

INFLUENCE OF CONTINUOUS MINING ARRANGEMENTS ON RESPIRABLE DUST EXPOSURES

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ABSTRACT

In underground continuous mining operations, ventilation, water sprays, and machine-mounted flooded bed scrubbers are the primary means of controlling respirable dust exposures at the working face. Changes in mining arrangements, such as, face ventilation configuration, orientation of crosscuts mined in relation to the section ventilation, and equipment operator positioning, can impact the ability of dust controls to reduce occupational respirable dust exposures. This study reports and analyzes dust concentrations measured by the Office of Mine Safety and Health Research for both remote-controlled continuous mining machine operators and haulage operators at ten U.S. underground mines. Results of these respirable dust surveys show that continuous miner exposures varied little based on depth of cut, but are significantly affected by ventilation configuration. Haulage operators experienced elevated concentrations in blowing face ventilation. The type of cut influenced exposures, with elevated exposures observed for both continuous miner operators and haulage operators when working in crosscuts driven into, or counter to, the section airflow. Individual cuts are highlighted to demonstrate instances of minimal and excessive dust exposure attributable to particular mining configurations. These findings form the basis of recommendations for lowering face worker respirable dust exposures when performing a variety of continuous mining cuts.

INTRODUCTION

Underground continuous coal mining operations may encounter a wide range of conditions and arrangements during production and development activities. These activities typically produce respirable coal mine dust, putting operators of continuous mining machines and coal haulers at risk for elevated exposures. In order to comply with federal regulations limiting respirable dust exposures for the duration of a working shift, mine operators typically implement ventilation, water sprays, and machine-mounted flooded-bed dust collectors (scrubbers) to dilute and control mine dusts during coal cutting. Nevertheless, changes in operational conditions can limit the ability of these controls to effectively reduce dust exposures. Some examples of conditions that can change during the course of mining include face ventilation configuration, orientation of crosscuts mined in relation to the section ventilation, and operator positioning. Because these arrangements are largely under the control of mine operators, any insight into associated exposures may inform future plans and behaviors, reducing occupational exposures to respirable dust.

The objective of this OMSHR study is to evaluate respirable dust exposures associated with a range of continuous mining arrangements by comparing occupational dust concentrations measured during a series of field surveys. These comparisons consider face ventilation configurations, depths of cut, and crosscut mining practices.

Face ventilation configuration

Room-and-pillar coal mine face ventilation systems can be grouped into the two broad types of blowing and exhausting, with fresh air directed to the face using either tubing or brattice/curtain. These general ventilation schemes are shown using ventilation curtains and

machine-mounted scrubbers in Figures 1 and 2. Prior research has demonstrated several benefits and drawbacks for each approach related to dust exposures and methane control.

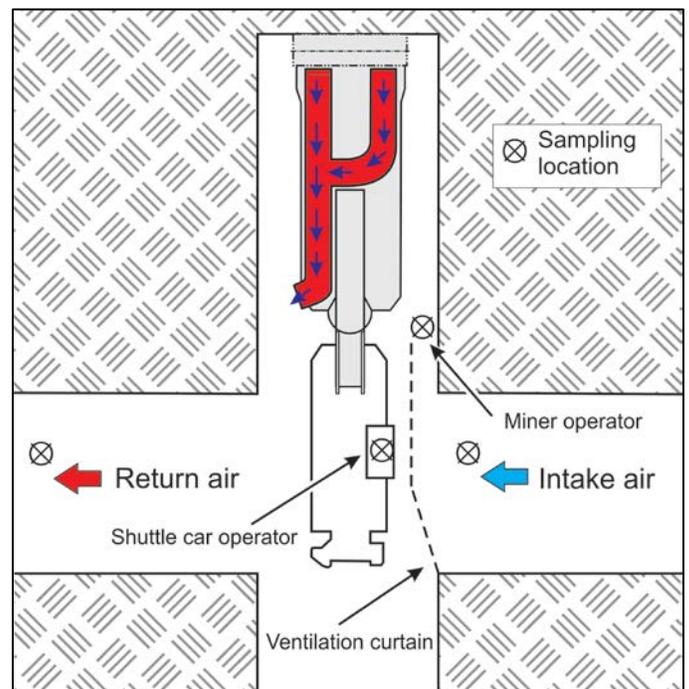


Figure 1. Layout of a blowing curtain face ventilation system.

In blowing ventilation intake air is directed toward the face from behind a length of line curtain on the opposite side of the entry to the continuous mining machine's on-board scrubber discharge. This has the benefit of allowing the curtain to be advanced to the face without interfering with scrubber exhaust. This technique has been found to more effectively sweep dust and methane from the face than in a similarly configured exhausting ventilated face (Luxner, 1969; Fields, 2007). The ease of installation and methane control have been cited as reasons for selecting blowing curtain over exhausting curtain (Luxner, 1969). One drawback of blowing face ventilation is that dust can bypass the sprays and the scrubber, allowing dust to circulate over the machine and cause excessive exposures to shuttle car (SC) operators and downwind workers (Mundell, 1977; Divers and Volkwein, 1987; Schultz and Fields, 1999). Additionally, dust generated during the loading of shuttle cars may pass over the SC operator in this ventilation arrangement. While blowing face ventilation has the advantage of positioning the continuous mining machine (CM) operator in the uncontaminated intake air at the end of the curtain, this also restricts changes in position and may create a lack of visibility of haulage operators due to the placement of the curtain.

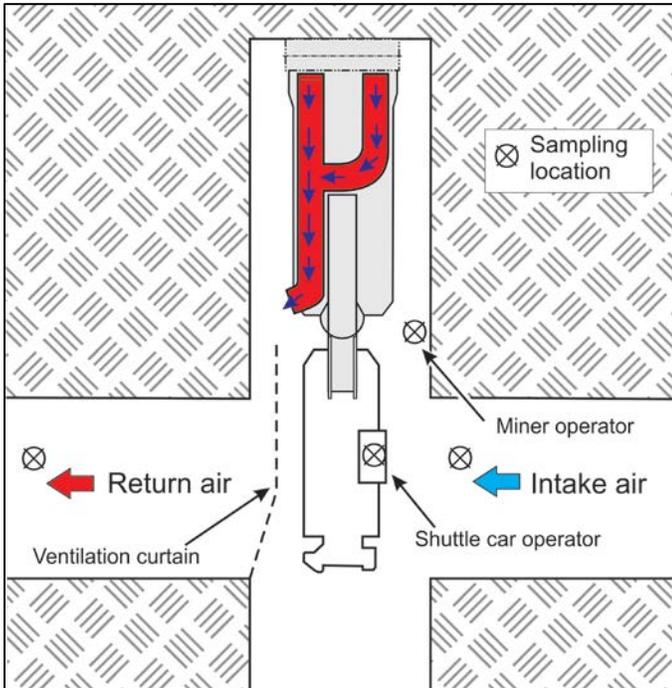


Figure 2. Layout of an exhausting curtain face ventilation system.

Exhaust ventilation as shown in Figure 2 uses a line curtain on the same side as the scrubber discharge and places the CM operator on the wide side of the entry in full view of the haulage operators. With the curtain on this side of the entry, the CM operator is afforded more options to avoid dusty air, mobile equipment, and other hazards. Exhaust ventilation has the additional benefit of positioning haulage operators in the intake airway when at the face, so that dusts generated at the mining face or during loading do not result in elevated exposures. This ventilation configuration is often credited with providing better dust control than blowing systems, especially when high concentrations of quartz are present (Schultz and Fields, 1999; MSHA, 2012).

Mining extended cuts

An extended or deep cut is defined as any cut in which the continuous mining machine advances more than 6.1-m (20 ft) in by the last row of permanent roof supports. Mines typically prefer these cuts as they reduce place changes and increase equipment production time. MSHA field studies have identified several critical elements necessary to control respirable dust in these cuts, including sufficient control of intake dust, scrubber capacity, face ventilation quantities and velocities, and proper worker positioning, work practices, and equipment selection (Schultz and Fields, 1999). This work suggests that even when properly undertaken these cuts may result in additional dust exposures compared to normal depth cuts.

In 2008 guidance was issued in the form of a Procedure Instruction Letter (PIL) to the MSHA coal mining districts for evaluating and approving operator plans incorporating extended cuts (PIL No. 108-V-3) (MSHA, 2008). This letter emphasizes the need to control respirable dust throughout the entire cut to a level below the applicable standard. The letter has been subsequently re-issued as PIL No. 112-V-11 (MSHA, 2012).

With approximately seventy percent of continuous mining machines extracting deep cuts, recent OMSHR research has investigated the exposures associated with mining headings of varying depths. (Potts et al. 2011). In this study researchers divided deep cuts into two segments, comparing the initial 6.1-m (20 ft) portion to the final 6.1-m (20 ft) part of a 12.2-m (40 ft) cut. This analysis found that increasing the depth of cut did not significantly increase dust exposures for CM or SC operators during the mining and loading of

coal. This outcome was demonstrated for six mines using blowing, exhausting, and no curtain face ventilation.

Mining crosscuts

Crosscuts are passages cut through a pillar of coal to allow ventilating currents to pass from one entry to another (Thrush, 1968). Figure 3 shows a general schematic of a crosscut being mined in the section and Figure 4 shows a detailed view of the equipment and curtain positions in a crosscut ventilated by blowing curtain. The process of mining crosscuts is considered to be possibly the most difficult and variable portion of underground room-and-pillar coal production (Turin et al., 1998). From 2001 to 2011, seven of the fifteen fatal roof fall accidents in U.S. coal mines occurred while turning a crosscut or while mining immediately adjacent to a crosscut (MSHA, 2011). Continuous mining machine operators must be aware of several potentially hazardous conditions, including roof stability and equipment movements and locations, all while positioning themselves in a location that enables visibility of the cutting face and is away from air contaminated by dust. Although MSHA personnel have evaluated different practices in turning these crosscuts, the authors provide minimal discussion and validation of CM operator respirable dust exposures in their placement recommendations (Gray et al., 2005).

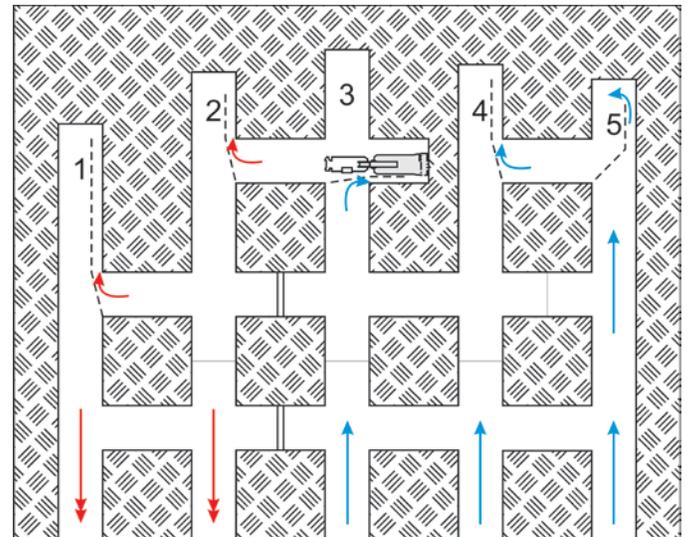


Figure 3. Layout of a five-entry section with the continuous mining machine working the 3-4 Right crosscut.

Completing crosscuts

The final cut, or break-through, of a crosscut produces a new connecting passageway between two adjacent headings. Depending on the orientation of the cut in relation to the section ventilation, these cuts can be described as being mined in the same direction as airflow (with airflow) or against the airflow. These situations are depicted in Figures 5 and 6 for mining the same crosscut from opposite directions. In Figure 5 as the break-through is mined with the airflow, the air will flow away from the mining machine and the CM operator into the adjacent entry. In Figure 6, the CM operator is mining against the airflow and the contaminated air will pass over the mining machine into the CM operator and SC operator work locations. In this instance of mining against the section airflow, there is no position that these personnel may assume to prevent exposure to this contaminated air. For this reason, MSHA recommends that mines develop crosscuts from the entry with higher pressure to the entry with lower pressure so that the contaminated air will travel away from the face workers (MSHA, 2012).

Use of scrubbers in crosscuts

In order to better ventilate mining faces, a majority of continuous mining machines are equipped with a flooded-bed scrubber (Taylor et al. 1996). This fan-powered dust collector collects dust-laden air near the face, cleans it by means of a wetted filter panel, and exhausts this air from the rear corner of the continuous mining machine. Tien (1988) demonstrated that the scrubber, though minimally increasing total air

quantity into crosscut entries, helps to deliver more fresh air to the face and increases face air velocities. The face velocities may be further increased through the advancement of a line curtain to the furthest extent possible. Kollipara et al. (2012) recently investigated the presence of face recirculation and low air velocities in crosscut entries for a range of computational fluid dynamics (CFD) test conditions. The regions characterized with both low air velocity and recirculation could negatively impact exposure to respirable dust for haulage and CM operators working in these contaminated zones. Scrubber operation and proper line curtain techniques to maintain the curtain at the farthest extent with the fewest leaks possible were shown to both significantly reduce recirculation and improve dust dilution at the face in these CFD models. While these models focused on blowing face ventilation, these similar conditions have been demonstrated using exhausting face ventilation in the full-scale continuous mining gallery at the Office of Mine Safety and Health Research (OMSHR) in Pittsburgh, Pennsylvania where increased curtain setbacks and reduced scrubber airflows were both demonstrated to increase dust and gas concentrations at the rear corners of the continuous mining machine (Organiscak and Beck, 2010).

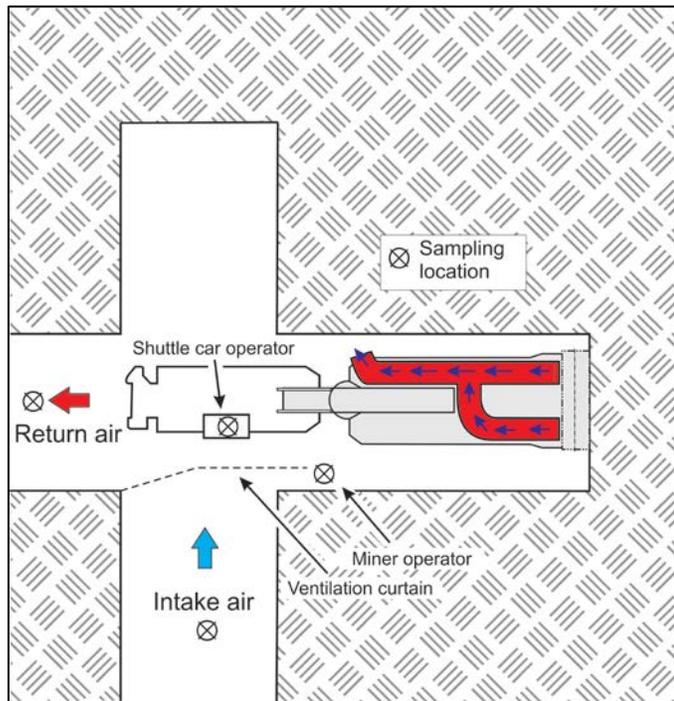


Figure 4. Continuous mining machine and shuttle car positioned in typical crosscut entry.

METHODS

Mine selection

Researchers with OMSHR have evaluated respirable dust concentrations at several underground coal mines from 2007 to 2014. These mines were each typically sampled over the period of four shifts in both single continuous mining machine and super-section arrangements. This current analysis includes those surveys that meet specific criteria. In order to be eligible for inclusion in this study, mine sections must be room-and-pillar with full mechanization, isolated from large upwind sources of dust, ventilated at the face using either blowing or exhausting line curtain, and utilizing continuous mining machines with on-board flooded bed scrubbers. Additionally, to be included in this study, researchers must have sampled at least two crosscuts during the study period at each mine and the mining conditions and parameters must have been maintained for the survey duration.

Field surveys

Respirable dust concentrations were measured using occupational sampling techniques at the CM operator location and in

the operator cabs of each shuttle car. Area samples were collected in the intake and return of each cut. These sampling locations for both blowing and exhausting situations are labeled in Figures 1 and 2, respectively. The sampling locations for crosscuts are labeled in Figure 4. The sampling package at each location consisted of two gravimetric Coal Mine Dust Personal Sampling Units (CMDPSUs) and one continuously logging personalDataRAM (pDR). The gravimetric sampling pumps were calibrated to 2 liters per minute prior to each week-long study. These pumps drew dust-laden air through Dorr-Oliver 10-mm nylon cyclones, depositing the respirable dust fraction onto preweighed 37-mm PVC filters. All filters were pre- and post-weighed in the environmentally controlled weighing laboratory at the OMSHR facility in Pittsburgh, Pennsylvania. Gravimetric dust concentrations were determined by dividing the accumulated mass by the total volume of air sampled. Dust concentrations were measured only during continuous mining machine operation and do not represent full-shift compliance samples. Though there were differences observed in ventilation and production rates and intake dust concentrations between mines and individual cuts, the dust concentrations used in this analysis are unadjusted for these factors.

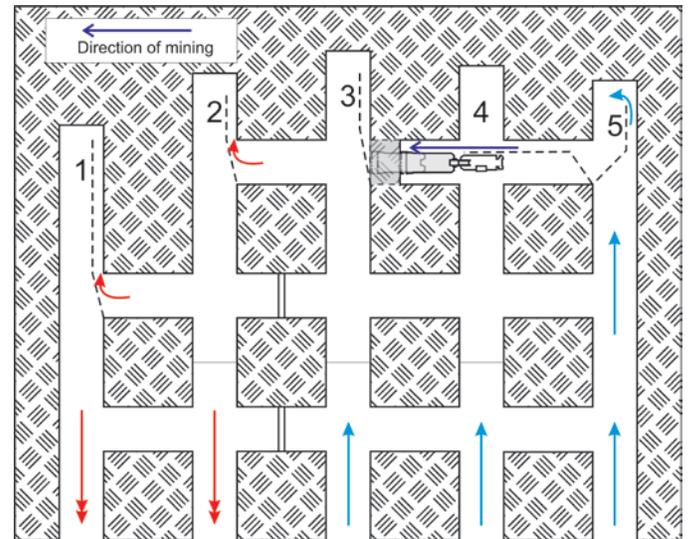


Figure 5. Mining the 4-3 Left crosscut in the same direction as the section airflow (with airflow) from Entry 4.

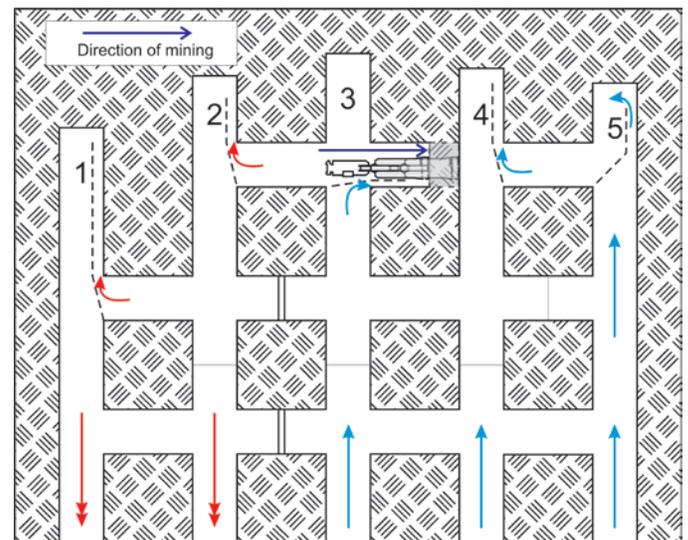


Figure 6. Mining the 3-4 Right crosscut against the section airflow from Entry 3.

Instantaneous dust concentrations were measured and recorded for each 5-second interval of the study period. Dust concentrations for each individual cut were determined by calibrating the pDR's

instantaneous measurements to the gravimetric dust concentration for the same sampling location. Correction factors for this calibration were calculated by dividing the gravimetric concentration by the daily average pDR concentration for the identical time period. The instantaneous pDR values for each 5-second interval were then multiplied by this correction factor. All dust concentrations reported in this study are gravimetrically adjusted pDR measurements.

Measurements to evaluate mine conditions and equipment activities were required in addition to dust concentrations. Face ventilation velocities were measured for each cut prior to activation of the on-board scrubber using a Davis vane anemometer at the mouth of the blowing or exhaust ventilation curtain. Airflow quantities were determined by the product of the air velocity and open area behind the curtain. Mining heights were measured periodically during the surveys with notations made of significant rock intrusions. Cut depth and curtain configuration were also recorded for each surveyed cut.

OMSHR researchers collected time study information to record the operation and placement of each continuous mining machine and shuttle car during production activities. Production times were recorded for each cut, removing downtime from other mining activities (e.g. tramming, cleaning scrubber ductwork) from the dust calculations so that dust generated during mining and loading could be distinguished. CM operator positions were observed to identify potentially unfavorable activities in regards to dust exposures, such as moving from behind the ventilation curtain on blowing faces.

Statistical methods

Data were evaluated using IBM SPSS Statistics Version 19.0 (Armonk, NY). Descriptive statistics included means, standard deviations, and minimum and maximum values. The dust concentration values were analyzed using Kolmogorov-Smirnov tests for normality. Nonparametric tests were used because the dependent variables exhibited a skewed distribution and did not pass tests for normality.

Mann-Whitney U tests, non-parametric alternatives to the two-sample Student's t-test, evaluated the potential that CM operator or SC operator dust concentration is affected by (1) the use of blowing vs. exhausting face ventilation, (2) the mining of standard vs. extended depth cuts, (3) the mining of headings vs. crosscuts, and (4) the mining of crosscuts with ventilation vs. against ventilation. These statistical tests were performed for the entire cohort with the comparison of headings and crosscuts performed for each individual mine site. Additional tests were performed on other dust concentration measurements to identify configurations that may pose a respirable dust hazard to other downwind occupations. Finally, evaluations compared CM operator and SC operator dust concentrations to identify situations with potentially disparate dust exposures.

All probabilities were computed using two-sided tests, because there is no clear directional relationship between the various mining arrangements and the resulting dust concentrations. The level of significance used for all statistical tests is 0.15 (85-percent CI). This significance was chosen due to the difficulty in detecting differences in respirable dust data collected in the mine environment, which may be affected by variability in sampling as well as operating parameters, such as, water spray pressures, ventilation rates, ventilation curtain setbacks, operator positioning, and scrubber flowrates. The 85-percent confidence interval has been used in past coal mining dust control research to draw conclusions from similar data with a reasonable degree of certainty (Potts et al., 2011).

RESULTS AND DISCUSSION

Field studies at ten mines were selected from 2007 to 2014 in order to characterize the dust concentrations associated with various mining and ventilation configurations. Two surveys were conducted at mines using blowing face ventilation, six at mines using exhausting ventilation, and two at mines using either blowing or exhausting curtain depending on the continuous mining machine's location in the section. Six of the mines were taking deep cuts between 7.6 and 12.2 m (25 and 40 ft), while four mined standard cuts of 6.1 m (20 ft) depth.

The basic characteristics of the study population are shown in Table 1. This study considered a wide range of room-and-pillar coal mining environments, with mine heights ranging from a low of 107 cm (42 in) to a high of 213 cm (84 in). Measured face ventilation rates varied from 3.935 m³/s (3,255 cfm) to 9.366 m³/s (19,845 cfm) of air. Eight of the mines were distributed across the central Appalachian region, with three in eastern Kentucky, one in western Virginia, and five in southern West Virginia. Two mines were located outside of the central Appalachian region in western Kentucky.

Table 1. Characteristics of mines and cuts included in the study (SD=standard deviation)

Study characteristic	Value
Number of mines	10
Mining height in cm (in), mean ± SD [minimum-maximum]	162.8 ± 42.4 [107–213] (64.1 ± 16.7 [42–84])
Ventilation rate in m ³ /s (cfm), mean ± SD [minimum-maximum]	3.935 ± 1.354 [1.536–9.366] (8338 ± 2870 [3255–19845])
No. of cuts sampled	167
No. of headings sampled	106
No. of crosscuts sampled	61

The breakdown of intake, return, CM operator, and SC operator dust concentrations by condition and type of cut is shown in Table 2 (see APPENDIX). In addition to these measurements, dust concentrations attributed to continuous mining machine generation are calculated by subtracting the intake dust concentrations for each cut from those measured in the return. CM operator dust concentrations averaged 1.82 mg/m³ for all sampled cuts, varying from a low concentration of 0.02 mg/m³ to a high of 26.60 mg/m³. SC operator dust levels varied over a much smaller range than CM operator dust levels, averaging just 0.83 mg/m³ for the 236 cuts sampled during the study period with minimum and maximum values of 0.07 and 6.30 mg/m³, respectively. It should be noted that because there were two shuttle cars operating on many cuts the number of shuttle car cases exceeds the number of cuts sampled.

Table 3 (see APPENDIX) details the measured respirable dust concentrations at each of the ten mine sites studied. Mining heights and ventilation rates averaged 162.8 cm (64.1 in) and 3.935 m³/s (8338 cfm), respectively. Intake concentrations showed very little variation across the ten mines sampled, with values ranging from 0.03 to 0.37 mg/m³. The return dust concentrations experienced a large difference depending on mine, with a high value of 14.04 mg/m³ at Mine A and a low value of 1.17 at Mine E. Because Mine A experienced continuous mining machine-generated dust concentrations over 10.0 mg/m³ higher than the cohort average, a deeper analysis was undertaken. Field observations noted that while the mine height averaged 198 cm (78 in), the CM operator was removing up to 91 cm (36 in) of sandstone in the roof. Mining of this harder and more abrasive material has been reported to produce considerably more respirable dust due to increased bit wear and potentially cause declines in scrubber airflow rates compared to mining just coal (Pollock et al., 2009). Without more frequent maintenance, these declines in bit life and scrubber performance could negatively impact the generation of respirable dust and allow contaminated air to more readily bypass the scrubber inlets into the return.

Face ventilation configuration

Occupational dust exposures for CM operators and SC operators were both significantly impacted by face ventilation configuration. Average CM operator exposures were 1.46 mg/m³ with blowing face ventilation and 2.04 mg/m³ with exhausting face ventilation. This difference is statistically significant at 85% CI (p=0.127). This is a logical result because in blowing ventilation the CM operator is typically positioned behind the ventilation curtain in the clean stream of air entering the cut. In contrast, SC operators were exposed to significantly higher dust concentrations in the same blowing faces, 1.25 mg/m³ for blowing and 0.59 mg/m³ for exhausting (p<0.001). Mundell (1977) found that SC operators experienced a 72 percent reduction in exposure when working in exhausting face ventilation compared to blowing ventilation. The present analysis supports this finding,

observing SC operator exposures that are 53 percent lower in exhausting systems.

OMSHR and MSHA have suggested practices intended to decrease SC operator exposures on continuous mining sections. The primary prevention method is to use exhausting face ventilation when appropriate to place the SC operator in fresh air (MSHA, 2012; Colinet et al., 2010). When blowing face ventilation is necessary for methane diffusion or other operational condition, the SC operator should be located on the curtain side of the entry, so that any potential leakage from the curtain will provide fresh air to the operator (Fields, 2007). If excess air is being delivered to the mining face, it is also suggested that the mouth of the blowing curtain be winged out, allowing fresh air to pass over the SC operator's cab (Schultz and Fields, 1999). Another method that shows promise is the provision of clean air to the SC operator by means of a canopy air curtain, though proper implementation requires that steps be taken to overcome the interference caused by the combination of ventilation currents and equipment movement (Powlesland, 1971) and to fully evaluate the particular installation for effective respiratory protection.

For all but two surveys, the CM operators were exposed to higher respirable dust concentrations than the SC operators. The two mines that experienced higher SC operator dust concentrations were the only mines that operated exclusively using blowing face ventilation. In exhausting headings, CM operators were exposed to significantly more dust than SC operators (1.66 mg/m³ vs. 0.56 mg/m³, p<0.001). This is likely a result of two sources of exposure: (1) dust rollback from the face, with the CM operator being located closer to the face than the SC operator, or (2) dust emissions during the loading of shuttle cars. For blowing headings, the observed exposures are similar between CM operators (1.25 mg/m³) and SC operators (1.41 mg/m³, p=0.573). This is an unexpected outcome because CM operators should typically be positioned in the clean intake air behind the ventilation curtain, with the SC operators working in the contaminated return air. It is possible that CM operators are selecting positions based on visibility or safety concerns, which may be at odds with ideal positions based on dust exposures. With intake dust concentrations averaging 0.16 mg/m³ for these cuts and average CM operator concentrations of 1.25 mg/m³, CM operators appear to be exposed to air contaminated partially by the return air. As in this study, recent field surveys of blowing face ventilation by MSHA observed that despite being positioned in the proper work location and following the ventilation plan, CM operators could be exposed to elevated dust concentrations (Schultz et al., 2010). The issue identified in the MSHA survey was insufficient curtain airflow quantities resulting in recirculation of contaminated air back into the intake. It is possible that this is also the cause of elevated CM operator exposures in this analysis.

Depth of cut

Because all cuts observed with blowing face ventilation were also deep cuts, an analysis of depth of cut focused only on exhausting headings. With measured dust concentrations of 1.29 mg/m³ for normal depth headings and 2.39 mg/m³ for deep cuts, depth of cut did not significantly alter CM operator dust exposures (p=0.557). SC operator exposures were also found to not vary significantly depending on depth of cut, with exposures of 0.51 mg/m³ in cuts exceeding 6.1 m (20 ft) compared to 0.58 mg/m³ for normal depth cuts (p=0.647). In contrast, return dust concentrations were significantly higher for extended cuts (p=0.008), with those concentrations averaging 6.67 mg/m³ compared to 3.41 mg/m³ for normal cuts. This finding suggests that face dust controls, namely the on-board scrubber, possibly experienced a decline in capacity during extended cuts. This effect has been shown in other recent OMSHR studies, with declines of 29 to 35 percent of scrubber capacity after just 6.1 m (20 ft) of advance (Colinet et al., 2013). MSHA (2012) and Potts et al. (2010) have emphasized the need to more frequently clean the on-board scrubber system when mining extended cuts, with recommendations to clean the filter panel as frequently as before each deep cut.

Mining crosscuts

While mean CM operator dust levels for the sixty-one crosscuts sampled were nearly 1.0 mg/m³ higher than those observed for headings, these exposures were not significantly different (2.39 mg/m³

vs. 1.46 mg/m³, p=0.380). However, when advancing crosscuts against airflow, the observed dust concentrations were found to be significantly higher compared to mining similar cuts in the direction of the ventilation (2.83 mg/m³ vs. 2.19 mg/m³, p=0.118). This is likely due to contaminated air passing over the continuous mining machine when breaking through into an adjacent entry. SC operators saw a similar effect when mining against airflow as well (1.03 mg/m³ vs. 0.57 mg/m³, p=0.001), though the mining of crosscuts regardless of orientation resulted in lower dust exposures compared to mining headings (0.72 mg/m³ vs 0.91 mg/m³, p=0.006).

Average dust concentrations for headings and crosscuts at each mine are shown in Table 4. When comparing intra-mine dust concentrations using Mann-Whitney U tests, CM operator dust concentrations are found to be significantly higher for crosscuts than for headings at three of the ten mines studied (Mines B, G, and I). Conversely, SC operator dust concentrations are significantly lower for crosscuts than for headings at three of the ten mines (Mines C, F, and I). This inconsistent result across mines demonstrates the potential variability of mine exposures, especially when mining crosscuts.

Table 4. Occupational dust concentrations for individual mines and Mann-Whitney U test results comparing headings to crosscuts (CM=continuous mining machine, SC=shuttle car)

Mine ID	CM operator dust concentration, mg/m ³			SC operator dust concentration, mg/m ³		
	Heading	Crosscut	p	Heading	Crosscut	p
A	5.72	5.31	0.586	NA*	NA*	--
B	2.87	7.82	0.088	0.71	1.25	0.372
C	2.37	0.43	0.465	1.13	0.42	0.011
D	1.15	2.07	0.637	0.49	0.48	0.899
E	0.68	0.80	0.375	0.41	0.48	0.891
F	1.04	0.82	0.594	1.21	0.64	0.015
G	1.01	2.58	0.137	0.90	0.82	0.589
H	0.52	0.86	0.245	0.35	0.24	0.354
I	0.41	0.80	0.083	1.64	0.87	<0.001
J	0.67	2.20	0.641	0.56	0.98	1.000

* - No sample available for this occupation

Note: Values in bold indicate significant differences at α=0.15.

Several approaches may be adopted to minimize dust when breaking crosscuts through into adjacent entries: (1) mine the final portion of the crosscut with airflow, or from the section intake to the return, (2) when mining against airflow, minimize the time spent in this contaminated air by delaying the break-through time as long as possible, (3) when mining against airflow, consider hanging a ventilation curtain on the upwind side of the crosscut to minimize the amount of air that travels through the newly mined crosscut. This final technique, shown in Figure 7, should only be considered when conditions are appropriate (e.g. low methane emission rates) and the procedure has been included in the mine's MSHA-approved ventilation plan. To delay the break-through as long as possible, the CM operator may advance the sump cut to near the break-through point and then mine the slab cut to the same distance before breaking through.

Effectiveness of scrubbers

Prior research has shown that the highest dust concentrations on continuous mining sections result from cutting and drilling activities (Kissell, 2003). This study demonstrates that the continuous mining machine contributes 3.59 mg/m³ of dust to the return airstream when operating in a face equipped with an on-board scrubber. This agrees with other recent OMSHR observations of average continuous mining machine contributions of 4.0 mg/m³ on faces with operating scrubbers (Colinet et al. 2013). On faces without operating scrubbers, these same researchers observed return dust concentrations exceeding 23 mg/m³. This contrast demonstrates that the scrubber is effective at reducing face dust concentrations. Despite these reductions, the air downstream of the scrubber-equipped continuous mining machine is contaminated by elevated concentrations of respirable dust, and operators should strive to limit time spent in these conditions.

Highlighted cuts

During the analysis, cuts were highlighted to demonstrate a particularly hazardous configuration to face workers or a situation that

warrants emphasis as an example of good or poor dust control practices.

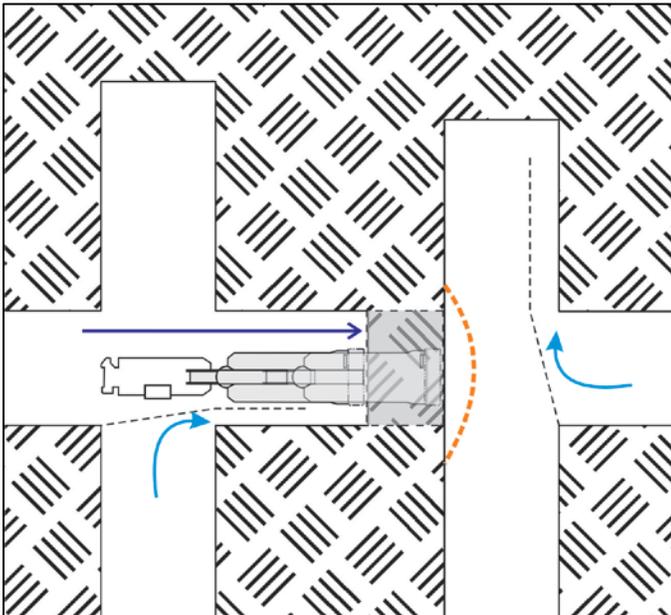


Figure 7. Diagram showing the placement of ventilation curtain on the upwind side of a crosscut to prevent the rollback of contaminated air.

Mining break-throughs against airflow – This first example illustrates the finding that finishing crosscuts against airflow can result in higher dust exposures for both SC and CM operators. Figure 8 details dust concentrations for a crosscut mined against airflow at Mine J. Instantaneous dust measurements at the CM operator and SC locations reached nearly 100 mg/m³ and 80 mg/m³, respectively, once the crosscut was broken through into the adjacent entry and dust-laden air entered their workspaces. Average CM operator and SC operator dust concentrations for the entire period shown were 8.91 mg/m³ and 3.86 mg/m³, respectively. This can be compared to a crosscut mined with airflow earlier in the week-long study, shown in Figure 9. Instantaneous dust concentrations at the CM operator location reached only 3.09 mg/m³ with a maximum SC operator concentration of 7.04 mg/m³. Average CM operator and SC operator dust concentrations for the entire period shown were 0.33 mg/m³ and 0.32 mg/m³, respectively.

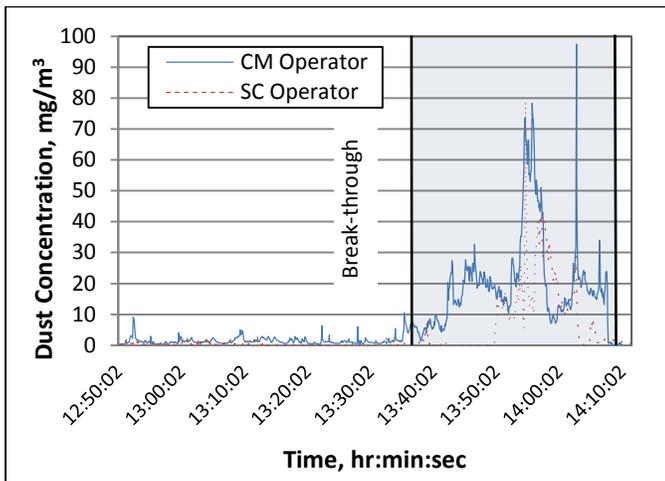


Figure 8. Instantaneous dust concentrations while mining the final portion of a crosscut counter-currently at Mine J.

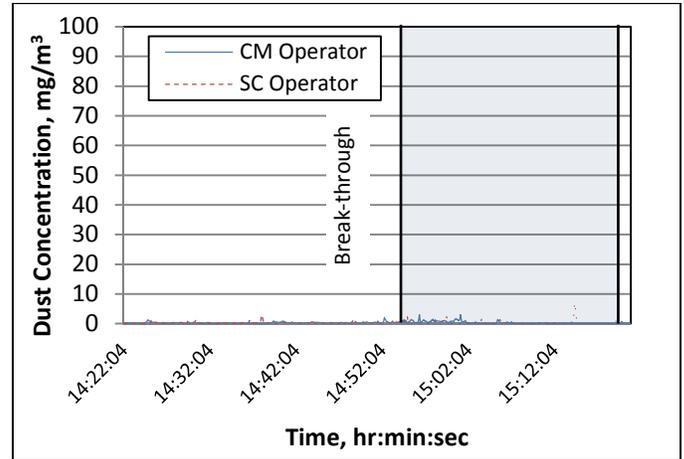


Figure 9. Instantaneous dust concentrations while mining the final portion of a crosscut co-currently at Mine J.

Improper CM operator positioning – CM operator movements were closely monitored at mining faces using blowing curtain ventilation to record if the operator stood in clean intake air. For many of the cuts at Mine I, the operator positioned himself within 3 m (10 ft) of the mouth of the curtain. In the first of the two cuts displayed in Figure 10, the CM operator mined a heading while standing in this location. The average CM operator exposure for Cut 1 was 0.13 mg/m³, with a maximum instantaneous concentration of 0.44 mg/m³.

Upon completion of this cut, a different CM operator began mining the adjacent heading (Cut 2). OMSHR researchers observed that this operator occasionally walked into the entry to reposition the continuous mining machine in the cut. These infrequent maneuvers produced instantaneous CM operator dust concentrations exceeding 5 and 6 mg/m³ and an average respirable dust concentration of 1.34 mg/m³ for the entire cut. These values can be compared with 0.52 mg/m³ (from Table 3) for the entire mine study. This result illustrates the need to train CM operators in proper positioning and to limit time spent in contaminated return air. The adoption of real-time personal dust monitoring instruments, such as the PDM 3600 Personal Dust Monitor (Thermo Scientific, Franklin, MA) may provide timely feedback about respirable dust exposures and assist in improving operator positioning (Peters et al., 2008). It is also suggested that the CM operator attempt to delay his movements into the entry until the scrubber has cleared the dust from the face region and fresh intake air has displaced or diluted any contaminated air.

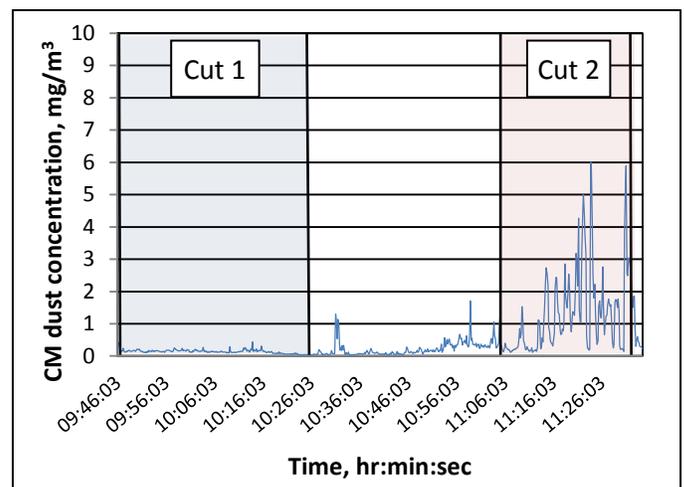


Figure 10. Instantaneous CM operator dust concentrations while mining two headings showing the effect of proper positioning (Cut 1) and operator movements into a contaminated atmosphere (Cut 2).

Mining of rock in the face – While many mines must remove large portions of rock to maintain haulage clearances, the mining of hard rock can increase the generation of dust due to accelerated bit wear and loss of scrubber performance (Pollock et al., 2009). A third highlighted example demonstrates the effect of rock on occupational dust exposures. Figure 11 details instantaneous CM operator dust concentrations for the mining of two cuts at Mine I. At a mining height of 213 cm (84 in), Cut 1 advanced 11.0 m (36 ft) in a face containing only coal and Cut 2 advanced 7.3 m (24 ft) in an adjacent face with 76-91 cm (30-36 in) of rock. Average CM operator dust concentrations were 0.20 mg/m³ and 0.95 mg/m³ for Cuts 1 and 2, respectively. Maximum instantaneous values measured at the CM operator location during these same cuts were 0.51 mg/m³ and 3.93 mg/m³, respectively. SC operator dust exposures during loading were also notably higher when mining the face containing rock with average loading concentrations of 2.63 mg/m³ in Cut 2 and 1.51 mg/m³ in Cut 1.

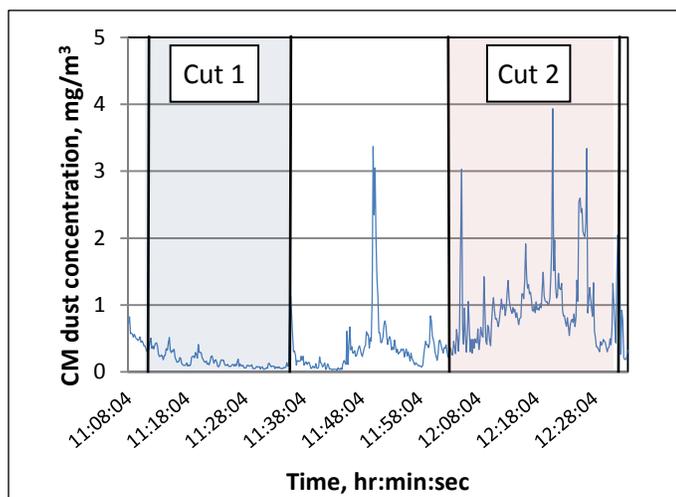


Figure 11. Instantaneous CM operator dust concentrations while mining a full face of coal (Cut 1) and mining 30-36 inches of rock (Cut 2).

Limitations of the study

The results of this study may be limited in generalizability because only ten mines were analyzed out of the almost five hundred underground coal mines in the U.S. (EIA, 2013). The regional concentration of these study sites also limits the generalizability to other regions of the U.S. Although the wide range of mining conditions studied provides a broad scope to the analysis, these disparate conditions may weaken this study's comparisons and conclusions. This analysis is also unable to evaluate whether respirable dust generation or exposures are a result of production, equipment selection, seam height, or another mining parameter not included in the analysis. Despite these limitations, the findings of this study can be illustrative and informative regarding particular practices and mining layouts.

SUMMARY

Continuous mining sections can encounter a wide range of conditions and adopt a similarly wide range of configurations during coal extraction. This OMSHR study investigates the respirable dust exposures associated with these continuous mining arrangements by reviewing dust surveys performed at ten U.S. mines.

Dust measurements taken during 167 continuous mining cuts show that face ventilation schemes can significantly influence both CM operator and SC operator exposures, with exhausting faces resulting in higher CM operator exposures than blowing faces. SC operators experienced the opposite effect, with higher dust exposures on blowing faces than on exhausting ventilation. Comparisons between CM operator and SC operator dust measurements show that in headings ventilated with exhaust curtain, CM operators were exposed to significantly higher dust concentrations than SC operators. In blowing headings, the difference in exposures was found to be not significant, although positioning at the mouth of the curtain should provide CM

operators with clean intake air while SC operators work in potentially contaminated return air on the wide side of the entry.

Mining extended or deep cuts did not result in statistically significant differences in CM operator and SC operator exposures when compared to normal depth cuts. A significant difference was found in the dust concentrations in the return airway, with higher levels associated with deeper cuts.

When comparing all crosscut orientations to all heading cuts, dust levels measured at the CM operator did not show a significant difference. The same comparison made for SC operators shows that crosscuts were significantly lower than headings. Comparisons of CM exposures made at the intra-mine level indicate that a significant difference exists with crosscut exposures being higher than headings at three of the ten survey locations. The same comparison made for SC operators found significantly lower respirable dust exposures in crosscuts than in headings at three mine sites. Crosscuts advanced and broken-through against section ventilation were shown to result in higher dust exposures for both CM operators and SC operators than similar cuts made in the direction of the ventilation.

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DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

REFERENCES

- Colinet, J.F., Rider, J.P., Listak, J.M., Organiscak, J.A., & Wolfe, A.L. (2010). Information Circular 9517: Best Practices for Dust Control in Coal Mining. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2010-110:1-76.
- Colinet, J.F., Reed, W.R., Potts, J.D. (2013). Report of Investigations 9693: Impact on Respirable Dust Levels When Operating a Flooded-bed Scrubber in 20-foot Cuts. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2014-105:1-59.
- EIA. (2013). Annual Coal Report, December 2013. Washington, DC: U.S. Department of Energy, Energy Information Administration. [http://www.eia.gov/coal/annual/pdf/acr.pdf]. Date accessed: August 2014.
- Fields, K.G. (2007). Ventilation – A principal control for dust and methane. In: Controlling Respirable Coal Mine Dust in Underground Mines, July 25, 2007. Beckley, WV: U.S. Department of Labor, Mine Safety and Health Administration. [http://www.msha.gov/S&HINFO/BlackLung/ControlDust2007/CTD2007.asp]. Date accessed: January 2014.
- Gray, W.J., Zelanko, J.C., Gauna, M. (2005). Turning crosscuts with remote control continuous miners – improving safety. In: Proceedings of the SME annual meeting, Salt Lake City, UT, SME Preprint 05-70. Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc.:1-8.
- Kissell, F.N. (2003). Information Circular 9465: Handbook for Dust Control in Mining. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease

- Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2003-147:1-131.
7. Kollipara, V. K., Chugh, Y. P., & Southern, D. D. R. (2012). A CFD analysis of air flow patterns in face area for continuous miner making a right turn cut. In: Proceedings of the SME annual meeting, Seattle, WA, SME Preprint 12-132. Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc.:1-8.
 8. Luxner, J.V. (1969). Report of Investigations 7223: Face ventilation in underground bituminous coal mines: Airflow and methane distribution in immediate face areas—line brattice. Washington, DC: U.S. Department of the Interior, Bureau of Mines:1-16.
 9. MSHA (2008). Procedure Instruction Letter No. I08-V-3 – Procedures for Evaluation of Requests to Make Extended Cuts With Remote Controlled Continuous Mining Machines. Arlington, VA: U.S. Department of Labor, Mine Safety and Health Administration.
 10. MSHA. (2011). Program Information Bulletin Number P11-33 – Re-Issue of P07-12 - Best Practices for Turning Crosscuts with Remote Controlled Continuous Mining Machines. Arlington, VA: U.S. Department of Labor, Mine Safety and Health Administration.
 11. MSHA. (2012). Procedure Instruction Letter No. I12-V-11 – Re-Issue of I10-V-09 – Procedures for Evaluation of Requests to Make Extended Cuts With Remote Controlled Continuous Mining Machines. Arlington, VA: U.S. Department of Labor, Mine Safety and Health Administration.
 12. Mundell, R.L. (1977). Informational Report 1059: Blowing Versus Exhausting Face Ventilation for Respirable Dust Control on Continuous Mining Sections. Pittsburgh, PA: U.S. Department of the Interior: Mining Enforcement and Safety Administration:1-11.
 13. Organiscak, J.A. & Beck, T.W. (2010). Continuous miner spray considerations for optimizing scrubber performance in exhaust ventilation systems. *Mining Engineering*, 62(10):41-46.
 14. Peters, R.H., Vaught, C., Hall, E.E., Volkwein, J.C. (2008). Information Circular 9501: Miners' Views About Personal Dust Monitors. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2008-110:1-47.
 15. Pollock, D.E., Potts, J.D., & Joy, G.J. (2009). Investigation into dust exposures and mining practices in mines in the southern Appalachian region. In: Proceedings of the SME Annual Meeting, Denver, CO, SME Preprint 09-009. Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc.:1-5.
 16. Potts, J.D., Reed, W.R., & Colinet, J.F. (2011). Report of Investigations 9680: Evaluation of Face Dust Concentrations at Mines Using Deep-Cutting Practices. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2011-131:1-94.
 17. Powlesland, J.W. (1971). New uses continue to be found for air curtains. *Canadian Mining Journal*, October 1971:84-93.
 18. Schultz, M.J., Fields, K.G. (1999). Dust control considerations for deep cut mining sections. In: Proceedings of the SME Annual Meeting, Denver, CO, SME Preprint 99-163. Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc.:1-4.
 19. Schultz, M.J., Tomko, D.M., Rumbaugh, V.E. (2010). Utilizing adequate intake line curtain air quantities to maintain respirable dust compliance. In: Proceedings of the 13th U.S./North American Mine Ventilation Symposium. Sudbury, Ontario, Canada, June 13-16, 2010. Hardcastle, McKinnon, eds., Sudbury, Ontario, Canada: MIRARCO - Mining Innovation, 2010:1-6.
 20. Taylor, C.D., Rider, J.P., Thimons, E.D. (1996). Changes in face methane concentrations using high capacity scrubbers with exhausting and blowing ventilation. In: Proceedings of the SME Annual Meeting, Phoenix, AZ, SME Preprint 96-167. Littleton, CO: Society for Mining, Metallurgy, and Exploration, Inc.:1-5.
 21. Thrush, P.W. (1968). A dictionary of mining, mineral, and related terms, compiled and edited by Paul W. Thrush and the Staff of the Bureau of Mines, Washington, DC: U.S. Department of the Interior, Bureau of Mines:1-1269.
 22. Tien, J. C. (1988). Face ventilation during cross-cut development in a room-and-pillar operation. In: Proceedings of the 4th Mine Ventilation Symposium, Berkeley, CA:202-208.
 23. Turin, F., Steiner, L., Cornelius, K. (1998). Evaluation of mining activities using a scenario interview approach. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 42(15), 1108–1112.

APPENDIX

Table 2. Types of cut sampled and the resulting area and occupational dust concentrations (SD=standard deviation)

Cut description (number of CM operator cases, number of SC operator cases)	Intake dust concentration, mg/m ³ , mean ± SD	Return dust concentration, mg/m ³ , mean ± SD	CM operator dust concentration, mg/m ³ , mean ± SD	SC operator dust concentration, mg/m ³ , mean ± SD	CM-generated dust concentration, mg/m ³ , mean ± SD
Overall (167, 236)	0.19 ± 0.24	3.78 ± 5.66	1.82 ± 3.15	0.83 ± 0.77	3.59 ± 5.63
Headings (106, 144)	0.18 ± 0.26	4.31 ± 6.73	1.46 ± 2.20	0.91 ± 0.71	4.13 ± 6.70
Blowing headings (44, 59)	0.16 ± 0.13	4.02 ± 8.96	1.25 ± 1.86	1.41 ± 0.70	3.86 ± 8.99
Exhaust headings (62, 85)	0.19 ± 0.32	4.52 ± 4.55	1.66 ± 2.42	0.56 ± 0.46	4.33 ± 4.43
Normal depth headings (55, 80)	0.15 ± 0.16	2.97 ± 2.90	1.18 ± 1.24	0.79 ± 0.70	2.81 ± 2.90
Deep cut headings (51, 64)	0.20 ± 0.33	5.73 ± 9.02	1.82 ± 2.88	1.05 ± 0.70	5.53 ± 8.98
Crosscuts (61, 92)	0.21 ± 0.22	2.88 ± 2.92	2.39 ± 4.29	0.72 ± 0.85	2.67 ± 2.89
Blowing crosscuts (19, 28)	0.28 ± 0.29	3.31 ± 2.98	1.95 ± 3.43	0.92 ± 0.54	3.03 ± 3.02
Exhaust crosscuts (42, 64)	0.18 ± 0.17	2.67 ± 2.90	2.59 ± 4.65	0.63 ± 0.94	2.49 ± 2.84
Crosscuts with airflow (42, 62)	0.24 ± 0.22	2.79 ± 2.82	2.19 ± 4.56	0.57 ± 0.81	2.55 ± 2.76
Crosscuts against airflow (19, 30)	0.15 ± 0.21	3.07 ± 3.18	2.83 ± 3.69	1.03 ± 0.85	2.92 ± 3.21

Table 3. Individual mine characteristics and measured dust concentrations (CM=continuous mining machine, SC=shuttle car).

Mine ID (number of cuts)	Face ventilation	Average mining height, cm (in)	Typical cut depth, m (ft)	Average face airflow, m ³ /s (cfm)	Intake dust conc., mg/m ³	Return dust conc., mg/m ³	CM operator dust conc., mg/m ³	SC operator dust conc., mg/m ³	CM-generated dust conc., mg/m ³
A (14)	Mixed	213 (84)	10.7 (35)	1.967 (4168)	0.03	14.04	5.63	N/A*	14.01
B (12)	Exhaust	107 (42)	6.1 (20)	3.304 (7000)	0.20	4.81	5.75	1.02	4.61
C (10)	Exhaust	107 (42)	6.1 (20)	4.012 (8500)	0.25	5.54	1.40	0.66	5.29
D (15)	Exhaust	188 (74)	7.6 (25)	4.512 (9560)	0.17	4.33	1.52	0.48	4.16
E (22)	Exhaust	114 (45)	6.1 (20)	2.454 (5200)	0.16	1.17	0.73	0.44	1.01
F (24)	Blowing	198 (78)	9.8 (32)	3.194 (6768)	0.26	2.64	0.98	1.04	2.38
G (28)	Mixed	183 (72)	6.1 (20)	3.407 (7219)	0.10	1.22	1.68	0.86	1.12
H (7)	Exhaust	152 (60)	12.2 (40)	4.684 (9925)	0.13	2.29	0.70	0.32	2.16
I (21)	Blowing	213 (84)	11.0 (36)	4.188 (8874)	0.24	1.87	0.52	1.41	1.63
J (14)	Exhaust	152 (60)	11.0 (36)	4.900 (10383)	0.37	5.80	1.21	0.71	5.43

* - No sample available for this occupation