Chapter 9

EVALUATION OF TWO DIESEL PARTICULATE SAMPLING DEVICES

by

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Abstract. As a result of recommendations made in the 1988 Report of the Mine Safety and Health Administration Advisory Committee on Standards and Regulations for Diesel-Powered Equipment in Underground Coal Mines, the Mine Safety and Health Administration (MSHA) initiated a program to develop and test a diesel particulate sampling device. The sampling device employed the principles of inertial impaction to separate respirable dust into two fractions; one fraction containing particulate material having an aerodynamic equivalent diameter equal to, or greater than, 1.0 micrometer, and the other fraction containing particulate material having an aerodynamic equivalent diameter less than 1.0 micrometer. The design criteria were based on data which showed that virtually all of the diesel particulate material and very little of the mine generated dust was less than 1.0 micrometer in size.

The instrument was tested in underground dieselized coal mines and in the laboratory. Comparative measurements were obtained with the MSHA designed impactor sampler, a University of Minnesota (UM) designed impactor sampler and MSHA's standard respirable coal mine dust sampler. Simultaneous measurements were also obtained with five of the MSHA and five of the UM designed impactor samplers to investigate between sampler precision.

The paper discusses the design differences between the MSHA and UM impactor samplers, the precision of replicate measurement obtained with both instruments and compares measurements obtained with the respective samplers of the sub- and supermicron fractions of the respirable material.

INTRODUCTION

In July of 1988, the U. S. Department of Labor's Mine Safety and Health Administration released a report, prepared by a specially appointed advisory committee, on "Standards and Regulations for Diesel-Powered Equipment in Underground Coal Mines". One of the primary recommendations made by the committee was that the Secretary of Labor "set in motion a mechanism whereby a diesel particulate standard can be set". The committee, recognizing the limitations of the current state-of-the-art technology for monitoring the amount of diesel particulate present in underground coal mines, further recommended that the Secretary of Labor, in concert with the U.S. Bureau of Mines (BuMines) and National Institute of Occupational Safety and Health (NIOSH), develop a sampling strategy for monitoring diesel particulate levels in coal mines.

The committee, as part of its charge, investigated the state-of-the-art technology available for measuring diesel particulate in underground coal mines. The investigation showed that the technology available to measure diesel particulate was limited to two research type samplers; one built by the NIOSH and the other by the University of Minnesota (UM). Both of these samplers employ inertial impaction to separate the diesel particulate material from the aerosol. The NIOSH sampler was designed to remove particulate material with an aerodynamic equivalent diameter greater than 1.0 micrometer in size while the UM sampler was designed to remove particulate material greater than 0.8 micrometer in size. The design characteristics of these samplers were based on the hypothesis that essentially all particles 1.0 micrometer, and less, in size would be diesel particulate and particles greater than one micrometer in size would be mineral dust. Only prototypes of both samplers were available.

About the time the committee was conducting its investigation, the Mine Safety and Health Administration (MSHA) completed the design and development of a prototype sampler for measuring diesel particulate material. The MSHA sampler also employed inertial impaction to separate the diesel and

nondiesel fractions of the aerosol sampled. The MSHA sampler was designed so that the nondiesel fraction of the aerosol consisted of particles greater than 0.8 micrometer in size. The major advantage of the MSHA sampler was that it was designed to be utilized with the approved respirable coal mine dust sampler. The MSHA sampler design also permitted both the respirable dust and diesel particulate concentrations to be determined with a single measurement.

Based on the recommendations made in the committee's report, the MSHA initiated a program to evaluate the diesel particulate samplers developed by the UM and the MSHA. The UM sampler was chosen for evaluation because it was considered to be the state-of-the-art impaction sampler at the time the committee undertook its investigation; the MSHA sampler was chosen because of its compatibility with the MSHA's current particulate sampling system. Although the original design of the UM sampler did not incorporate a 10 mm nylon cyclone preseparator to remove the nonrespirable fraction of a sampled aerosol before it entered the sampler, preliminary testing of the device showed that it was necessary to reduce, or eliminate, overloading of the impaction plate. Based on the need to couple the UM sampler to a preseparator, the housing of the unit was redesigned to also permit its use with the MSHA's respirable coal mine dust sampler.

This paper presents the results of the MSHA's evaluation of the UM and MSHA diesel particulate samplers in the laboratory and in four underground coal mines which utilized diesel powered haulage equipment.

DESIGN OF SAMPLERS

Figures 1 and 2, respectively, show schematic diagrams of the UM's and the MSHA's samplers. Both samplers utilize a three stage design: the first stage consisting of a 10 mm diameter nylon cyclone preseparator; the second stage consisting of either a single nozzle (MSHA) or multiple nozzle (UM) impactor; and the third stage consisting of a 37 mm vinyl metricel filter. Both instruments are designed to be operated at a flow rate of 2.0 liters per minute.

At 2.0 liters per minute the respirable fraction defined by the 10 mm nylon cyclone is the same as that of MSHA's respirable coal mine dust sampler. This permits respirable dust measurements obtained with the samplers to be converted to equivalent MRE concentrations using MSHA's previously established conversion factor (Tomb, T. F., et al., 1970). At this flow rate, the cut points for the UM and MSHA samplers have been established (Rubow, K. L., et al., 1990)

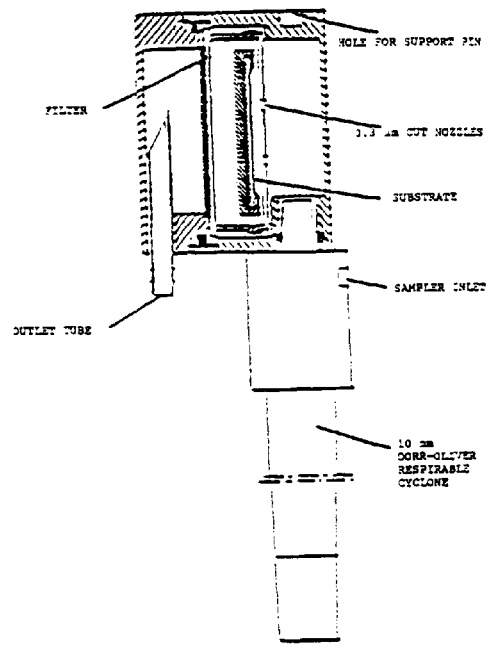


FIGURE 1. SCHEMATIC UNIVERSITY OF MINNESOTA IMPACTOR SAMPLER

to be 0.76 and 0.83 micrometer, respectively. The cut points for both samplers were established using the impactor theory and design guidelines developed by Marple, V. A., 1970, Marple, V. A., et al., 1986, and Rader, K. L., et al, 1985.

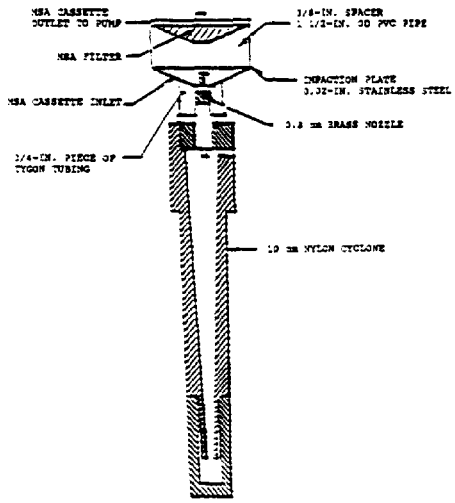


FIGURE 2. SCHEMATIC MSHA IMPACTOR SAMPLER

The multiple orifice design of the UM impactor employs four 0.057 centimeter (cm) diameter (No. 74 drill) nozzles symmetrically arranged on a 1.1 cm diameter circle. The single nozzle utilized in the MSHA sampler has a diameter of 0.1 cm (No. 61 drill). The advantage of employing an impactor utilizing a multiple orifice design is that the pressure drop across the impaction plate is reduced according to the following relationship:

$$P_2 = P_1/(n)^{2/3}$$

where P_2 is the pressure drop for multiple nozzles, P_1 is the pressure drop for one nozzle and n is the number of nozzles. The pressure drop across the two impactors samplers is approximately four inches (H_2O); for the multiple orifice impactor and increases to eight inches (H_2O) for the single orifice impactor. Approximately two inches of the pressure is due to the collection filter.

Both samplers have been designed to be utilized with the personal respirable dust sampler holder that is a standard part of the respirable coal mine dust sampler approved (U. S. 30 CFR, Part 74) for measuring respirable coal mine dust concentrations. The UM sampler requires a modification to be made to the bracket; the MSHA sampler is a direct substitution for the currently approved respirable dust filter cassette.

PROCEDURES

Laboratory

Laboratory testing of the samplers was performed to determine between sampler precision under controlled conditions, the relationship between simultaneous measurements obtained with the two samplers, the relationship between respirable dust measurements obtained with the respective impactor samplers and the approved respirable coal mine dust samplers and the limitations imposed by impaction plate loading.

Comparative measurements were obtained in a 3.2 m^3 hexagonal chamber (Marple, V. A., et al., 1983) with five MSHA and five UM impactor samplers. Dust was introduced into the chamber using a lift-tube dust feed system. To evaluate potential reentrainment of material due to impaction plate loading, five repetitive tests were run. Each test consisted of mounting five pairs of samplers, of alternating type, adjacent to each other in two rows. Because of the odd number of pairs, the last sampler pair was at the same end of the two rows. Sampling with all 10 samplers was initiated at the same time. Sampling was terminated for adjacent pairs of samplers at intervals of one hour. The chamber dust concentration for the first test was approximately 4.0 mg/m^3. The concentration was systematically increased for each subsequent test. In addition, a measurement was obtained for the full test duration with an approved coal mine respirable dust sampler. Average "full test" respirable dust concentrations ranged from 4.0 to 14.0 mg/m^3.

To measure between sampler precision, the same experimental arrangement was used, but all samplers were operated for a full three hour duration. Five tests were conducted. For these tests, average full test respirable concentrations ranged from 2.7 to 6.6 mg/m^3.

Prior to sampling, the sampling pumps were calibrated to 2.0 liters per minute with a pressure drop of either four or eight inches water gauge; each pump was used with an impactor with the same pressure drop as that used for pump calibration. Impaction plates were coated with grease and heat treated to remove volatiles. Both the impaction plate and filter were preweighed to 0.001 mg.

At the completion of each test, the impactors were disassembled and the plates and filters post weighed to 0.001 mg. A blank filter and coated impaction plate were also weighed before and after each test and the net change in weight used to correct for environmental changes.

Relationships between comparative measurements were derived using least squares regressions analyses. The standard error of estimate ($S_{y/x}$) and correlation coefficient (r) were also calculated for the respective relationship's derived.

Underground

Underground testing of the samplers was performed to evaluate between sampler relationships and the precision of measurements obtained in the underground environment. The specific sampler relationships evaluated were:

MSHA Impactor versus UM Impactor (respirable and diesel concentration determinations).

Impactor Respirable Dust Concentration Determinations versus Respirable Dust Concentration Determinations (Standard Method).

The underground testing consisted of obtaining comparative measurements in four underground coal mines utilizing diesel-powered equipment. Comparative measurements were obtained in section intakes (outby the last intake stopping), in haulageways (inby the section dump point), on various pieces of face equipment (continuous miners and diesel ram cars) and in the return airways. A schematic of a typical mine section illustrating the sampling locations is shown on Figure 3.

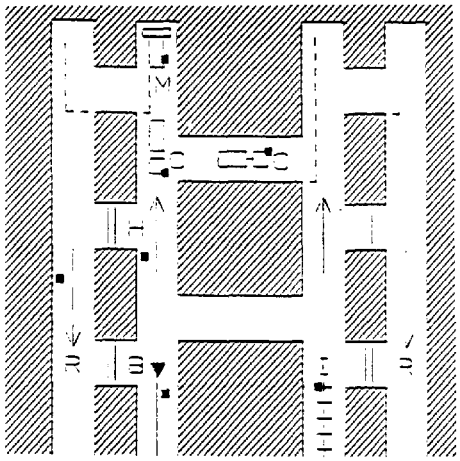


FIGURE 3. SCHEMATIC SHOWING SAMPLING LOCATIONS

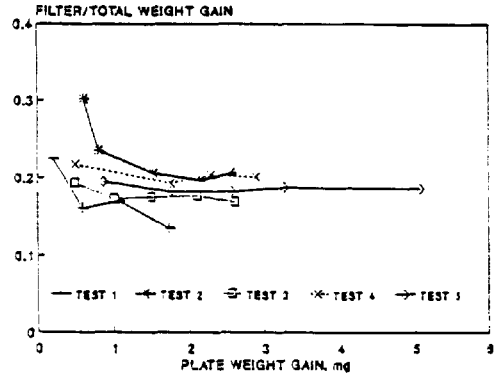


FIGURE 4. RATIO OF FILTER TO TOTAL WEIGHT GAIN AS A FUNCTION OF UM IMPACTOR PLATE WEIGHT GAIN

At the return location, comparative measurements were obtained using a sampling package containing two of MSHA's standard respirable coal mine dust samplers, two total dust samplers, five MSHA impactors, five UM impactors and two Sierra 298 impactors. At all the other locations, comparative measurements were obtained using a sampling package containing one of each type of the impactor samplers and MSHA's standard respirable coal mine dust sampler. The primary purposes of the return sampling location and the assemblage of equipment in the package at that location, were to have an environment with sufficient dust for evaluating the accuracy and precision of measurements obtained with the impactor samplers and to evaluate potential problems associated with impaction plate loading.

The analytical procedures used to prepare the impaction plates of the impactor samplers and to determine the net mass of material collected after sampling were the same as those used for the laboratory tests.

DISCUSSION OF RESULTS

Laboratory

To determine if dust collected on the impaction plate of the impactor samplers was subject to reentrainment as dust loading on the impaction plate increased, the ratio of the mass of dust penetrating the impaction plate and the total mass of dust collected by the impactor sampler (mass of dust on plate plus mass of dust collected by the filter) was compared to the mass of dust collected on the impaction plate. A plot of this comparison for the UM and MSHA samplers is shown on Figures 4 and 5, respectively. The data shown on Figure 4 for the UM impactor sampler show that the ratio remains relatively constant for plate dust loadings up to 5.0 milligrams (mg), indicating that up to this mass loading no reentrainment is occurring. The data shown on Figure 5 for the MSHA impactor show that the ratio is not as constant as that obtained with the UM sampler for plate loadings above 1.0 mg. The data also show that for three of the five tests, there is a coincidental peak in the ratio data at plate loadings between 1.5 mg and 2.0 mg, indicating that reentrainment of impacted material may have occurred. The variation in the ratio obtained for plate dust loadings below 1.0 mg was found to be attributable to the low masses of dust collected on the filter after only one hour of sampling and to the time required for the size distribution of the aerosol to stabilize in the dust chamber.

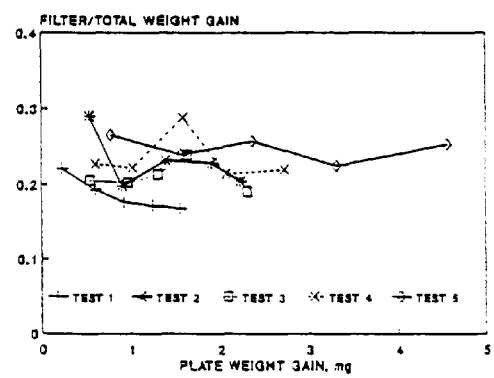


FIGURE 5. RATIO OF FILTER TO TOTAL WEIGHT GAIN AS A FUNCTION OF MSHA IMPACTOR PLATE WEIGHT GAIN

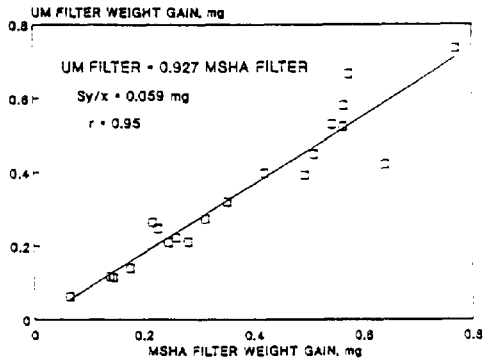


FIGURE 6. COMPARISON OF SUBMICRON MASSES OBTAINED FROM COMPARATIVE MEASUREMENTS IN THE LABORATORY

Comparisons of the mass of dust penetrating the impaction plates and the total mass of dust (mass collected on filter plus mass collected on impaction plate) collected by the respective samplers, for simultaneous measurements, are shown on Figures 6 and 7. Comparison of the total masses collected with the respective instruments (Figure 6) shows that comparative total mass measurements obtained with the two samplers will be within three percent. The

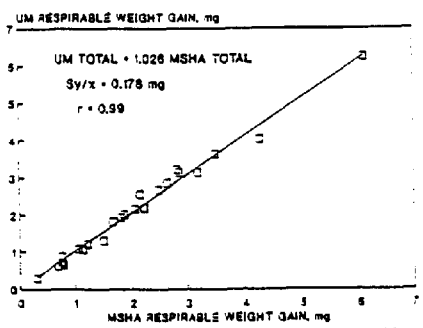


FIGURE 7. COMPARISON OF THE RESPIRABLE MASS OF MATERIAL COLLECTED BY THE IMPACTOR SAMPLERS IN THE LABORATORY

comparison of the mass of dust penetrating the impactor plates (Figure 7) indicates that mass concentration determinations with either sampler, for particulates less than one micrometer, differ by approximately seven percent.

The precision of the impactor samplers was evaluated by calculating the standard deviation (SD) and coefficient of variation (CV) for each group of five samplers of each type. A plot of the individual SDs and CVs

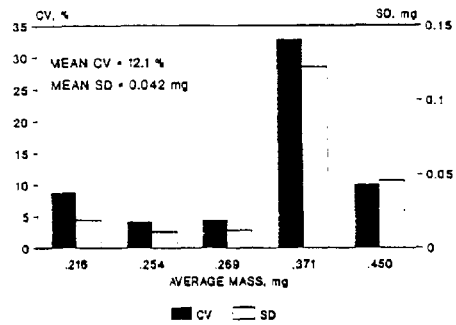


FIGURE 8. PRECISION OF COMPARATIVE LABORATORY MEASUREMENTS OF THE SUBMICRON FRACTION OBTAINED WITH UM IMPACTOR

versus the mean mass collected on the filters of each sampler group is shown on Figures 8 and 9. As shown on these figures, the mean SD and CV are 0.031 mg and 9.47 percent for the MSHA sampler and 0.042 mg and 12.1 percent for the UM sampler. As depicted on Figure 8, the higher values obtained with the UM sampler are due to one relatively high SD and CV. Except for this one occurrence, the mean SD and CV for the UM sampler would be 0.022 mg and 6.9 percent. For both samplers, neither the SD nor the CV appears to depend on the mass of dust collected. Only on the one occasion with the UM impactor was the standard deviation greater than 0.1 mg.

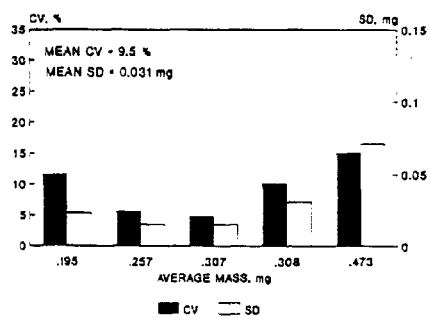


FIGURE 9. PRECISION OF COMPARATIVE LABORATORY MEASUREMENTS OF THE SUBMICRON FRACTION OBTAINED WITH MSHA IMPACTOR

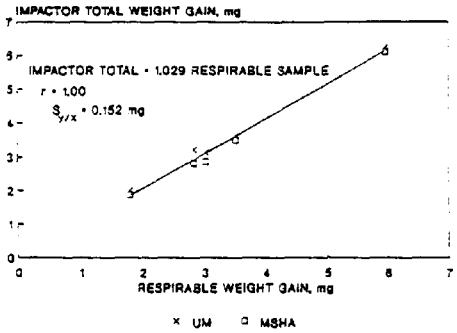


FIGURE 10. COMPARISON OF IMPACTOR TOTAL WEIGHT GAIN TO RESPIRABLE SAMPLE WEIGHT GAIN

Figure 10 shows a comparison of the total respirable mass sampled by the respective impactor samplers and MSHA's approved personal respirable coal mine dust sampler. This comparison shows that, for the limited data obtained, respirable dust determinations obtained by combining the mass of dust deposited on the impaction plate and the mass of dust collected on the filter are within three percent of those obtained with the standard respirable coal mine dust sampler.

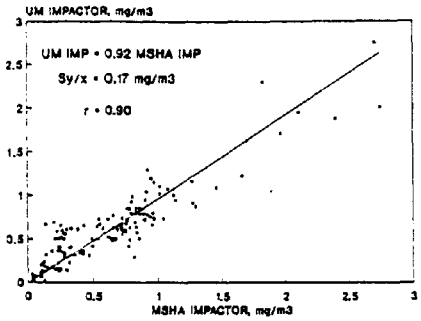


FIGURE 11. DIESEL PARTICULATE MEASUREMENTS COMBINED DATA (0-3.0 mg/m3)

Underground

Figures 11 and 12 show the relationships derived for comparative diesel particulate measurements obtained with the respective impactor samplers. As depicted, relationships were derived for two ranges of measurements: 0 to 3.0 mg/m^3 and 0 to 1.0 mg/m^3. This was done to determine if the comparative measurements obtained for diesel particulate concentrations above 1.0 mg/m^3 had a biasing effect on the relationship determined for comparative measurements. In general, the relationships show that diesel

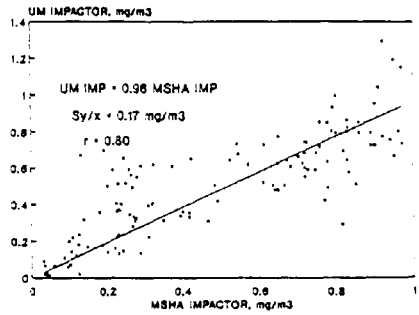


FIGURE 12. DIESEL PARTICULATE MEASUREMENTS COMBINED DATA (0-1.0 mg/m3)

particulate concentrations measured with the MSHA impactor sampler are four to eight percent greater than those measured with the UM impactor sampler. This difference is similar to that obtained from the comparison of measurements in the laboratory and would be expected since the cut-point of the MSHA impactor sampler is greater than that of the UM sampler. However, a test of significance on the slopes of the derived regression lines showed that except, for the relationship derived from the data shown in Figure 11, the slope was not shown to differ from unity. The standard error of estimate ($S_{y/x}$), derived for both relationships, shows that the imprecision for comparative measurements below 1.0 mg/m^3 will be greater than 17 percent. Also, a comparison of the relationships derived for the separate ranges indicates that the comparative measurements above 1.0 mg/m^3 did not influence the relationship derived.

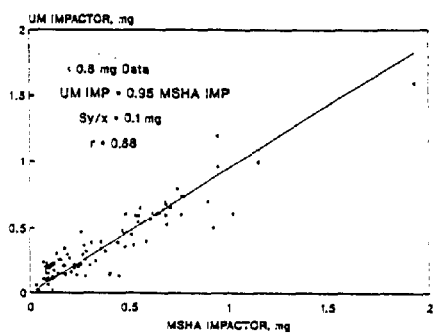


FIGURE 13. COMPARISON OF DIESEL PARTICULATE MEASUREMENTS

Figure 13 shows a similar relationship derived using the mass (not the concentration) of diesel particulate collected. The

data plotted on this figure show that most of the samples collected had a net weight gain of less than 0.8 mg. This is because most of the samples were not collected for a full work shift. Had they been collected for a full work shift, the mass of diesel particulate collected would have been two to three times greater. Therefore, although the above comparison of concentration determinations showed that concentrations above 1.0 mg/m^3 did not influence the relationship derived, any influence may not have been detected because the amount of material collected was limited.

Reentrainment of dust from the impaction plate of the MSHA sampler was evaluated by comparing the ratio of diesel particulate material collected with the MSHA and UM impactor samplers to the dust deposited on the impaction plate of the MSHA sampler. This comparison is shown on Figure 14. Although there is limited data for plate loadings greater than 1.0 mg, the data shown indicates that no reentrainment occurred for plate loadings up to approximately 3.0 mg. However, the field data collected to date is too limited to determine at what impactor plate loading reentrainment of dust is likely to occur. In making this comparison, it was assumed that no reentrainment had occurred on samples collected with the UM impactor. If reentrainment was occurring with both samplers, it would not be detected by this comparison.

The precision of the respective impactor samplers was evaluated by calculating the standard deviation (SD) and the coefficient of variation (CV) for each group of five samples (on several occasions four samples were obtained) simultaneously collected at the return location.

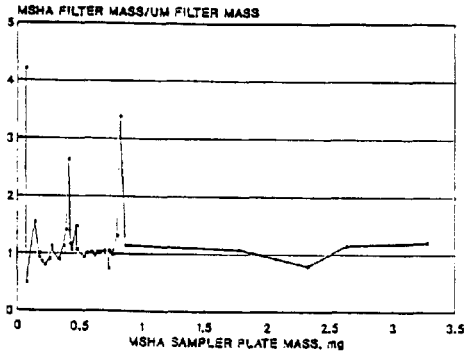
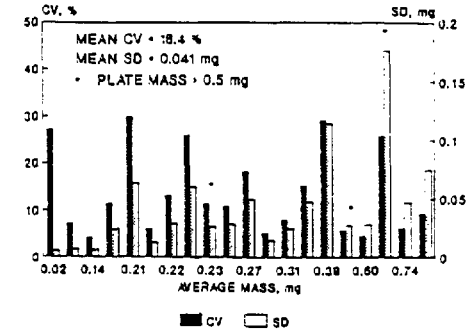


FIGURE 14. EFFECT OF PLATE MASS ON FILTER MASS (DATA FROM ONE MINE)

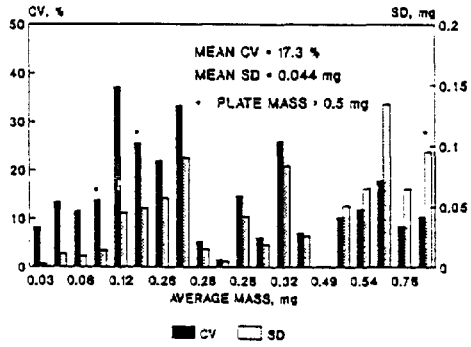
A plot of the individual SDs and CVs versus the mean mass of diesel collected by each group of impactors is shown on Figures 15 and 16. As shown on these figures, the mean SD



UM IMPACTOR

FIGURE 15. PRECISION OF DIESEL PARTICULATE MEASUREMENTS (FOUR/FIVE SIMULTANEOUS MEASUREMENTS)

and CV determined for both impactor samplers is approximately the same: 0.044 and 17 percent, respectively. The data also show that neither the SDs nor the CVs were dependent on the mass of diesel particulate collected and that the standard deviation was greater than 0.1 mg on two occasions with the UM sampler and only one occasion with the MSHA sampler. Also noted on the figures are the occurrences when the mass of dust collected on the impaction plate was greater than 0.5 mg. A comparison of the SDs and CVs obtained for these occurrences indicates that if dust deposited on the impactor plate was being reentrained there was no systematic increase in the SD or CV.



MSHA IMPACTOR

FIGURE 16. PRECISION OF DIESEL PARTICULATE MEASUREMENTS (FOUR/FIVE SIMULTANEOUS MEASUREMENTS)

Because the design of these samplers enables the mass of both the super and submicron fractions of the respirable dust to be determined, the respirable dust concentrations determined from the total respirable dust collected (super plus submicron) was compared to the comparative respirable dust concentrations determined

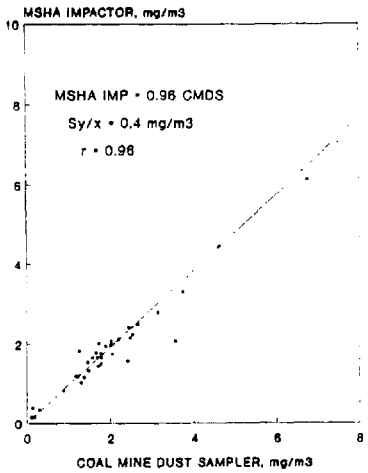


FIGURE 17. RESPIRABLE MEASUREMENT COMPARISON (DATA FROM ONE MINE)

with the approved respirable coal mine dust sampler. These comparisons are shown on Figures 17 and 18. The data shown on these figures are only representative of comparative data collected at one of the mines where comparative measurements were obtained. The data shown are typical of those obtained at the other mines. The relationships derived between comparative

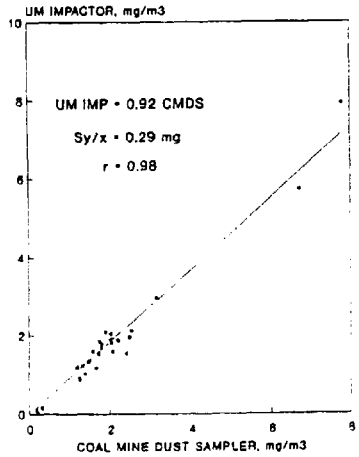


FIGURE 18. RESPIRABLE MEASUREMENT COMPARISON (DATA FROM ONE MINE)

measurements obtained with the respective impactor samplers and the standard coal mine dust sampler show that comparative measurements obtained with the impactor samplers underestimated the respirable dust concentration determined with the standard respirable coal mine dust sampler. Measurements obtained with the UM sampler underestimated the concentration by approximately eight percent and those obtained with the MSHA sampler four percent. This difference was dissimilar to that found from the comparison of measurements obtained in the laboratory. A test of significance on the slopes showed only that the slope derived for the UM sampler relationship was significantly different from unity. Additional investigative work is needed to determine whether these differences are statistically signficant or whether it may be a result of dust being deposited on the internal surfaces (wall loss) of the impactor samplers. The laboratory data indicated that wall loss was not occurring. As shown by the standard error of estimate derived for the regression equation, the precision of comparative respirable dust easurements obtained with the impactor samplers is similar to that obtained with the presently approved respirable coal mine dust sampler (Tomb, T. F., et al., 1973).

CONCLUSIONS

The relationship derived from comparative measurements obtained with the UM and MSHA impactor samplers showed that, for submicron particulate concentrations of 1.0 mg and less, the concentration determined with the UM sampler would be approximately five percent less than the concentration determined with the MSHA sampler.

Laboratory data indicate that particulate material deposited on the impaction plate of the MSHA sampler may be subject to reentrainment at a plate loading of approximately 2.0 mg. However, analysis of the limited field data showed no evidence of reentrainment. More investigative work needs to be conducted to determine if reentrainment is a problem at plate loadings likely to be encountered at underground coal mining operations (approximately 1.4 mg).

For samples collected in underground coal mines, the mean standard deviation determined for comparative samples containing up to 1.0 mg of submicron particulate was approximately 0.044 mg for both impactor samplers. For comparative samples collected in the laboratory, the mean standard deviation was no more than 0.031 mg.

The impactor samplers can be used as dichotomous samplers to provide a measure of the total respirable dust concentration as well as the concentration of the submicron fraction of an aerosol sampled.

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