Inaccuracy of area sampling for measuring the dust exposure of mining machine operators in coal mines

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Introduction

This study examines the accuracy of area sampling for measuring the dust exposure of mining machine operators at coal mine working faces. Area sampling refers to general air monitoring for measuring employee exposures, typically at some fixed location near the worker.

The work was prompted by the development of a prospective new type of dust sampling instrument called the machine-mounted continuous respirable dust monitor (MMCRDM). However, the MMCRDM is more than a new sampling instrument. It also changes the location where samples are collected. The current method of working-face compliance sampling for coal mine dust uses "personal sampling" equipment worn by workers. The MMCRDM, housed in a 73-kg (160-lb) box, must be mounted in a fixed location. Thus, it can only be used for area sampling.

Modern industrial hygiene practice has been to avoid area sampling and to sample airborne contaminants using "personal sampling" equipment worn by workers. It is well known that personal samples provide more accurate results than area samples when the contaminant source is nearby. Near contaminant sources, the dilution air and the contaminants are not evenly mixed. Therefore, exposure measurements must be taken from the worker's breathing zone to be accurate (Leidel et al., 1977). However, area sampling equipment can have more functionality because of the relaxed size and weight restrictions on the instrumentation. For example, an area-sampling instrument can be more sensitive and can be made to run continuously over long periods, rather than for just an eight-hour shift. Area sampling also relieves workers from the nuisance of having to wear a sampling device for the entire work shift. Thus, depending on the level of inaccuracy introduced, it is possible to imagine circumstances where area sampling provides better results overall.

Inaccuracy resulting from use of the MMCRDM has two sources. One is the MMCRDM itself (Kissell and Thimons, 2001).[1] The other is the potentially more significant source of inaccuracy associated with the switch to area sampling. This study deals only with the inaccuracy resulting from the switch to area sampling. For this purpose, the authors compared breathing zone samples to area samples using "personal samplers" in both locations. The effort had two parts: The first part was a literature survey that extracted data from previous area sampling studies. The second part was the authors own study on area sampling at one continuous miner face and at one longwall face.

Literature survey on area sampling

The authors found 12 studies that are relevant to area sampling of dust in coal mine working faces:

Listak et al. (1999) conducted the most recent study on area sampling, comparing fixed-location area samples

[1]The results of MMCRDM measurements and the performance of the MMCRDM itself are being reported elsewhere.

Abstract

This study examines the accuracy of area sampling for measuring the dust exposure of mining machine operators in coal mines. The specific objective of this research was to find locations where an area sampler might work better than earlier studies have indicated. The results show that fixed-location area sampling cannot accurately predict the dust exposure of a machine operator, even when the best fixed location is sought, the fixed location is quite close to the operator and the bias due to the dust concentration gradient is corrected. Industrial hygienists have known for many years that area sampling is unsuitable for measuring air contaminant exposures in the workplace. Near contaminant sources, the dilution air and the contaminants are not evenly mixed. Therefore, when workers are near contaminant sources, exposure measurements must be taken from the worker's breathing zone to be accurate.

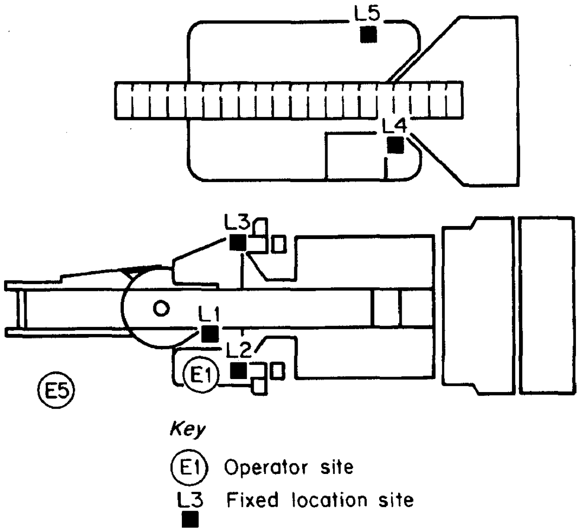


FIGURE 1

Miner-bolter and loader showing operator and fixed-location sites.

to operator breathing zone samples. Data at deep cut sections in five mines where remote operators controlled the mining machines were gathered. Listak et al. concluded that there was little predictive capability between the two locations. If the fixed-point dust level was 1.5 mg/m^3, then the 95% confidence level predicted operator breathing zone exposure could vary from zero to 2.6 mg/m^3.

In a study of nine longwalls, Sun et al. (1997) found no relationship between the dust concentration at the shearer operator and the concentration at the tailgate. However, Sun et al. also described another study conducted at one longwall in Australia. The Australian study found a correlation between the shearer operator dust concentration and the average of the observed concentrations at three locations (headgate, support #50 and tailgate) along the face.

Kissell and Jankowski (1993) summarized several studies conducted by Foster-Miller to reduce continuous miner dust. During this work, Foster-Miller measured dust levels at the boom hinge point and in the operator cab. The mean concentration ratio (hinge point: operator cab) was 4.15, and the standard deviation was 1.85.

Babbitt et al. (1990) obtained dust concentration profiles around a longwall shearer during mining. The profiles showed a strong gradient across the shearer. The machine had a well-designed shearer-clearer system that functioned to hold the dust cloud against the face as it moved downwind from the shearer. When shield movers worked within 15 m (50 ft) of the return side of the shearer, their dust levels were the same or less than those measured at the shearer.

Kelly et al. (1990) measured tracer gas gradients at a full-scale model longwall shearer. Methane gas was released at the drums and the concentration at various locations around the shearer was measured. One location was at the headgate-side operator position and another was the zone downwind of the headgate-side drum on the face side of the shearer. Both the gradient and the variability in the gradient were high. The average ratio (face concentration/headgate operator concentration) in 32 tests was 66, with a standard deviation of 56. In addition, Kelly et al. obtained a dust profile map of the headgate area during mining. The dust level varied from less than 0.5 mg/m^3 to more than 1.5 mg/m^3 across the entry.

Jayaraman et al. (1987) studied methods to reduce the dust level of continuous miner operators who use radio remote control to operate ma-

TABLE 1

Results of tests conducted by Divers et al. (1982).

Shift	Respirable dust concentration, mg/m^3 Cab operator	Remote	Ratio cab:remote
1	4.34	0.14	31
2	3.33	0.09	37
3	1.95	0.08	24

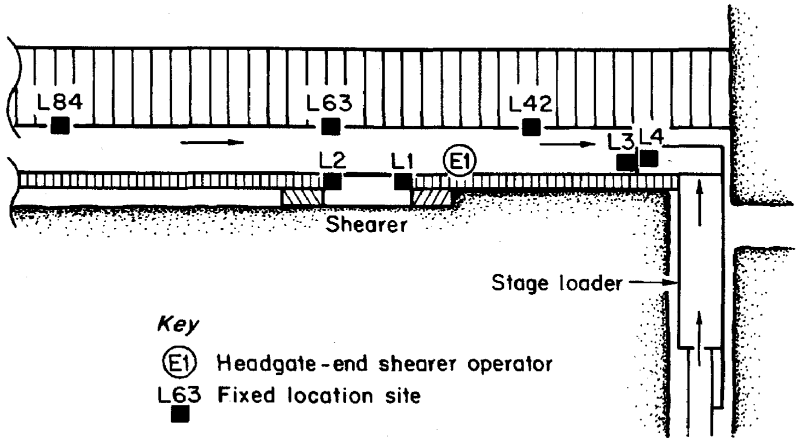
TABLE 2

Results of the five published studies that provide enough information to calculate a mean concentration ratio.

Published study	No. of mines	Mean ratio F/O	RSD
Listak et al., 1999	5	3.07	0.59
Kissell and Jankowski, 1993	5	4.15	0.45
Kelly et al. 1990	Lab test	66	0.85
Divers et al. 1982	1	30.7	0.21
Kost and Saltsman, 1977	6	3.53	0.81

FIGURE 2

Longwall operator and fixed-location sites.



chines equipped with dust scrubbers. It was found that, while these scrubbers remove a large portion of the dust, correct positioning of the operator can realize additional gains. When the machine operator positioned himself directly in front of the blowing curtain, his dust exposure level was 0.2 mg/m^3. When the operator moved away from the curtain and positioned himself next to the miner, his dust exposure level was 3.1 mg/m^3.

Peng and Chiang (1986) took dust measurements near the shearer during longwall mining. Depending on the cut direction and the operator position measured, the concentration over the shearer ranged from 18% to 71% above the operator concentration. Peng and Chiang also obtained other data about the dust gradient along the face. In the study, the dust concentration in the walkway 9 m (30 ft) downwind of the shearer varied from being similar to 12 times higher when compared to the walkway at the shearer. Changes in the shearer water sprays caused this large variation.

Grayson and Peng (1984) conducted a regression analysis on the dust data from a longwall panel to predict the concentration at specific locations. It was found that by using "location on face" as a single independent variable ($V1$), dust level C_m in mg/m^3 could be predicted as $C_m = -0.2835 + 0.8106\ V1$, where the correlation coefficient r was equal to 0.8054, and r^2 equaled 0.65. The fitted model explained 65% of the total variation. However, to improve the predictive capability, it was necessary to incorporate other variables such as condition of roof, method of cutting, cutting time and air quantity.

In a study of six mines, Jankowski and Organiscak (1983) found that dust concentrations in the walkway 9 m (30 ft) on the return side of the shearer varied from being similar to three times higher when compared to the walkway at the shearer. Jankowski and Babbitt (1986) got similar results in a laboratory study using tracer gas, finding that the gas concentration downwind of the shearer varied from being similar to ten times higher than the walkway concentration at the shearer.

Divers et al. (1982) conducted a three-shift dust study in a mine that used remote control to guide the miner. The mine also used a push-pull ventilation system with both blowing and exhaust curtains in the working place. The remote control operator positioned himself 3 to 6 m (10 to 20 ft) behind the miner. Respirable dust samples were taken at the cab and at the remote control operator location. The results are shown in Table 1.

Rankin and Rodgers (1980) conducted dust concentration surveys at locations *away from* the working face in intake air. Dust concentration correlations between area sampling locations and personal sampling of the section boss and shuttle-car operator were found. How-

[2] The concentration ratio is analogous to the bias as described by Kennedy et al. (1995). Bias is the relative discrepancy between the mean of a distribution of measurements and the true concentration. In this paper, the conclusions are based on the assumption that all bias will be corrected. Failure to correct bias leads to greater errors than described here.

[3] In dust sampling, the failure to correct area sampling bias invites "strategic sampling"— that is, placement of dust samplers to achieve readings consistently higher or lower than the true exposure of the worker.

[4] It was assumed that the data cited in the literature survey are normally distributed. In the studies at the Federal #2 and Baker mines, Battelle concluded that the data from these mines was normally distributed.

TABLE 3

Federal #2 Mine results for the fixed-location sites and the personal sample in the cab.

Concentration ratio between:	Shown as	Mean ratio F/O	RSD
Fixed loc. cab/pers. sample cab	L1/E1	0.865	0.27
Fixed loc. right bolter/pers. sample cab	L2/E1	0.726	0.27
Fixed loc. left bolter/pers. sample cab	L3/E1	1.22	0.46
Fixed loc. right loader/pers. sample cab	L4/E1	0.488	0.406
Fixed loc. left loader/pers. sample cab	L5/E1	0.429	0.438

TABLE 4

Federal #2 Mine results for the fixed-location sites and the remote operator location.

Concentration ratio between:	Shown as	Mean ratio F/O	RSD
Fixed loc. cab/pers. sample remote op.	L1/E5	2.49	0.285
Fixed loc. right bolter/pers. sample remote op.	L2/E5	2.07	0.299
Fixed loc. left bolter/pers. sample remote op.	L3/E5	3.32	0.304
Fixed loc. right loader/pers. sample remote op.	L4/E5	1.33	0.243
Fixed loc. left loader/pers. sample remote op.	L5/E5	1.17	0.325

ever, Rankin and Rogers cautioned not to expect good correlations near working-face dust sources, because shift-to-shift coefficient of variation values there varied from 25% to 60%.

Kost and Saltsman (1977) measured dust concentrations near continuous miner operators at eight sections in six different mines. It was concluded that the dust profiles showed a zone of high concentration near the face, separated from a zone of clean air. The boundary between these two zones was near the operator, which made the location of the sampler critical. Kost and Saltsman saw a large variation in the dust gradient from mine to mine, concluding that no single correction factor applies for all mines. Kost and Saltsman also saw a large variation in the concentration gradient from shift to shift in the same section, concluding that even a single-section correction factor is impractical.

Establishing an accuracy criterion

The issue at hand is whether a measurement made at a "fixed location" (an area sample) will effectively show how much dust a worker, typically the operator of a mining machine, is breathing. Because the dust source is nearby, the average concentration at the two locations will obviously be different. In other words, there will be a gradient that can be represented by a "concentration ratio." If the variability in this ratio is small, then a fixed-location measurement can be used to show worker exposure when the concentration ratio is applied as a correction factor.[2,3]

For the literature survey results to be useful, one must convert those results to a common denominator and then compare them to well-established measures of accuracy. Fortunately, five of the studies gave enough information to enable the authors to calculate a concentration ratio between the fixed location and the mining machine operator for each shift. These concentration ratios were then averaged over all shifts in the test, and the standard deviation calculated. The relative standard deviation (RSD) was calculated from the standard deviation and the mean concentration ratio. Then, from the RSD in this concentration ratio, the authors could determine whether the accuracy criteria had been met.

Two accuracy criteria, ±25% and ±50%, were used. These are analogous to the NIOSH instrumentation accuracy criterion (Kennedy et al., 1995) and the European Community standard for "screening measurements" (CEN, 1994). For normally distributed data[4], 95% of the measurements fall within the range $\pm 1.96s$, where s is the standard deviation. For example, assuming that the mean is 100, for the criterion of ±25%, then $1.96s = 25$ or $s = 12.7$. Because the mean is 100, the standard deviation divided by the mean (called the relative standard deviation or RSD) is 0.127. Thus, the ±25% accuracy criterion is met at RSD = 0.127 or less[5]. For the criterion[6] of ±50%, $2s = 50$ or $s = 25$. Hence, the RSD is 0.25, and the ±50% criterion is met at RSD = 0.25 or less.

Results from the literature survey

The five published studies that provided enough information to calculate a mean concentration ratio between the fixed location and the mining machine operator (F/O) and to calculate a relative standard deviation for the concentration ratios are shown in Table 2. These values for RSD fail to meet the ±25% criterion, for which the RSD is 0.127, and, with only one exception (Divers et al.), they also fail to meet the 50% criterion, for which the RSD is 0.25. The average shift-weighted RSD for all the mines studied (omitting the lab test) was 0.58.

Comprehensive study on area sampling in two mines

The results from the literature survey showed that area sampling resulted in poor accuracy — that is, high RSD values. Therefore, between January and March 1999, the authors conducted a comprehensive area sampling study in two mines to determine if they could find locations where area sampling might yield better results.

For this two-mine study, the authors used the personal samplers normally employed for coal mine compliance sampling — that is, a 10-mm Dorr-Oliver cyclone, a

[5] Assuming that all bias is corrected.

[6] $2s$ is the value corresponding to 95.4% of the measurements.

[7] A more complete statistical analysis of the area sampling studies at the Federal #2 and Baker mines was undertaken by Battelle Inc. under contract to NIOSH. Copies of this Battelle report are available from the authors.

[8] In this mine, the air on the longwall face moved from the tailgate to the headgate, and so the headgate-end shearer operator was the designated sampling position.

37-mm filter and a Mine Safety Appliances Co. Elf-Escort flow-controlled pump operated at 2 L/min. Pump calibration was checked before each sampling shift using a Gillibrator calibrator and a filter load.

The fixed location sample (the surrogate for the MMCRDM) was a package of three samplers, with the average concentration of the three designated as the fixed-location measurement. For the personal samples, one sampler was used with the cyclone attached to the lapel of the worker in the conventional manner. MSHA pre- and postweighed the filters to a precision of 11 µg in its automated sample-weighing facility (Kogut et al., 1997). One filter blank was established for each shift of samples, and filter post-weights were corrected for weight changes in the blank.

The data were analyzed using the same "concentration ratio" approach employed in the literature survey. The authors adopted[7] this approach to allow a direct comparison to the literature survey results.

Federal #2 Mine. The authors conducted the Federal #2 study on a miner-bolter section. Dust samples were collected for 11 shifts at five worker exposure sites and five possible fixed-location sites for the MMCRDM. Concentration ratios were calculated between each of the five fixed-location sites, and the two most prominent operator personal-exposure sites as shown in Fig. 1. These operator exposure sites were in the miner cab and at the location where the operator would stand if the machine were being operated remotely.

Table 3 shows the results for the fixed-location sites and the personal sample in the cab. Table 4 shows the results for the fixed-location sites and the personal sample at the remote operator location. All of the RSD values fail to meet the ±25% criterion, and all but one fail the ±50% criterion.

Baker Mine. The authors conducted the Baker Mine study on a longwall section. Eleven shifts of dust samples were collected at six worker exposure sites and at seven possible fixed-location sites for the MMCRDM. Concentration ratios were calculated between the most prominent worker personal-exposure site, the headgate-end shearer operator[8] (HGSO) and each of the seven fixed-location sites, as shown in Fig. 2.

These fixed-location sites were at shield #42, shield #63, shield #84, on the shearer at the headgate end, on the shearer at the tailgate end and at two places on the stage loader. Results are shown in Table 5. All of the RSD values fail to meet both the ±25% and the ±50% criteria. The most surprising finding is the lack of correlation between the personal sample on the headgate-side shearer operator and the fixed location on the headgate side of the shearer (L1/E1), with an RSD value of 0.503.

The results from the Federal #2 and Baker mines were unfavorable, with an overall average RSD of 0.37.

TABLE 5

Baker Mine results.

Concentration ratio between:	Shown as	Mean ratio F/O	RSD
Fixed loc.shield #42/pers.sample HGSO	L42/E1	0.798	0.380
Fixed loc.shield #63/pers.sample HGSO	L63/E1	0.713	0.450
Fixed loc.shield #84/pers.sample HGSO	L84/E1	0.490	0.302
Fixed loc.shearer headgate end/pers. sample HGSO	L1/E1	1.138	0.503
Fixed loc.shearer tailgate end/pers. sample HGSO	L2/E1	1.015	0.591
Fixed loc.#1 stage loader/pers.sample HGSO	L3/E1	1.564	0.423
Fixed loc.#2 stage loader/pers.sample HGSO	L4/E1	1.574	0.378

TABLE 6

Kost and Saltsman study results.

Mine	Fixed location (F)	No. of shifts	Mean ratio (F/O)	RSD
C	right rear post	12	0.666	0.39
C	left rear post	12	0.806	0.33
D	rear cab	10	0.690	0.38
E	left rear post	8	0.934	0.60
E	right rear post	8	1.07	0.58
F	rear cab	8	0.956	0.28

Subset of data from samplers located within 760 mm (30 in.) of worker

The literature survey and the two-mine study yielded unfavorable results. Therefore, the authors reanalyzed all of the data in the belief that samplers that were closer to each other might provide better correlation. The authors focused on a subset of two cases in which the fixed location was within 760 mm (30 in.) of the machine operator. The literature survey and the two-mine study each provided one case.

Kost and Saltsman study Kost and Saltsman (1977) conducted a dust gradient study in six mines to assess the impact of moving the sampler away from the continuous miner operator. The dust concentration measured at the operator's lapel and the dust concentration measured elsewhere on the mining machine were compared. In four of the mines, Kost and Saltzman placed samplers on the rear post of the canopy that covered the operator cab. These were the samplers closest to the operator, and they were never more than 610 mm (24 in.) from the sampler on the operator's lapel.

TABLE 7

Federal #2 study results.

Concentration ratio between:	Shown as	Mean ratio (F/O)	RSD	Distance
Fixed loc.cab/pers. sample cab	L1/E1	0.865	0.27	18 in.
Fixed loc.right bolter/pers. sample right bolter	L2/E2	0.859	0.32	30 in.
Fixed loc.left bolter/pers. sample left bolter	L3/E3	1.00	0.39	30 in.

Table 6 gives the mean concentration ratio for each mine and the std.dev./mean or relative standard deviation (RSD). Every value fails both the ±25% and the ±50% criteria. This is a surprising result considering that the samplers were within a few feet of each other.

Federal #2 study. In the Federal #2 study, three data pairs represented cases where the operator sampler and the fixed-location samplers were very close to each other. These were as follows: the fixed-location measurement at the miner cab vs. a personal sample on the continuous miner operator who sits in the cab (L1/E1); the fixed location at the right bolter vs. the personal sample at the right bolter (L2/E2); and the fixed location at the left bolter vs. the personal sample at the left bolter (L3/E3). The mean ratios and RSDs for these cases are shown in Table 7. These values also fail both the ±25% and the ±50% criteria.

The Federal #2 samplers were very close to each other. The fixed-location samplers at the cab (L1) were only 460 mm (18 in.) from the personal sampler worn by the operator in the cab (E1). In addition, the fixed-location samplers at each bolter (L2 and L3) were only 760 mm (30 in.) from the corresponding personal sampler (E2 and E3). Yet the RSDs for ratios L1/E1, L2/E2 and L3/E3 were 0.27, 0.32 and 0.39, respectively. The average RSD for this two-mine subset was 0.39. These results show a surprisingly wide variation in dust levels between samplers located within a few feet of each other.

Variance from the samplers

The high RSD values for the fixed-location/personal sampler ratios warranted an analysis of the samplers themselves. In the two-mine study, each fixed location value was the average of a three- sampler package in which the cyclone inlets were only 75 to 125 mm (3 to 5 in.) apart. In the Federal #2 Mine study, 11 shifts of dust samples were taken at five fixed-location sites, for 55 values.

In the Baker Mine study, 11 shifts of dust samples were taken at seven fixed-location sites, for 77 values. The mean sampler-to-sampler RSD for the 132 fixed-location values in both mines was 0.12. An RSD value of 0.12 for samplers only 75- to 125-mm (3- to 5-in.) apart accounts for part of the poor correlation observed for samplers separated by greater distances.

Conclusions

The results of this work show that fixed-location area samples cannot predict the shift dust exposure of a machine operator, even if the best fixed location is sought, the fixed location is quite close to the operator and the bias due to the concentration gradient is corrected.

The average RSD from the literature survey was 0.58. From the two-mine comprehensive study, the value was 0.37, and, from the subset of area samplers within 760 mm (30 in.) of the worker, the value was 0.39. A part of this variability is due to the samplers themselves, which had an RSD of 0.12. ■

Acknowledgments

The authors gratefully acknowledge the important contribution of those who collected the data for this analysis: NIOSH employees Bruce Cantrell, Calvin Garbowsky, Gregory Green, Thomas Mal, Shawn Vanderslice and Jeanne Zimmer; MSHA employees Karl Ahlen, David Atchison, Ken Fields, Everett Gerbec and Brian Murphy.

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