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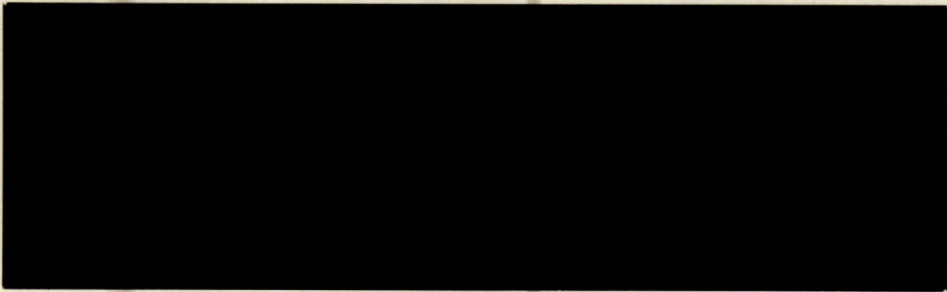


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MRL 86-81(OP)C.2

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Canmet Information  
Centre  
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JAN 25 1997  
555, rue Booth ST.  
Ottawa, Ontario K1A 0G1

1-7994561

**MONITORING AND ASSESSMENT OF AIR QUALITY IN  
DIESELIZED MINES**

M.K. Gangal, J.P. Mogan and E.D. Dainty

DIVISIONAL REPORT MRL 86-81(OP)

JUNE 1986

PRESENTED AT THE DISTRICT NO. 1 MEETING OF THE CIM, HALIFAX, NOVA SCOTIA,  
NOVEMBER 20-22, 1986.

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# MONITORING AND ASSESSMENT OF AIR QUALITY IN DIESELIZED MINES

*by*

M.K. Gangal\*, J.P. Mogan\* and E.D. Dainty\*

## ABSTRACT

The monitoring techniques, presently used at CANMET, for the assessment of diesel pollutants generated by diesel vehicles in underground mines, are described. A comparison of gaseous measurements performed in underground mines by different techniques, including long-term detector tubes, integrated real time analysis, and Palmes samplers, is given. Finally, the concept of using Air Quality Index (AQI) criterion for quantitatively assessing the underground environment in dieselized mines is discussed.

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\* Research Scientists, Mining Research Laboratories, CANMET, Energy, Mines and Resources, Ottawa, Ontario, Canada.

# SURVEILLANCE ET ÉVALUATION DE LA QUALITÉ DE L'AIR DANS LES MINES OÙ DE L'ÉQUIPEMENT DIESEL EST UTILISÉ

*par*

M.K. Gangal\*, J.P. Mogan\* et E.D. Dainty \*

## RÉSUMÉ

L'auteur donne une description des techniques de surveillance utilisées actuellement par le CANMET pour l'évaluation des gaz polluants s'échappant de l'équipement diesel dans les mines souterraines. Il établit également une comparaison entre les différentes techniques de mesure des gaz d'échappement dans les mines souterraines, y compris les appareils de détection à long terme, l'analyse intégrée en temps réel et les échantillonneurs Palmes. Enfin, l'utilisation du critère "Indice de la qualité de l'air (IQA)" pour l'évaluation quantitative de l'environnement souterrain dans les mines où de l'équipement diesel est utilisé, est examinée.

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\* Chercheurs Scientifiques, Laboratoires de Recherche Minière, CANMET, Énergie, Mines et Ressources, Ottawa, Ontario, Canada.

## KEY-WORDS

Monitoring	Diesel emissions
Underground environment	Air quality
Palms samplers	Instrumentation
Ventilation	Diesel soot
Noxious gases	Long-term detector tubes

## MOTS-CLÉS

Surveillance	Émissions de diesel
Environnement souterrain	Qualité de l'air
Échantillonneurs de Palmes	Appareillage
Ventilation	Suie de diesel
Gaz nocifs	Tubes de détection de longue durée

## INTRODUCTION

Diesel machines are extensively used in highly mechanised Canadian mines, mainly from the point of view of reduced costs resulting from greater mobility. During the operation of these machines a number of pollutants are emitted into the mine environment, which create a health hazard to workers. The pollutants of main concern to the workers and the potential ones which we monitor in the mines are: carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), nitric oxide (NO), nitrogen dioxide (NO<sub>2</sub>), sulphur dioxide (SO<sub>2</sub>) and respirable combustible dust (RCD).

It is important that the pollutants be monitored as accurately as possible in order to determine the quality of air to which workers are exposed, and to study the effectiveness of various devices used in the mine to control diesel pollutants. It has been a common practice to determine the gas concentrations in mines by using short-term detector tubes which do not provide the mean value of gas concentration during the worker's full shift. Also, the precision is poor. The large number of interfering substances in diesel pollutants contribute to the lack of precision.

During the last few years, a monitoring methodology was developed by Michigan Technological University (MTU) under a contract to the U.S. Bureau of Mines. In 1983 CANMET acquired a similar system from MTU in the form of a portable instrumentation package incorporating a CO, CO<sub>2</sub>, NO, NO<sub>2</sub>, and particulate matter monitoring system for use in underground Canadian mines (1). Since then, this system has continuously been modified based on our field experience, and has been used at a number of production mines to evaluate the underground mine environment and to assess the effectiveness of diesel emissions control technology (2,3).

This paper summarizes the instrumentation and techniques which we have been using in mines to monitor the underground environment. The pollutants measured are mostly time-weighted-average (TWA) values and can be used in characterizing the combined effects of the major diesel pollutants, using the recently developed Air Quality Index (AQI) criterion. The AQI criterion and its usefulness in controlling the pollutants in mines are also described in detail.

We hope that the information provided here will be beneficial to those who need to monitor and control the mine environment.



## DIESEL EXHAUST POLLUTANTS

Diesel exhaust is a mixture of many compounds which are emitted in the mine environment when diesel fuel is burned in the engine. The main gaseous components present in diesel emissions are: nitrogen oxides, sulphur oxides, carbon monoxide and carbon dioxide. Diesel exhaust also contains particulate matter (diesel soot). All of these gaseous and particulate constituents are recognized as pollutants and should be monitored and controlled to minimize the health risk to workers.

The standards limiting the exposure to diesel pollutants are governed by provincial inspectorates and may vary from province to province. However, these limiting values are, in some form, based on threshold limit values (TLV's) set by the American Conference of Government and Industrial Hygienists (ACGIH).

## AIR QUALITY INDEX

The air quality index (AQI) was developed in 1977 in response to requests from the mining industry and regulatory agencies for a ventilation criterion, which, in addition to providing an engine specific recommendation, could also take account of the differences in exhaust gas composition resulting from the application of a variety of emission control strategies. The contractor engaged by CANMET, Ian W. French and Associates, examined the sparse (pre-1977) literature on the health impact of exposure to diesel exhaust, plus the voluminous information on exposure to various exhaust components, (CO<sub>2</sub>, CO, NO<sub>2</sub>, SO<sub>2</sub>, hydrocarbons etc.), both alone and in combination with respirable particles (4). From this they formulated a mathematical representation of the interaction between these components which they called "V" (5):

$$V = \frac{CO}{50} + \frac{NO}{25} + \frac{RCD}{2} + 1.5 \left[ \frac{SO_2}{3} + \frac{RCD}{2} \right] + 1.2 \left[ \frac{NO_2}{3} + \frac{RCD}{2} \right] = AQI$$

where CO, NO, NO<sub>2</sub> and SO<sub>2</sub> are concentrations in the ambient air in parts per million (ppm) and RCD is the concentration of Respirable Combustible Dust in the ambient air in mg/m<sup>3</sup> (In a typical mine, the contractors estimated that RCD would contain about 75% diesel soot).

From an examination of the levels of "V" in dieselized underground mines, plus available epidemiological evidence, the contractors concluded that a level of "V" below 3 would minimize risks to health. At "V" between 3 and 4 they suggested the use of personal protective equipment (such as Air Stream Helmets), and above 4, indicated that the level of ventilation should be increased (5).



"V" was later renamed the Air Quality Index or AQI. Calculating a similar value for the concentrations of the same substances in undiluted exhaust produces the EQI, or Exhaust Quality Index. Since the goal is an AQI of 3, dividing the EQI by 3 yields the number of equivalent volumes of fresh air which must be added to the exhaust to reach an AQI of 3: a ventilation recommendation. The AQI/EQI concept thus provides a means for comparing emission control strategies, and for developing recommended ventilation levels for treated and untreated exhaust, or for use of "Special" or "Regular" fuel (6).

During the period 1979 to 1984, the diesel was perceived as the ideal replacement for passenger car engines. The unknown implications of this potentially large increase in urban diesel soot burden stimulated a substantial government and industry research program of diesel health effects research. This work included a number of programs involving animal exposure to dilute diesel exhaust. Several of the investigations spanned the levels of exposure to diesel contaminants which are normally encountered in dieselized underground mines and thus provided an unparalleled opportunity to compare the contractor's action level of 3 with the results of controlled animal studies (The contractors issued an 607 page update on the topic in 1984 (7) summarizing this new information). Some of the relevant animal study results are summarized in Table 1.

If the AQI of the General Motors study at  $0.25 \text{ mg/m}^3$  is adjusted for exposure duration, it becomes  $0.6 \times 20 \times 5.5 / 40 = 1.6$ . This is not far off the other (Lovelace) value of 1.1 for which no adverse response was observed. At the next lowest AQI value (after the other GM levels have also been adjusted for exposure duration), 4.9, the animals exhibited symptoms of obstructive lung disease, and lung tissue damage. Thus these animal studies definitively established that the contractor's 1977 AQI recommendation of 3 maximum was not unduly conservative.

The AQI reflects the interaction of various components of diesel exhaust which impair the mechanisms by which oxygen reaches the cells of the body. It does not contain any parameter which is relevant to the role of diesel soot as a tumorigenic agent. Animal studies at Southwest Research Institute (SWRI), sponsored by General Motors, at the same exposures as the General Motor Research studies, Table 1, yielded an anomalous incidence of malignant lung tumours (15) (The anomaly consisted of a higher incidence at the middle exposure). Animal studies at higher exposure levels have recently been presented which suggest that the SWRI findings are part of a continuum and are thus indicative of a real hazard at the SWRI exposure levels. Fortunately, these studies also show that the excess tumour production disappears when the soot is removed from diesel exhaust; a fact which has considerable significance regarding the role of soot filters (such as the Corning unit) in future underground diesel operations.

Table 1- Exposure of Animals to Dilute Diesel Exhaust

Laboratory	Engine	Cycle	Exposure duration	Species	Soot Concentration mg/m <sup>3</sup>	AQI	Health impact		References
							Tissue response	Respiratory function	
General Motors Research	GM 5.7 L passenger car diesel	64 km/h	20 hours/day 5.5 days/week	rats, guinea pigs	0.25	0.6	normal	normal	8, 9
					0.75	2.0	quasi pathological changes	normal	
					1.5	3.9	quasi pathological changes	normal	
Environmental Protection Agency Health Effects Research Laboratory	Caterpillar 3304	Coal mine tramcar cycle	7 hours/day 5 days/week	rats, monkeys	2.0	4.9	pathological changes	obstructive lung disease	10, 11
Lovelace Biomedical and Environmental Research Inst.	GM 5.7 L passenger car diesel	FTP urban cycle	7 hours/day 5 days/week	rats, mice	0.35	1.1	normal	normal	12
					3.5	10.6	pathological changes	restrictive lung disease	
					7.0	19.3	pathological changes	restrictive lung disease	
Fraunhofer Institut fur Toxikologie und Aerosolforschung	Mercedes 2.4 L	25% load at 2400 rpm	7 hour/day 5 days/week	hamsters	4.2	10.5	some tissue abnormalities	normal	13
Environmental Protection Agency Health Effects Research Laboratory	Nissan 3.24 L	FTP short cycle	8 hours/day 7 days/week	hamsters, cats	6.3	16.6	—	normal (after 1 year)	14
					11.7	27.4	pathological changes	restrictive lung disease	

The mutagenic activity of the soluble fraction of diesel soot has been accepted as indicative of carcinogenic potential (16). The mutagenic activity of the soluble fraction of soot from engines normally used underground is significantly lower than that of the GM engine (17). Catalytic purifiers, however, increase the mutagenic activity to levels above the GM unit (17, 18). Thus some degree of safety is present due to duration and engine type even though the low SWRI exposure is below current mine levels. The effect of a catalytic purifier on this safety margin is, however, as yet uncertain.

## MONITORING DIESEL POLLUTANTS

We use various devices and instruments for monitoring CO, CO<sub>2</sub>, NO, NO<sub>2</sub>, and particulate matter. These are described in this section with emphasis on their use in the mining environment. References to specific instruments does not constitute an endorsement of the equipment.

### Electronic Instruments

The real time monitoring of CO, CO<sub>2</sub>, NO and NO<sub>2</sub> gases is done by using electronic instruments. These instruments are mainly designed for applications on the surface, but with reasonable precautions they can be used in harsh underground conditions. All of the instruments described here operate on rechargeable batteries, which are sufficient for continuous operation for a full mine shift. These instruments are suitable for fixed point monitoring only and should not be moved in the mine from one location to another while operating.

The instrument used to measure CO concentration in the ambient air is contained in an aluminium carrying case with dimensions 33.0 x 18.7 x 18.7 cms. and is shown in Fig. 1. The instrument contains an electrochemical sensor which produces an electrical current output, the magnitude of which represents the level of gas in the sample. The resulting current is amplified and displayed on the front panel of the instrument in parts per million (ppm) with  $\pm 1$  percent of full scale accuracy. The instrument comes with dual ranges of 0-50 ppm and 0-100 ppm. We found that this instrument is easy to use and requires few calibrations during continuous operation for a full shift. The instrument is used for real time CO monitoring traces at a fixed location and for reading the CO bag for TWA results, discussed later.

The equipment used for NO and NO<sub>2</sub> monitoring, based on the electrochemical cell principle, is contained in an aluminium carrying case with dimensions 40.6 x 20.3 x 20.3 cms. and is shown in Fig. 2. It contains two separate instruments with dual ranges for NO

(0-10 and 0-50 ppm) and NO<sub>2</sub> (0-2 and 0-10 ppm) with  $\pm 1$  percentage of full scale accuracy. These instruments are also easy to use in the field provided span gas concentrations are sufficiently stable to carry out measurements. They require more frequent calibrations than the CO instrument when used in a mine.

With the Ecolyzer instruments, it was necessary to change the electrochemical cell whenever it was not possible to adjust the zero and span readings during the calibration process. On an average, a cell lasts from six to twelve months. It is advisable to purchase the cells just before the field work as they are expensive and do not have a long shelf-life. If the instruments are to be used in a very dusty areas of a mine then it is advisable to use a filter in the intake air sample to remove particulates.

Figure 3 shows a Fuji ZFP5 NDIR (non-dispersive infrared ray system) CO<sub>2</sub> gas analyzer with dimensions of 15.5 x 21.5 x 26.5 cms. The instrument has dual ranges of 0-0.2 % and 0-0.5 % with  $\pm 5$  percentage of full scale accuracy at the low range and  $\pm 10$  percentage accuracy at the high range. It is a very reliable and trouble-free instrument and does not require frequent calibrations in the field.

All of the instruments discussed above provide voltage outputs for real time tracing of pollutants using chart recorders. The recorder we use is a Rustrack model 288, which is contained in a surplus army box along with a rechargeable battery, and is shown in Fig. 4. The recorder was modified in the laboratory to provide a fixed chart speed of 76.2 centimeter per hour (30 in./hr.) and to facilitate the span calibration of the recorder. The chart recorders are used with gas monitoring instrumentation to monitor mucking operations using LHD's and to study the effectiveness of ventilation in flushing out pollutants. The TWA values of pollutants are calculated by integrating the pollutant curves using a Hi-State Electronic Digitizer.

All of the the electronic instruments mentioned above require suitable calibration for zero and span readings. Surface calibration is not suitable because of temperature differences and effects of moving the instruments underground. For zero and span calibration purposes we use large aluminium cylinders (about 5 m<sup>3</sup> of gas at STP) which are commercially available. However, the stated concentration values in these cylinders are not always stable. Therefore, we also use standard gases available from the National Bureau of Standards (NBS), which are more reliable and stable. These gases are used mainly to check the concentration of gases in large cylinders. Unfortunately, NO<sub>2</sub> span gas is very unstable and is not available from NBS. Therefore, we use the laboratory chemiluminescent analyser with various NO<sub>2</sub> span gases in the laboratory to check NO<sub>2</sub> gas concentration in large cylinder.

The large cylinders are too bulky for instrument calibration in mines. We use the small cylinders (about 0.2 m<sup>3</sup> gas at STP) shown in Fig. 5 to carry span and zero gases in mines. The smaller cylinders are filled at the surface from the large cylinders. Gas transfer at high pressures can be very dangerous and should not be done by inexperienced personnel who are not familiar with the potential safety hazards.

#### CO and CO<sub>2</sub> Monitoring by Bag Method

The time-weighted-average concentration values for CO and CO<sub>2</sub> are determined by collecting the ambient mine air sample in a 22-litre Calibrated Instruments snout-type bag by using a Dupont P125 constant flow pump running at approximately 50 cc/min flow rate. At the end of the shift the gas sample in the bag is analyzed by using recently calibrated electronic instruments. The bags are very durable and can be reused often. The whole assembly is neatly placed in a plywood box as shown in Fig. 6. This method is inexpensive and suitable for multi-location measurements. This method is not suitable for NO and NO<sub>2</sub> measurements.

#### NO and NO<sub>2</sub> Monitoring by Diffusion Method

The Palmes sampler for the measurement of nitrogen dioxide (NO<sub>2</sub>) and total oxides of nitrogen NO<sub>x</sub> (= NO and NO<sub>2</sub>), based on the principle of molecular diffusion, was developed by New York University on a USBM contract. The sampler is made of rigid plastic tubing of fixed dimensions and is shown in Fig. 7. In our underground work, we use samplers in triplicate for NO<sub>2</sub> and NO<sub>x</sub>, and the concentration of NO is determined from the difference. The samplers in sufficient quantity are prepared in the laboratory just few days before intended use. It is important that the makeup of samplers and the final analysis should be completed within 30 days, otherwise the results may be in error. We have found good repeatability among triplicate samplers. For reliable results, the concentration of the gas in parts per million times the total sampling period in hours should be at least one. If gas concentration at a sampling site is low, sampling should be done for a longer period. Further details on the use of Palmes samplers can be found in several references (19, 20, 21).

The samplers are very easy to use in the field. Simply uncap three samplers each for NO<sub>2</sub> and NO<sub>x</sub> at the sampling site. Recap all samplers at the end of the sampling time, and note down the sampling time and sampler identification numbers. Since samplers are analyzed in the laboratory, results are not available immediately.

For preparation the samplers are thoroughly cleaned in the laboratory to remove any residue, and clean stainless steel screens are chemically coated with triethanolamine (TEA) to trap  $\text{NO}_2$ . Three screens are stacked in each of the samplers. For  $\text{NO}_x$  samplers, chromic acid discs are prepared in the laboratory and inserted in the samplers just before their use at the mine. The chromic acid disc is used to convert  $\text{NO}$  to  $\text{NO}_2$  which is then trapped by the TEA coated screens in the  $\text{NO}_x$  sampler. The chromic acid disc is removed from the samplers after sampling is completed. The analysis for  $\text{NO}_2$  and  $\text{NO}_x$  is done in the laboratory by dissolving the trapped  $\text{NO}_2$  in the freshly prepared reagent. Colorimetric analysis of the solution is performed by using the Spectrophotometer, shown in Fig. 8. The results are given in parts per million x hours. The average concentration is determined by dividing this number by the sampling time in hours. While laboratory work associated with Palmes samplers is precise, it is very time consuming. It should be undertaken only by trained personnel.

#### Dräger Long-Term Detector Tubes

The long-term detector tubes are used to determine the mean value of gas concentrations in the ambient air over a sampling period. It is a very simple device to use and provides concentration on the spot with simple calculations. The instruments required for this system is a Dräger Polymer Pump with dimensions 5.0 x 8.5 x 17.0 cms., shown in Fig. 9, and a detector tube for the gas to be measured. We use detector tubes to determine  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{NO}_2$ , and  $\text{NO}_x$  concentrations.  $\text{NO}$  values are determined from differences in  $\text{NO}_x$  and  $\text{NO}_2$  values. Some details on the tubes are given in Table 2. Use of the tubes in field is simple. The tips of the detector tubes are broken and inserted in the Polymer. A counter reading for the pump is recorded and the pump is switched on. At the end of the sampling period the pump is switched off and the final counter reading taken. The detector tube is located inside the Polymer in such a way that the tube is protected against external damage. The Polymer contains a hose pump, which continuously sucks air through the tube at a fixed volume rate of 15 cc/min. A counter on the Polymer records the number of revolutions of the pump, so that the total air volume rate can be calculated. The hose in the Polymer should be changed before each measurement.

The detector tube is marked with numbers in microlitres. The sampling gas reacts with the chemicals in the tube and the layers change color. The discoloration of layers for different gases is indicated in Table 2. The total length of discoloration can be read easily which indicates the measure of the concentration. The actual mean value of the gas concentration is obtained by dividing this number by the volume of air passed through the tube in litres. A volume of approximately one litre is passed through the tube in one hour.

The exact value of the air volume is determined by the difference of the initial and final counter readings multiplied by the known hose factor (this is given on each hose pack).

**Table 2- Dräger Long-Term Tubes for the Measurement of Gases**

Type of tube	Max. period of use (h)	Measuring range( $\mu\ell$ )	Discoloration	Measuring range for max. period use*
CO	4	10-100	white→ brown	2.5-25 ppm
CO <sub>2</sub>	4	1000-6000	orange→ pale yellow	0.025-0.15 %
NO <sub>2</sub>	8	10-100	yellow→ blue-grey	1.25-12.5 ppm
NO <sub>x</sub>	4	5-50	white→ brown	1.25-12.5 ppm

\* higher concentration can be measured by sampling for shorter period

The Polymer pump has a rechargeable battery and is sufficient for a continuous eight hours of sampling. For reliable operation of the system, the pump should be fully charged and checked for flow rate before each measurement.

### SO<sub>2</sub> Determination

SO<sub>2</sub> is not measured directly but calculated from CO<sub>2</sub> concentration, the fuel sulphur content in the diesel fuel, and the assumption that all of the fuel is combusted. For exhaust which is passed through a properly working PTX catalytic convertor, 90% of the fuel sulphur is assumed to be combusted to SO<sub>2</sub> and 10% to SO<sub>4</sub>. This conversion rate is likely to be on the low side for a normally operating LHD machine. For exhaust gas passed through the ceramic filter, 97.5% of the fuel sulphur is assumed to be combusted to SO<sub>2</sub> and 2.5% to SO<sub>4</sub>.



## Particulate Matter Measurement

Particulate matter measurements are made in duplicate by drawing air through a 10 mm nylon cyclone using a Dupont P4000 constant air flow pump. The particulate matter is collected on a preweighed 37 mm Gelman A/E fiber glass filter which is supported in the cassette by a clean stainless steel screen. The collection device is shown in Fig. 10. The total particulate matter is calculated by reweighing the filter after the sample collection and dividing the increase in weight by the air volume flow rate through the pump during the sampling period.

Usually the amount of particulate matter collected is very small, and even a small amount of moisture on the filter can result in a significant error in particulate matter determination. Therefore, all the filters are oven dried at 150°C just prior to weighing on an ultramicrobalance.

The respirable combustible dust (RCD) is calculated by combusting the sample for about four hours in a preheated oven at 500°C. The weight loss on the filter is due to the combustible matter which, when divided by the air volume flow rate, gives the RCD part of the total dust. In the case of low dust concentration level the cyclone from the dust assembly system may be removed in order to collect a measurable amount of sample on the filter for weighing. During such measurements the assumption is made that most of the combusted dust is respirable and is diesel soot. If there is an excess source of non-diesel combusted material in the environment (such as in the ore, oil leakage from the machines, oil mists from the drills etc.), then this source may be determined separately and subtracted from the filter measured dust in order to calculate the diesel-produced RCD only. Table 3 provides a list of items used in the collection of dust samples and their analysis along with comments on the method used for the determination of RCD.

The Gelman A/E fiber glass filters are suitable for RCD measurement because of their relatively low and fairly constant background level of combustible materials. Table 4 shows moisture contents and the amount of combustible material in clean and unused filters. The mean value for moisture content and combustible material is respectively 0.13 mg and 0.27 mg. It should be noted that for the five filters tested, combustible material varied between 0.26 and 0.29 mg. The combustible fraction of the filter material would appear to be reasonably constant. In our dust analysis data was corrected to allow for the combustible material filter component.

**Table 3- Items Required for Respirable Combustible Dust Measurement**

Items required	Application	Comments on measurement
Dupont P4000 pump	-High flowrate sampling pump	Easy to use.
Dust sampler assembly	-Filter, screen & cassette holder	Delayed results.
Cyclone	-Coarse dust remover	TWA total
Gelman A/E glass fibre filter	-Filter for dust samples	particulate matter.
Bubble meter	-Calibrate pumps	TWA respirable
Perkin Elmer electronic ultramicrobalance	-Weigh dust filters	combustible dust.
Oven to heat at 150°C	-Remove moisture from filter	Duplicate samples.
Oven to heat at 500°C	-Combust dust	Require daily check of pumps.

**Table 4- Amount of Combustible (comb.) Material in Glass Fiber Filters**

Sample number	Weight at room temp. mg	Dry weight at 150°C mg	Non-comb. material mg	Weight of moisture mg	Weight of comb. material mg
1	72.27	72.16	71.90	0.11	0.26
2	73.06	72.92	72.63	0.14	0.29
3	70.14	70.03	69.75	0.11	0.28
4	71.01	70.87	70.60	0.14	0.27
5	70.86	70.70	70.44	0.16	0.26
Mean	71.47	71.34	71.06	0.13	0.27

## DISCUSSION ON GASEOUS MEASUREMENTS IN MINE

The instruments, devices and methods used for the determination of CO and CO<sub>2</sub> in the mines, described in the previous sections, are summarized in Table 5 for comparison purposes. The table also includes general comments on each method and should not be taken as comments on the items required. It should be noted that real time monitoring requires the use of electronic analyzers and chart recorders. The TWA values can easily be

**Table 5- CO/CO<sub>2</sub> Measurement Techniques**

Method	Items required	Comments on method only
Bag method	<ul style="list-style-type: none"> <li>-Ecolyzer electro-chemical CO analyser</li> <li>-Fuji infrared CO<sub>2</sub> analyser</li> <li>-Dupont constant flow pump</li> <li>-22 litre snout-type 5 layer bag</li> <li>-5 micron nominal filter</li> <li>-Zero and span calibration gases</li> </ul>	<ul style="list-style-type: none"> <li>Easy to use.</li> <li>Reliable.</li> <li>Fast results.</li> <li>Reusable bags.</li> <li>TWA values.</li> <li>Calibration required at the end of test.</li> <li>Inexpensive for multi measurements.</li> </ul>
Long-term tubes	<ul style="list-style-type: none"> <li>-Dräger polymeter pump</li> <li>-Long-term tubes for CO/CO<sub>2</sub></li> </ul>	<ul style="list-style-type: none"> <li>Very easy to use.</li> <li>Fast results.</li> <li>Not suitable for very low concentrations.</li> <li>TWA values.</li> </ul>
Electronic instruments	<ul style="list-style-type: none"> <li>-Ecolyzer electro-chemical CO analyser</li> <li>-Fuji infrared CO<sub>2</sub> analyser</li> <li>-Rustrack paper chart recorder</li> <li>-Zero and span calibration gases</li> </ul>	<ul style="list-style-type: none"> <li>Require calibration at the test site.</li> <li>Provide traces.</li> <li>Delayed TWA values.</li> <li>Time consuming.</li> <li>More suitable for real time traces.</li> </ul>

determined by use of long-term detector tubes, provided the gas concentration at the site is within the measuring range of the tubes.

Table 6 compares the results of underground mine CO and CO<sub>2</sub> measurements by bag collection and long-term tube methods. It should be noted from the limited tests that the ratio of gas concentrations by the bag and Dräger methods varies from 0.93 to 1.08, with a mean value of 1.01 for CO, and from 0.94 to 1.12 with a mean value of 1.03 for CO<sub>2</sub>, which indicates that both methods are suitable. Therefore, one method over the other can be selected on the basis of the availability of instrumentation, number of simultaneous measurements to be made, cost of measurements and the expertise available. We feel that the Dräger method is very convenient for mine use. However, further testing of the Dräger method is warranted and planned.

**Table 6— CO/CO<sub>2</sub> Results by Bag Method and Long-Term Dräger Tubes**

Day	CO			CO <sub>2</sub>		
	ppm		Ratio	%		Ratio
	Bag	Dräger	$\frac{\text{Bag}}{\text{Dräger}}$	Bag	Dräger	$\frac{\text{Bag}}{\text{Dräger}}$
1	4.10	3.81	1.08	0.194	0.207	0.94
2	5.10	5.48	0.93	0.211	0.189	1.12
Mean	4.60	4.65	1.01	0.203	0.198	1.03

The measurement techniques for determining NO and NO<sub>2</sub> along with the items required for each method plus comments on the methods, are provided in Table 7. It is our feeling that the most suitable method is the long-term tubes method as the other two methods are very time consuming and tedious, and require a great deal of expertise.

The simultaneously measured values of NO<sub>2</sub> and NO<sub>x</sub> in a mine by Palmes samplers, and the values from integrated real time traces, are given in Table 8. For sampling days 1-4 the LHD machine operating in the test area was equipped with catalytic convertors while for days 5-7 the machine was equipped with ceramic filter traps. There is a noticeable difference in NO<sub>2</sub> concentrations for the two test methods. However, the mean NO<sub>2</sub> values suggests that both methods appear to provide acceptable overall results. The mean values for NO<sub>x</sub> differ more than the NO<sub>2</sub> values. However, the mean values suggest that the gas sampling methodology is adequate for engineering evaluation of the air quality in mines.

Table 7- NO/NO<sub>2</sub> Measurement Techniques

Method	Items required	Comments on method only
Diffusion Method	<ul style="list-style-type: none"> <li>-Palmer personal samplers</li> <li>-Sequoia-Turner spectrophotometer</li> <li>-Mettler electronic balance</li> <li>-Various chemicals</li> </ul>	<p>Easy to use at the site.            Delayed results.            Suitable for multi measurements.            TWA values.            Preparation and analysis is very time consuming and tedious.</p>
Long-term tubes	<ul style="list-style-type: none"> <li>-Dräger Polymer pump</li> <li>-Long-term tubes for NO<sub>2</sub>/NO<sub>x</sub></li> </ul>	<p>Very easy to use.            Fast results.            Not suitable for very low concentrations.            TWA values.</p>
Electronic instruments	<ul style="list-style-type: none"> <li>-EcoLyzer electro-chemical NO/NO<sub>2</sub> analyser</li> <li>-Rustrack paper chart recorder</li> <li>-Zero and span calibration gases</li> </ul>	<p>Require frequent calibration at site.            Delayed TWA values.            Time consuming.            More suitable for real time traces.            Problems with NO<sub>2</sub> span gas.            Provide traces.</p>

**Table 8– NO<sub>2</sub>/NO<sub>x</sub> Results by Palmes Samplers and Integrated Real Time Traces**

Day	Sample time (h)	NO <sub>2</sub> (ppm)		NO <sub>x</sub> (ppm)	
		Palmes	Integrated	Palmes	Integrated
1	3.27	0.39	0.15	1.73	2.00
2	5.33	0.13	0.28	1.57	2.99
3	4.97	0.15	0.29	–	–
4	4.75	0.34	0.31	–	–
Mean (1–4)	4.58	0.25	0.26	1.61	2.50
5	4.77	0.17	0.10	1.66	1.03
6	3.88	0.09	0.21	2.98	2.73
7	4.67	0.14	0.04	2.08	1.81
Mean (5–7)	4.44	0.13	0.12	2.24	1.86

Table 9 compares the results of simultaneously measured values of NO<sub>2</sub> and NO<sub>x</sub> in a mine by Palmes sampler and Dräger long-term detector tubes. In general, gas concentrations by Dräger tubes provide higher values than Palmes samplers. On the average, the results for NO<sub>2</sub> and NO<sub>x</sub> measured by Palmes samplers are 0.67 times the level obtained with Dräger tubes. The measurement by Dräger tubes may not be possible in areas of low concentrations. The minimum sampling time period can be calculated from the information provided in Table 2.

Table 9— NO<sub>2</sub>/NO<sub>x</sub> Results by Palmes Samplers and Long-Term Dräger Tubes

Day	NO <sub>2</sub>			NO <sub>x</sub>		
	ppm		Ratio	ppm		Ratio
	Palmes	Dräger	$\frac{\text{Palmes}}{\text{Dräger}}$	Palmes	Dräger	$\frac{\text{Palmes}}{\text{Dräger}}$
1	0.95	1.39	0.68	8.28	10.08	0.82
2	0.62	0.92	0.67	5.99	12.02	0.50
Mean	0.79	1.16	0.68	7.14	11.04	0.66

### SUMMARY AND CONCLUSIONS

The monitoring techniques and devices described in this paper are adequate for monitoring diesel-produced pollutants in underground mines for the purpose of air quality assessment. However, some modifications or new methods need to be evaluated in order to make the methodology simpler and more portable. Only the instruments we have used in production mines are discussed in this paper, and no attempt is made to cover all the instruments which might be commercially available. The main aim is the development of monitoring techniques to permit better air control for the health of miners. Our experience leads to the following comments:

1. The Palmes samplers for time-weighted-average monitoring of NO and NO<sub>2</sub> are simple and practical to use at the mine. We have found an excellent repeatability between triplicate samplers. The samplers makeup and analysis are time consuming, and should be done by trained personnel only. At low gas concentrations the samplers require a longer sampling time for accurate results.
2. The limited underground testing of Dräger long-term tubes for the monitoring of CO, CO<sub>2</sub>, NO<sub>2</sub>, and NO<sub>x</sub> provided reasonably accurate measurements. They are very simple, portable and practical to use and provide fast results without need of calibration system. They might not be suitable for gas measurements at very low concentrations. Perhaps, in future, the bulky items and time consuming analysis required in other gas monitoring techniques can be replaced by the use of long-term tubes.
3. Electronic instruments for gaseous measurements are more suitable for real time monitoring. Frequent field calibration is required and the calibration gases may not be stable



during long periods. NO<sub>2</sub> is very unstable at low concentration levels, suitable NBS gas cylinders for this gas are not available.

4. The bag sampling method for CO and CO<sub>2</sub> is simple and inexpensive and calibration of the analysers is required only once at the time of bag reading.
5. The measurement for RCD is simple and practical to use at the mine where no other source of combustible materials are present. However, in practice, there is almost always some non-diesel combustible matter present (such as from ore dust, drill oil mist, leaked lubricating or hydraulic oil from the hot surfaces of engines etc.), which can have a large influence on RCD measurements. Therefore, further work is required to estimate the non-soot component of RCD. Any significant deviation from the estimated 75% soot in the RCD measurement will bias the AQI determination because of three RCD terms in the AQI expression.
6. The AQI criterion is a very practical and powerful tool to evaluate the air quality and to assess the effectiveness of various options to control diesel pollutants.
7. Recent diesel-exhaust animal exposure studies indicate that removal of the soot fraction (with a Corning filter for example) can significantly reduce the risk to health of workers in underground dieselized mines.

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#### ACKNOWLEDGEMENTS

The authors want to acknowledge the following individuals who have contributed to our knowledge on the instrumentation described and to the results presented in this paper.

J.H. Johnson, D.H. Carlson and A. Johnson of Michigan Technological University,  
G. Schnakenberg, Jr. and J.E. Chilton of USBM,  
M. Bapty and L. Weitzel of COMINCO Ltd.,  
R. Blanchard of Brunswick Mining and Smelting,  
D. McKinnon and K. Wheeland of Noranda Research, and  
J. Vallieres, E. Dainty and J. Ebersole of CANMET.

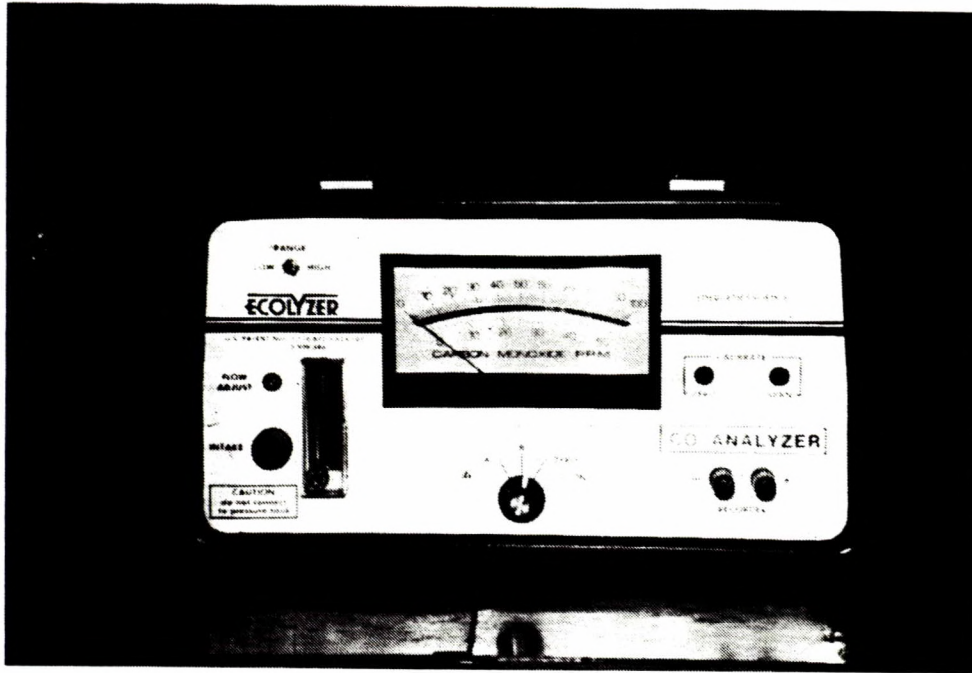


Fig. 1- Ecolyzer 2106 CO analyzer

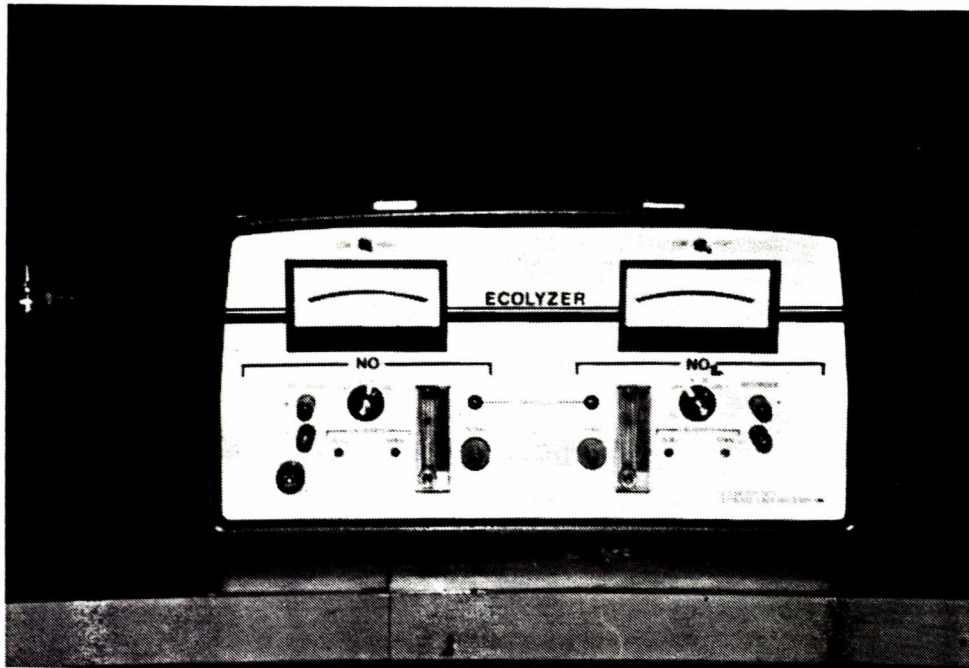


Fig. 2- Ecolyzer 7230 NO/NO<sub>2</sub> analyzer

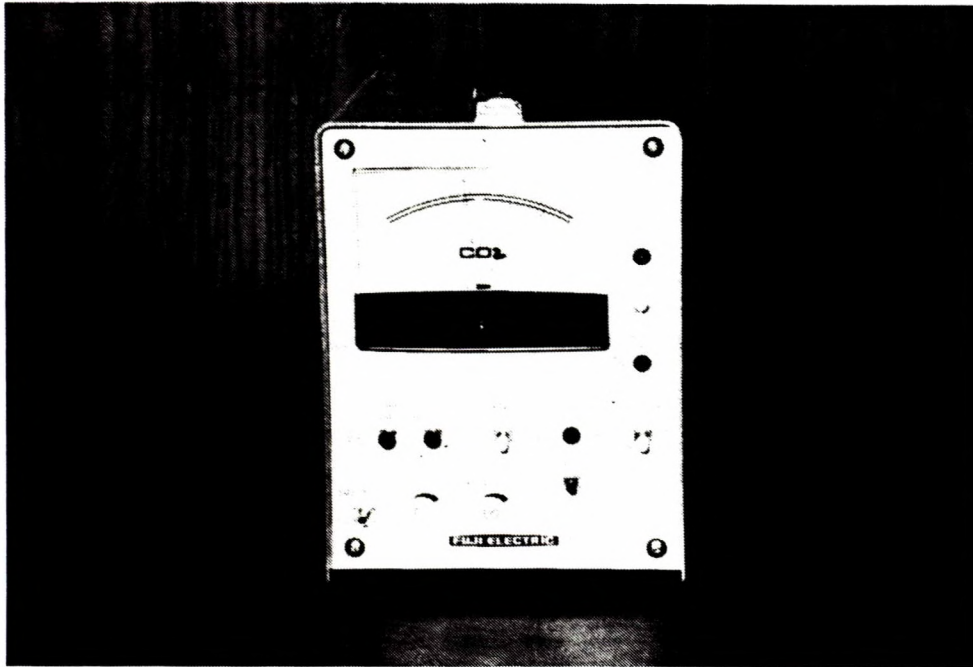


Fig. 3- Fuji ZFP5 CO<sub>2</sub> analyzer

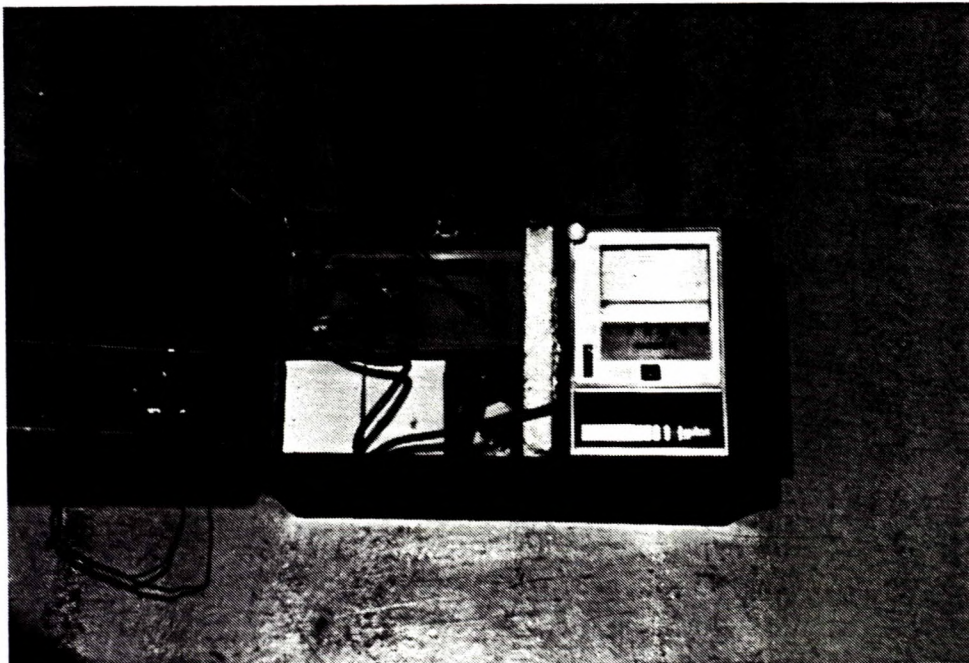


Fig. 4- Rustrack 288 chart recorder



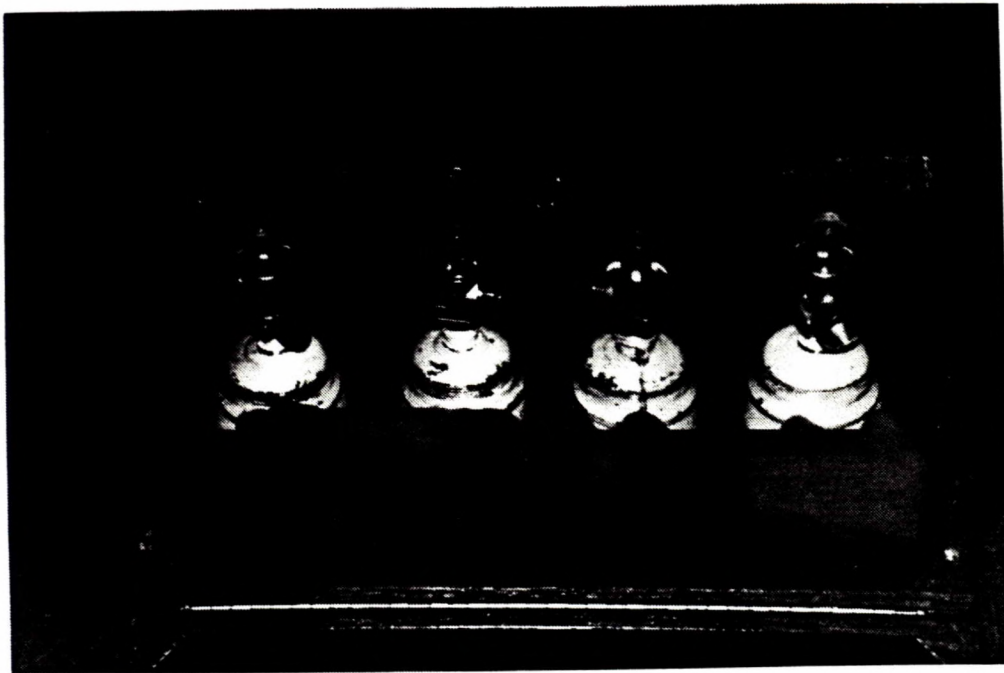


Fig. 5- Portable span gas bottles for in-mine calibration of electronic analyzers

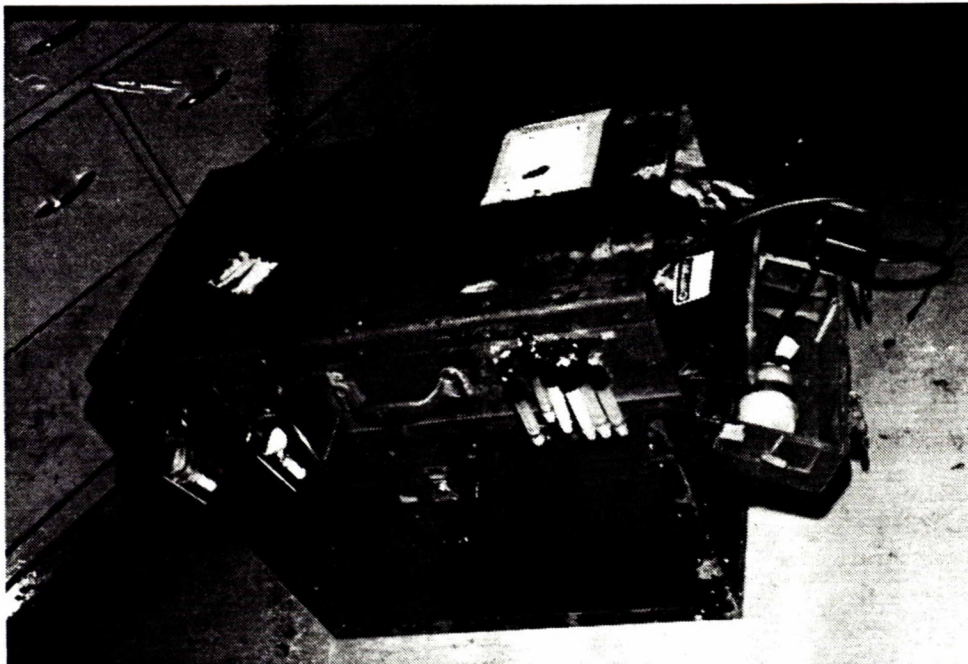
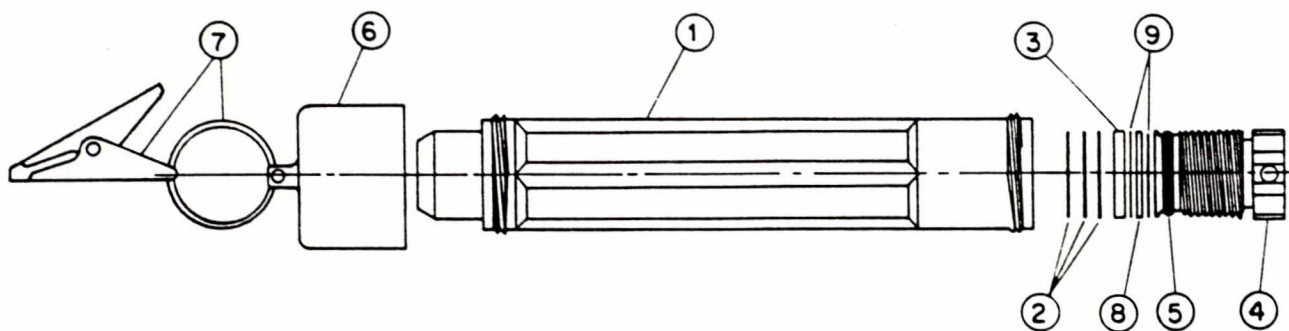


Fig. 6- Instruments for monitoring diesel pollutants



- |                               |  |
|-------------------------------|--|
| ① Polypropylene sampling tube | ⑥ Protective cap                                     |
| ② Tea coated screens          | ⑦ Clip assembly                                      |
| ③ Polyethylene spacer         | ⑧ Chromic acid disc for NO <sub>x</sub> sampler only |
| ④ Screw in cap                | ⑨ Uncoated screen for NO <sub>x</sub> sampler only   |
| ⑤ O-ring                      |  |

Fig. 7- Palmes sampler for NO<sub>2</sub>/NO<sub>x</sub> monitoring



Fig. 8- Spectrophotometer for analyzing Palmes samplers



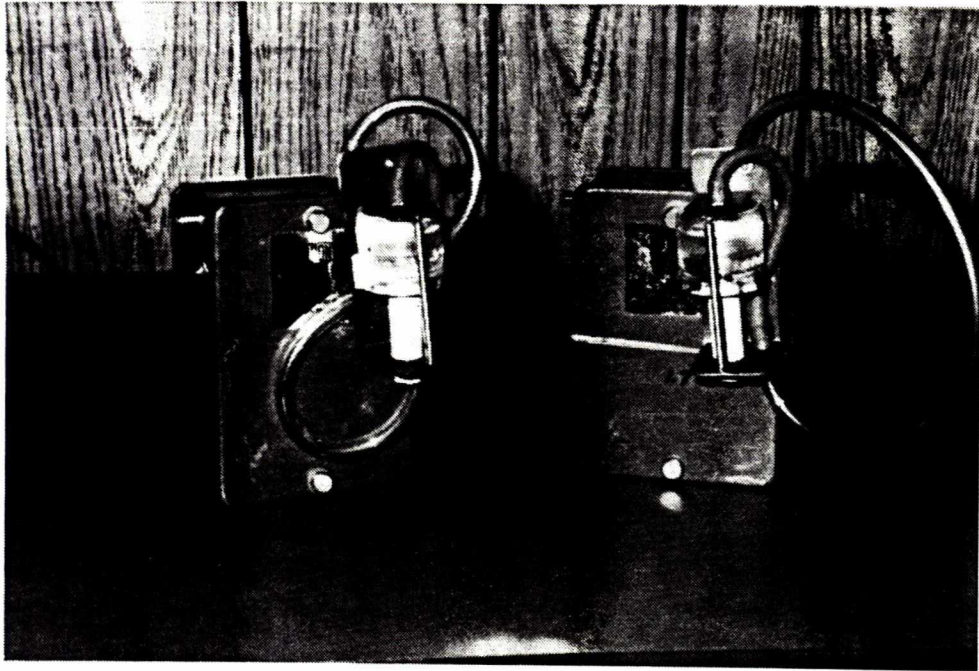


Fig. 9- Dupont pump for particulate matter sampling

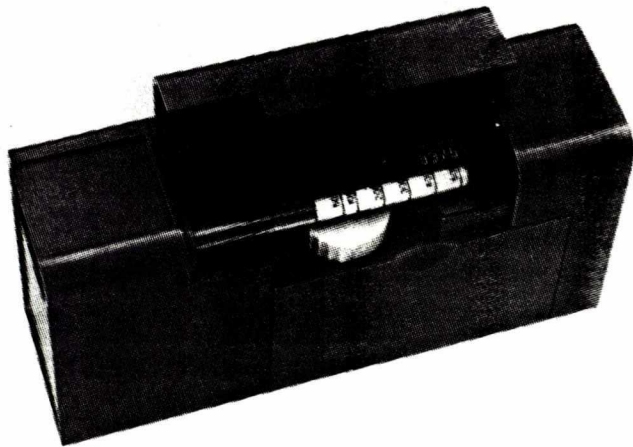


Fig. 10- Dräger Polymeter pump

