranging from 0.2 to 7% and were outside NIOSH limits for several certified tubes\*.
3. Interference errors are greater than 35% of the correct reading for significant percentages of measurements with each of the detector tube types tested.

\*NIOSH certified tubes, at the time of this study, had been tested and found to read individual single-component calibration gases to within +35% of the correct value at concentrations equal to 1/2 the TLV for the contaminant measured and to within +25% of the correct value at concentrations equal to 1, 2, and 5 times the TLV. NIOSH no longer certifies detector tubes.

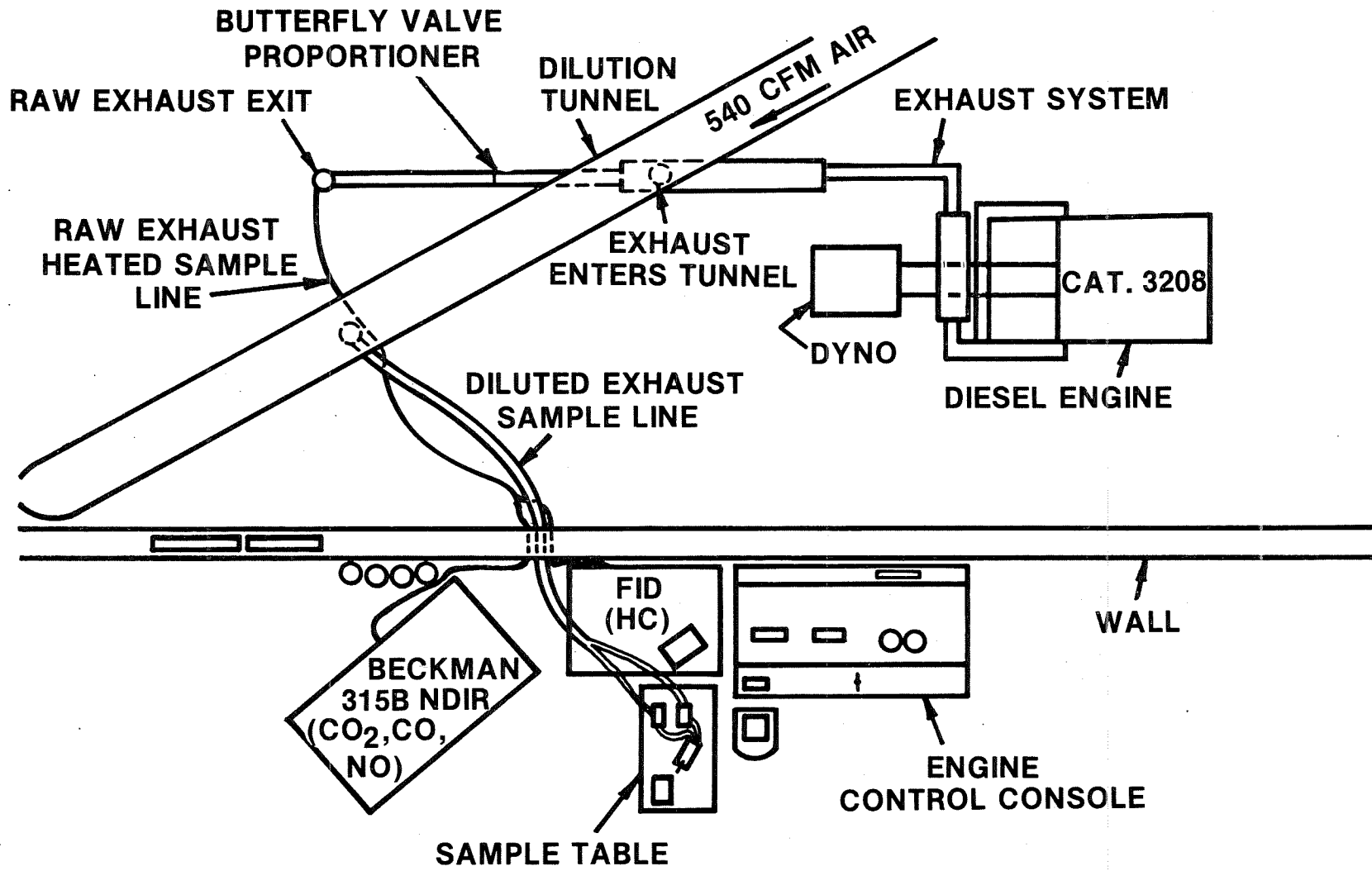


Figure 18. Top view of test cell and instrumentation for detector tube tests. (55)

Based on the findings and the wide acceptance of detector tubes in industrial hygiene air monitoring, further studies are recommended to broaden the data base and to provide the information needed to enable the industrial hygienist to make an intelligent choice among the numerous possible approaches to air monitoring.

Detailed findings are reported in Ref. 57. Detector tubes are clearly not sufficiently accurate or precise for carrying out the three quality measurement functions described in Figure 1, i.e., the full-scale study, fixed-point CO<sub>2</sub> concentration and EMA-2 tailpipe measurement.

## REFERENCES

1. Wagner, W., Marano, D., White, K., Croft, B., Kennedy, W., "Development of a Mine Air Containment Measurement Program - Diesels and Explosives," Contract JO100004, Bureau of Mines, United States Department of Interior, Washington, DC, 1984.
2. Michelbacher, J.A., "Analysis of CO, CO<sub>2</sub>, NO, NO<sub>2</sub>, and Particulate Matter Ambient Air Data Obtained with Portable Instruments in an Underground Mine Using Diesel Powered Equipment," M.S. Thesis, Michigan Technological University, Houghton, Michigan 49931, 1975.
3. Bunting, B.G., "Performance of Portable and Trailer Based Air Pollution Instruments in Underground Mines Using Diesel Powered Equipment," M.S. Thesis, Michigan Technological University, Houghton, Michigan 49931, 1975.
4. Johnson, J.H., Carlson, D.H., Bunting, B.G. and Michelbacher, J., "The Development and Application of Advanced Mine Air Monitoring Techniques to Mines Using Diesel Powered Equipment," Final Report to the Mining Enforcement and Safety Administration for contract No. SO144094, February 15, 1976. Michigan Technological University, Houghton, Michigan, Report No. PB-258038/9WP, National Technical Information Service, Springfield, Virginia 21161.
5. Vuk, C.T., Jones, M.A., and Johnson, J.H., "The Measurement and Analysis of the Physical Character of Diesel Particulate Emissions," SAE Paper No. 760131, 1976.
6. Johnson, J.H., Carlson, D.H., and Bunting, B.G., "The Application of Advanced Mine Air Monitoring Techniques to Mines Using Diesel Powered Equipment," Annual Report to the United States Department of Interior, Bureau of Mines for Grant Agreement No. G0166027, January 15, 1977, Michigan Technological University, Houghton, Michigan, Report No. PB272456/AS; National Technical Information Service, Springfield, Virginia 22161.
7. Reinbold, E.O., "Analysis of Air Quality in Two Underground Mines Using Diesel Equipment," M.S. Thesis, Michigan Technological University, Houghton, Michigan 49931, 1977.
8. Lipkea, W.H., Johnson, J.H., and Vuk, C.T., "The Physical and Chemical Character of Diesel Particulate Emissions-Measurement Techniques and Fundamental Considerations," SAE SP-430, 1978.
9. Khatri, N.J., Johnson, J.H., and Leddy, D.G., "The Characterization of the Hydrocarbon and Sulfate Fractions of Diesel Particulate Matter," SAE Paper No. 780111, 1978.

10. Johnson, J.H., Carlson, D.H., and Bunting, B.G., "The Application of Advanced Mine Air Monitoring Techniques to Mines Using Diesel Powered Equipment," Second Annual Report to the United States Department of Interior, Bureau of Mines for Grant Agreement No. GO166027, June 15, 1978, Michigan Technological University, Houghton, Michigan 49931. NTIS PB30074 24/AS.
11. Khatri, N.J., and Johnson, J.H., "Physical Size Distribution Characterization of Diesel Particulate Matter and the Study of the Coagulation Process," Society of Automotive Engineers Technical Paper Series, No. 780788, Presented at the Off-Highway Vehicle Meeting & Exposition MECCA, Milwaukee, September 11-14, 1978.
12. Johnson, J.H., "Monitoring for Diesel Exhaust Emissions," Industrial Hygiene for Mining and Tunneling - Proceedings of an ACGIH Topical Symposium, Nov. 6-7, 1978, The American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio.
13. Olds, P.R., "The Design of a Portable Data Acquisition System for Monitoring the Operation of a Diesel Powered Mine Vehicle," M.S. Thesis, Michigan Technological University, Houghton, Michigan 49931, 1978.
14. Smaby, S.A., "The Development and Application of Statistical Air Quality Data Analysis Techniques," M.S. Thesis, Michigan Technological University, Houghton, Michigan 49931, 1978.
15. Frisch, L.E., Johnson, J.H., and Leddy, D.G., "Effect of Fuels and Dilution Ratio on Diesel Particulate Emissions," SAE Paper No. 790417, Presented at Congress and Exposition, Cobo Hall, Detroit, MI, February, 1979.
16. Funkenbusch, E.F., Leddy, D.G. and Johnson, J.H., "The Characterization of the Soluble Organic Fraction of Diesel Particulate Matter," SAE Technical Paper No. 790418 Presented at Automotive Congress and Exposition, Detroit, Michigan, February 26-March 3, 1979.
17. Carlson, D.H. and Johnson, J.H., "The Monitoring of Diesel Pollutants in Underground Mines," Paper No. 76-69, Presented at AIME Annual Meeting, February 18-23, 1979.
18. Reinbold, E.O., Carlson, D.H., and Johnson, J.H., "Ambient Pollutant Concentrations in Two Underground Metal Mines Using Diesel Equipment," Paper No. 79-77, Presented at AIME Annual Meeting, February 18-23, 1979.
19. Johnson, J.H., "An Overview of Monitoring and Control Methods for Diesel Pollutants in Underground Mines Using Diesel Equipment," Paper presented at 81st Annual General Meeting of CIM, April 22-25, 1979.

20. Johnson, J.H., Carlson, D.H., and Reinbold, E.O., "The Application of Advanced Mine Air Monitoring Techniques to Mines Using Diesel Powered Equipment," Final Report to United States Department of Interior, Bureau of Mines for Grant Agreement No. G0166027, July 31, 1979, Michigan Technological University, Houghton, Michigan 49931. NTIS PB80-207541.
21. Schock, H.J., "Simulation and Measurement of Dispersing Gaseous Exhaust Emissions from Diesel Engines in a Mine Environment," Ph.D. Dissertation, Michigan Technological University, Houghton, Michigan, 1979.
22. Carlson, D.H., and Johnson J.H., "Monitoring Diesel Pollutants Case Study: Underground Mining," Hazardous Materials Management Journal Vol. 2, No. 1, pp. 21-30, November/December, 1980.
23. Keski-Hynnala, D.E., "Development and Use of Experimental Techniques for the Evaluation of Heading and Vehicle Ventilation Control Methods in Underground Mines Using Diesel Powered Equipment," M.S. Thesis, Michigan Technological University, 1980.
24. Schock, H.J., Johnson, J.H., and Bunting, B.G., "An Experimental Comparison of Pollutant Concentrations for Three Ventilation Configurations in a Downsloping Dead-Ended Drift," Preprint No. 80-342, Presented at SME-AIME Fall Meeting and Exhibit, Minneapolis, Minnesota, October 22-24, 1980.
25. Reinbold, E.O., Carlson, D.H., and Johnson, J.H., "Ambient Pollutant Concentrations in Two Underground Mines Using Diesel Equipment," Mining Engineering Journal, Vol. 33, No. 1, pp. 57-67, January 1981. AIME Transactions (Mining), Vol. 269, 1981.
26. Hunter, G., Scholl, J., Hibbler, F., Bagley, S., Leddy, D., Abata, D., Johnson, J., "The Effect of an Oxidation Catalyst on the Physical, Chemical and Biological Character of Diesel Particulate Emissions," SAE Paper No. 810263, February, 1981.
27. Schock, H.J., and Johnson, J.H., "Simulation and Measurement of Space and Time Varying Pollutant Concentrations From a Diesel Powered Vehicle in a Dead-Ended Drift," Paper No. 81-64, Presented at AIME Annual Meeting, February 22-26, 1981.
28. Johnson, J.H., Reinbold, E.O., and Carlson, D.H., "The Engineering Control of Diesel Pollutants In Underground Mines," SAE Technical Paper No. 810684, Presented at SAE Earthmoving Industry Conference, April 6-8, 1981.
29. Carlson, D.H. and Johnson, J.H., "An Overview of Methods for Monitoring Diesel Pollutants in Underground Mines," Mining Engineering Journal, Vol. 33, No. 9, pp. 1358-1367, September, 1981, AIME Transactions (mining), Vol. 269, 1981.

30. Hunter, G., Scholl, J., Hibbler, F., Bagley, S., Leddy, D., Abata, D., and Johnson, J., "The Effects of Fuels on Diesel Oxidation Catalyst Performance and the Physical, Chemical, and Biological Character of Diesel Particulate Emissions," SAE Paper No. 811192, October, 1981.
31. Hunter, G., "The Effect of an Oxidation Catalyst on Diesel Emissions," M.S. Thesis, Michigan Technological University, Houghton, Michigan 49931.
32. Ha, K., "The Computer Simulation of Diesel Exhaust Pollutant Concentrations within a Dead-Ended Heading in an Underground Mine," M.S. Thesis, Michigan Technological University, 1981.
33. Schock, H.J., Johnson, J.H., and Bunting, B.G., "Summary of Experimental Work Comparing Three Ventilation Configurations in a Downsloping Dead-Ended Drift," Transactions of SME of AIME, Vol. 270, pp 1964-1976, 1982.
34. Clerc, J.C., "A Computer Model for Predicting Temperature, Solids Concentration and Adsorbed Hydrocarbon Concentration for Dilute Diesel Particulate Emissions," M.S. Thesis, Michigan Technological University, 1982.
35. Clerc, J.C., and Johnson, J.H., "A Computer Heat Transfer and Hydrocarbon Adsorption Model for Predicting Diesel Particulate Emissions in Dilution Tunnels," SAE Technical Paper Series No. 821218, Presented at Fuels and Lubricants Meeting, Toronto, Ontario, Canada, October 18-21, 1982.
36. Miller, Paul, R., "A Study of Close-Coupled Exhaust Port Catalysts and Porous Ceramic Particulate Traps for Diesel Emission Control," M.S. Thesis, Michigan Technological University, 1982.
37. Miller, P.R., Scholl, J., Bagley, S., Leddy, D., and Johnson J.H., "The Effects of a Porous Ceramic Particulate Trap on the Physical, Chemical and Biological Character of Diesel Particulate Emissions," SAE paper 830457, Presented at International Congress & Exposition, Detroit, Michigan, February 28-March 4, 1983.
38. Johnson, J.H., "Monitoring Methods for Underground Diesel Pollutants," Diesels in Mining, World Mining/World Coal, November 1982.
39. Johnson, J.H., "The Control of Diesel Pollutants in Underground Mining," Paper submitted to 70th Annual National Safety Congress and Exposition, Chicago, October 18-21, 1982.
40. Johnson, J.H., and Carlson, D.H., "The Application of Advanced Measurement and Control Technology to Diesel Powered Vehicles in an Underground Salt Mine," Paper No. 102, 86th Annual General Meeting of CIM, Ottawa, Ontario, Canada, April 15-19, 1984.

41. Carlson, D.H., Final letter report to Mr. Harrison Daniel on Homestake Mine Air Quality Monitoring Study, U.S. Bureau of Mines, Purchase Order No. P3330635, May 13, 1983.
42. Daniel, H.J., "Diesels in Underground Mining: A Review and an Evaluation of an Advanced Air Quality Monitoring Methodology," Master Thesis, Graduate School, University of Idaho, August 1983.
43. Daniel, H.J., "Diesels in Underground Mining: A Review and an Evaluation of an Air Quality Monitoring Methodology," Bureau of Mines Report of Investigations, RI No. 8884, 1984.
44. Schaeffer, P.M., and Johnson, J.H., "Simulation of the Pollutant Concentrations for a Conventional Side and a Modified Rear LHD Exhaust System -- A Basis for an Engineering Approach to Diesel Pollutant Monitoring and Control in Underground Mines," Paper submitted to CIM Bulletin for publication.
45. Schnakenberg, G.H. Jr., Schaefer, P., and Johnson, J.H., "The Use of CO<sub>2</sub> Measurements in Monitoring Air Quality in Deadend Drifts," Proc. International Ventilation Conference, London, April 1984.
46. Carlson, D.H. and Johnson, J.H., Development of a Portable Underground Environment Air Quality Monitoring System, Final Report to Department of Energy, Mines and Resources, Canada for Contract No. OSQ82-00152, March 15, 1983.
47. Johnson, J.H. and Carlson, D.H., "A Study of Diesel Pollutants in an Underground Production Metal Mine Using an Advanced Monitoring and Data Analysis Methodology," Final Report to CANMET, Contract No. OSQ82-00210, March 1984.
48. Johnson, J.H., and Carlson, D.H., "A Study to Assess the Effects of Diesel Emissions on Air Quality in the PCS Mining Lanigan Division Underground Potach Mine," Final Report to CANMET, Energy Mines and Resources, Canada for Contract No. OSQ84-00228, February 15, 1985.
49. Miller, A.S., "Monitoring and Control of Diesel Pollutant Levels in Underground Mines Using the Pollutant Characteristic Curve Methodology," M.S. Thesis, Michigan Technological University, 1985.
50. Johnson, J.H., Carlson, D.H. and Schimmelman, M.K., "Monitoring and Control of Mine Air Diesel Pollutants: Mine Measurements and Interpretation Relative to Standards and Control Technology, Design and Development of a Tailpipe Emissions Measurement Apparatus (EMA-2) and On-Board Drift Ventilation Systems Evaluation," Annual Task Report to the U.S. Department of Interior, Bureau of Mines for Contract No. J0199125, Michigan Technological University, Houghton, Michigan 49931, February 15, 1984.

51. Keski-Hynnala, D.E., Reinbold, E.O., and Johnson, J.H., "Evaluation of Heading and Vehicle Ventilation Control Methods in Underground Mines Using Diesel Equipment," Paper presented at CIM Annual General Meeting, May 4, 1981.
52. Keski-Hynnala, D.E., Reinbold, E.O., and Johnson, J.H., "An Underground Mine Air Quality Laboratory for Studying Ventilation, Vehicle and Diesel Engine Pollutant Control Techniques," CIM Bulletin, Vol. 74, No. 835, November, 1981, pgs. 74-83.
53. Osborne, M.D., Johnson J.H., and Reinbold, E.O., "The Effects of Catalysts and a Particulate Trap on Diesel Emissions in Underground Mining, submitted for publication in the CIM Bulletin.
54. Osborne, M.D., "Development and Application of Data Collection and Analysis Techniques for Evaluating Aftertreatment and On-Board Fans for Control of Diesel Pollutants in Underground Mining," M.S. Thesis, Michigan Technological University, Houghton, Michigan 49931, 1982.
55. Johnson, J.H., Carlson, D.H., Osborne, M.D., Reinbold, E.O., Cornilsen, B.C., and Lorprayoon, V., "Monitoring and Control of Mine Air Diesel Pollutants: Tailpipe Emissions Measurements, Aftertreatment Device Evaluation, and Quantification of Diesel and Coal Fractions of Particulate Matter by Raman Spectroscopy," Annual Report to the United States Department of Interior, Bureau of Mines for Contract No. J0199125, Michigan Technological University, Houghton, Michigan 49931, November 15, 1982.
56. Johnson, J.H., Carlson, D.H., Reinbold, E.O., and Osborne, M.D., "Monitoring of Mine Air Diesel Pollutants: Tailpipe Emissions Measurement Apparatus, Detector Tube Interferences, and Exhaust Ventilation System Control," Annual report to the United States Department of Interior, Bureau of Mines for Contract No. J0199125, July 31, 1980, Michigan Technological University, Houghton, Michigan. NTIS Order No. PB82-148388.
57. Carlson, D.H., Osborne, M.D., and Johnson, J.H., "The Development and Application to Detector Tubes of a Laboratory Method to Assess Accuracy of Occupational Diesel Pollutant Concentration Measurements," American Industrial Hygiene Association Journal, Vol. 43, April 1982, Pages 275-285.