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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 have impacts on the ability of dust controls to reduce occupational respirable dust exposures. This study reports and analyzes dust concentrations measured by the Pittsburgh Mining Research Division for remote-controlled continuous mining machine operators as well as haulage operators at 10 U.S. underground mines. The results of these respirable dust surveys show that continuous miner exposures varied little with depth of cut but are significantly higher with exhaust ventilation. Haulage operators experienced elevated concentrations with blowing face ventilation. Elevated dust concentrations were 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 exposures attributable to particular mining configurations. These findings form the basis for recommendations for lowering face worker respirable dust exposures.

Keywords

Dust; Continuous mining; Ventilation

Introduction

Background

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 miners 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, or scrubbers, to

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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.

The objective of this study by the Pittsburgh Mining Research Division (PMRD) of the U.S. National Institute for Occupational Safety and Health (NIOSH) is to evaluate respirable dust exposures associated with a range of continuous miner 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. 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.

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 with ventilation curtains and machine-mounted scrubbers in Figs. 1 and 2. Prior research had demonstrated several benefits and drawbacks for each approach related to dust exposures and methane control.

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 miner'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 a blowing curtain over an 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 operators and downwind workers (Mundell, 1977; Volkwein and Divers, 1987; Schultz and Fields, 1999; Jayaraman, Babbitt and O'Green, 1988). Additionally, dust generated during the loading of shuttle cars may pass over the shuttle-car operator in this ventilation arrangement. While blowing face ventilation has the advantage of positioning the continuous miner 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.

Exhaust ventilation as shown in Fig. 2 uses a line curtain on the same side as the scrubber discharge and places the continuous miner 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 continuous miner 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; Mine Safety and Health Administration, 2012).

Mining extended cuts

An extended or deep cut is defined as any cut in which the continuous miner advances more than 6.1 m (20 ft) inby the last row of permanent roof supports. Mines typically prefer these cuts as they reduce place changes and increase equipment production time. Field studies conducted by the U.S. Mine Safety and Health Administration (MSHA) had 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). The studies suggest that even when properly undertaken, these cuts may result in additional dust exposures compared with normal depth cuts.

In 2008 guidance was issued in the form of a procedure instruction letter, PIL No. I08-V-3, to the MSHA coal mining districts for evaluating and approving operator plans incorporating extended cuts (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 reissued as PIL No. I12-V-11 (MSHA, 2012).

With approximately 70 percent of continuous miners extracting deep cuts, a recent PMRD study investigated the exposures associated with mining headings of varying depths (Potts, Reed and Colinet, 2011). In this study, researchers divided deep cuts into two segments, comparing the initial 6.1-m (20-ft) portion with the final 6.1-m (20-ft) part of a 12.2-m (40-ft) cut. Their analysis found that increasing the depth of cut did not significantly increase dust exposures for continuous miner or shuttle-car 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 Fig. 4 shows a detailed view of the equipment and curtain positions in a crosscut ventilated by blowing curtain. For continuous miner operators, the process of mining crosscuts is considered to be possibly the most difficult and variable portion of underground room-and-pillar coal production (Turin, Steiner and Cornelius, 1998). From 2001 to 2011, seven of the 15 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 miner 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 had evaluated different practices in turning these crosscuts, they provided minimal discussion and validation of continuous miner operator respirable dust exposures in their placement recommendations (Gray, Zelanko and Gauna, 2005).

Completing crosscuts

The final cut, or breakthrough, 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 the airflow (with the airflow) or in the opposite direction as the airflow (against the airflow). These situations are depicted in Figs. 5 and 6 for mining the same crosscut from opposite directions. In Fig. 5, as the breakthrough is mined with the airflow, the air will flow away from the mining machine and the continuous miner operator into the adjacent entry. In Fig. 6, the continuous miner operator is mining against the airflow and the contaminated air will pass over the mining machine into the continuous miner operator and shuttle car 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 miners are equipped with a flooded-bed scrubber (Taylor, Rider and Thimons, 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 miner. 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. The effect of improved ventilation into crosscuts with higher curtain lengths was further demonstrated by Aminossadati and Hooman (2008) using computational fluid dynamics (CFD) analyses. Kollipara, Chugh and Southern (2012) recently investigated the presence of face recirculation and low air velocities in crosscut entries for a range of CFD test conditions. The regions characterized with both low air velocity and recirculation could have a negative impact on exposure to respirable dust for haulage and continuous miner 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, similar conditions have been demonstrated by PMRD researchers in a full-scale continuous miner gallery using exhausting face ventilation. Increased curtain setbacks and reduced scrubber airflows both resulted in increased dust and gas concentrations at the rear corners of the continuous miner (Organiscak and Beck, 2010).

Methods

Mine selection

Researchers with PMRD evaluated respirable dust concentrations at 10 underground coal mines from 2007 to 2014. These mines were each typically sampled over the period of four shifts in both single continuous miner and supersection 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 using continuous miners 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 continuous miner 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 Figs. 1 and 2, respectively. The sampling locations for crosscuts are labeled in Fig. 4. The sampling package at each location consisted of two gravimetric coal mine dust personal sampling units and one continuously logging personal DataRAM (pDR) (Thermo Fisher Scientific, Waltham, MA). The gravimetric sampling pumps were calibrated to 2 L/min prior to each weeklong study. These pumps drew dust-laden air through Dorr-Oliver 10-mm (0.4-in.) nylon cyclones, depositing the respirable dust fraction onto pre-weighed 37-mm (1.5- in.) polyvinyl chloride filters. All filters were pre- and post-weighed in the environmentally controlled weighing laboratory at the PMRD facility in Pittsburgh, PA. Gravimetric dust concentrations were determined by dividing the accumulated mass by the total volume of air sampled. Dust concentrations were measured only during continuous miner 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.

Instantaneous dust concentrations were measured and recorded for each five-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 five-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.

PMRD researchers collected time study information to record the operation and position of each continuous miner and shuttle car during production activities. Production times were recorded for each cut, removing downtime from other mining activities, such as tramming or cleaning scrubber ductwork, from the dust calculations so that dust generated during mining and loading could be distinguished. Continuous miner operator positions were observed to identify potentially unfavorable activities in regard 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 statistical-analysis software (IBM Corp, Armonk, NY). Descriptive statistics included means, standard deviations, and minimum and maximum values. The dust concentration values were analyzed using Shapiro-Wilk 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, nonparametric alternatives to the two-sample Student's t-test, were performed to evaluate the potential that continuous miner operator or shuttle-car operator dust concentration is affected by (1) the use of blowing versus exhausting face ventilation, (2) the mining of standard versus extended depth cuts, (3) the mining of headings versus crosscuts and (4) the mining of crosscuts with ventilation versus 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 continuous miner operator and shuttle-car 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 was 0.15, corresponding to an 85 percent confidence interval. 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 had been used in past coal mining dust control research to draw conclusions from similar data with a reasonable degree of certainty (Potts, Reed and Colinet, 2011).

Results and discussion

Field studies at 10 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 miner'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 1.536 m^3/s (3,255 cfm) to 9.366 m^3/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.

The breakdown of intake, return, continuous miner operator and shuttle-car operator dust concentrations by condition and type of cut is shown in Table 2. In addition to these measurements, dust concentrations attributed to continuous miner generation were calculated by subtracting the intake dust concentrations for each cut from those measured in the return. Continuous miner operator dust concentrations averaged 1.82 mg/m^3 for all sampled cuts, varying from a low concentration of 0.02 mg/m^3 to a high of 26.60 mg/m^3. Shuttle- car operator dust levels varied over a much smaller range than continuous miner operator dust levels, averaging just 0.83 mg/m^3 for the 236 cuts sampled during the study period with minimum and maximum values of 0.07 and 6.30 mg/m^3, 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 details the measured respirable dust concentrations at each of the 10 mine sites studied. The mines are listed in chronological order. Mining heights and ventilation rates averaged 162.8 cm (64.1 in) and 3.935 m^3/s (8,338 cfm), respectively.

Intake concentrations showed little variation across the 10 mines sampled, with values ranging from 0.03 to 0.37 mg/m^3. The return dust concentrations exhibited a large difference depending on the mine, with a high value of 14.04 mg/m^3 at Mine A and a low value of 1.17 mg/m^3 at Mine E. Because Mine A experienced continuous miner-generated dust concentrations that were more than 10.0 mg/m^3 higher than the cohort average, a deeper analysis was undertaken. Field observations noted that while the mine height averaged 198 cm (78 in.), the continuous miner operator was removing up to 91 cm (36 in.) of sandstone in the roof. Mining of this harder and more abrasive material had been reported to produce considerably more respirable dust due to increased bit wear and to potentially cause declines in scrubber airflow rates compared with mining just coal (Pollock, Potts and Joy, 2010). Without more frequent maintenance, these declines in bit life and scrubber performance could have a negative impact on 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 continuous miner operators and shuttle-car operators were both significantly affected by face ventilation configuration. Average continuous miner operator exposures were 1.46 mg/m^3 with blowing face ventilation and 2.04 mg/m^3 with exhausting face ventilation. This difference is statistically significant at 85 percent confidence interval ($p = 0.127$). This is a logical result because in blowing ventilation the continuous miner operator is typically positioned behind the ventilation curtain in the clean stream of air entering the cut. In contrast, the shuttle-car operators were exposed to significantly higher dust concentrations in the same blowing faces, 1.25 mg/m^3 for blowing and 0.59 mg/m^3 for exhausting ($p < 0.001$). Mundell (1977) found that shuttle-car operators experienced a 72 percent reduction in exposure when working in exhausting face ventilation compared with blowing ventilation. The present analysis supports this finding, observing shuttle-car operator exposures that are 53 percent lower in exhausting systems.

PMRD and MSHA have suggested practices intended to decrease shuttle-car operator exposures on continuous miner sections. The primary prevention method is to use exhausting face ventilation when appropriate to place the shuttlecar operator in fresh air (MSHA, 2012; Colinet et al., 2010). When blowing face ventilation is necessary for methane diffusion or other operational condition, the shuttle-car 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 shuttle-car operator's cab (Schultz and Fields, 1999). Another method that shows promise is the provision of clean air to the shuttle-car 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 continuous miner operators were exposed to higher respirable dust concentrations than the shuttle-car operators. The two mines that experienced higher shuttle-car operator dust concentrations were the only mines that operated exclusively using blowing face ventilation. In exhausting headings, continuous miner operators were exposed to significantly more dust than shuttle-car operators: 1.66 mg/m^3 versus 0.56 mg/m^3, $p < 0.001$). This is likely a result of two sources of exposure: (1) dust rollback from the face, with the continuous miner operator being located closer to the face than the shuttle-car operator, or (2) dust emissions during the loading of shuttle cars. For blowing headings, the observed exposures are similar between continuous miner operators and shuttle-car operators: 1.25 and 1.41 mg/m^3, respectively, $p = 0.573$. This is an unexpected outcome because continuous miner operators should typically be positioned in the clean intake air behind the ventilation curtain, with the shuttle-car operators working in the contaminated return air. It is possible that continuous miner operators are selecting positions based on visibility, productivity or safety concerns, which may be at odds with ideal positions based on dust exposures. With intake dust concentrations averaging 0.16 mg/m^3 for these cuts and average continuous miner operator concentrations of 1.25 mg/m^3, continuous miner 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, continuous miner operators could be exposed to elevated dust concentrations (Schultz, Tomko and Rumbaugh, 2010). The issue identified in the MSHA survey was insufficient curtain airflow quantities, resulting in the recirculation of contaminated air back into the intake. It is possible that this is also the cause of elevated continuous miner operator exposures in the present 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/m^3 for normal depth headings and 2.39 mg/m^3 for deep cuts, depth of cut did not significantly alter continuous miner operator dust exposures ($p = 0.557$). Shuttle-car operator exposures were also found to not vary significantly depending on depth of cut, with exposures of 0.51 mg/m^3 in cuts exceeding 6.1 m (20 ft) compared with 0.58 mg/m^3 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/m^3 compared with 3.41 mg/m^3 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 PMRD studies, with declines of 29 to 35 percent of scrubber capacity after just 6.1 m (20 ft) of advance (Colinet, Reed and Potts, 2013). MSHA (2012) and Potts, Reed and Colinet (2011) 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 continuous miner operator dust levels for the 61 crosscuts sampled were nearly 1.0 mg/m^3 higher than those observed for headings, these exposures were not significantly different: 2.39 mg/m^3 versus 1.46 mg/m^3, $p = 0.380$. However, when advancing crosscuts against airflow, the observed dust concentrations were found to be significantly higher compared with mining similar cuts in the direction of the ventilation: 2.83 mg/m^3 versus 2.19 mg/m^3, $p = 0.118$. This is likely due to contaminated air passing over the continuous miner when breaking through into an adjacent entry. Shuttle-car operators saw a similar effect when mining against airflow as well, with 1.03 mg/m^3 versus 0.57 mg/m^3, $p = 0.001$, though the mining of crosscuts regardless of orientation resulted in lower dust exposures compared with mining headings: 0.72 mg/m^3 versus 0.91 mg/m^3, $p = 0.006$.

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, continuous miner operator dust concentrations were found to be significantly higher for crosscuts than for headings at three of the 10 mines studied: Mines B, G and I. Conversely, shuttle-car operator dust concentrations were significantly lower for crosscuts than for headings at three of the 10 mines: Mines C, F and I. This inconsistent result across mines demonstrates the potential variability of mine exposures, especially when mining crosscuts.

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 breakthrough 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 Fig. 7, should only be considered when conditions are appropriate, such as when methane emission rates are low, and the procedure has been included in the mine's

MSHA-approved ventilation plan. To delay the break-through as long as possible, the continuous miner operator may advance the sump cut to near the breakthrough point and then mine the slab cut to the same distance before breaking through.

Effectiveness of scrubbers

Prior research had shown that the highest dust concentrations on continuous miner sections result from cutting and drilling activities (Kissell, 2003). The present study demonstrates that the continuous miner contributes 3.59 mg/m^3 of dust to the return airstream when operating in a face equipped with an on-board scrubber. This agrees with other recent PMRD observations of average continuous miner contributions of 4.0 mg/m^3 on faces with operating scrubbers (Colinet, Reed and Potts, 2013). On faces without operating scrubbers, these same researchers observed return dust concentrations exceeding 23 mg/m^3. This contrast demonstrates that the scrubber is effective at reducing face dust concentrations. Despite these reductions, the air downstream of the scrubber-equipped continuous miner 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:

Mining breakthroughs against airflow—This first example illustrates the finding that finishing crosscuts against airflow can result in higher dust exposures for both shuttle-car and continuous miner operators. Figure 8 details dust concentrations for a crosscut mined against airflow at Mine J. Instantaneous dust measurements at the continuous miner operator and shuttle-car locations reached nearly 100 mg/m^3 and 80 mg/m^3, respectively, once the crosscut was broken through into the adjacent entry and dust-laden air entered their workspaces. Average continuous miner operator and shuttle-car operator dust concentrations for the entire period shown were 8.91 and 3.86 mg/m^3, respectively. This can be compared with a crosscut mined with airflow earlier in the week-long study, shown in Fig. 9. Instantaneous dust concentrations at the continuous miner operator location reached only 3.09 mg/m^3, and the maximum shuttle-car operator concentration was 7.04 mg/m^3. Average continuous miner operator and shuttle-car operator dust concentrations for the entire period shown were 0.33 and 0.32 mg/m^3, respectively.

Improper continuous miner operator positioning—Continuous miner 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 Fig. 10, the continuous miner operator mined a heading while standing in this location. The average continuous miner operator exposure for Cut 1 was 0.13 mg/m^3, with a maximum instantaneous concentration of 0.44 mg/m^3.

Upon completion of this cut, a different continuous miner operator began mining the adjacent heading (Cut 2). PMRD researchers observed that this operator occasionally walked into the entry to reposition the continuous miner in the cut. These infrequent maneuvers produced instantaneous continuous miner operator dust concentrations exceeding 5 and 6 mg/m^3 and an average respirable dust concentration of 1.34 mg/m^3 for the entire cut. These values can be compared with 0.52 mg/m^3 (from Table 3) for the entire mine study. This result illustrates the need to further investigate operator positioning and develop interventions to reduce time spent by continuous miner operators in contaminated return air. The adoption of near-real-time personal dust monitoring instruments may provide timely feedback about respirable dust exposures and assist in improving operator positioning (Peters et al., 2008). It is also suggested that the continuous miner 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.

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, Potts and Joy, 2010). A third highlighted example demonstrates the effect of rock on occupational dust exposures. Figure 11 details instantaneous continuous miner 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 to 91 cm (30 to 36 in.) of rock. Average continuous miner operator dust concentrations were 0.20 and 0.95 mg/m^3 for Cuts 1 and 2, respectively. Maximum instantaneous values measured at the continuous miner operator location during these same cuts were 0.51 and 3.93 mg/m^3, respectively. Shuttle-car operator dust exposures during loading were also notably higher when mining the face containing rock with average loading concentrations of 2.63 mg/m^3 in Cut 2 and 1.51 mg/m^3 in Cut 1.

Limitations of the study

The results of this study may be limited in generalizability because only 10 mines were analyzed out of the nearly 500 underground coal mines in the United States (Energy Information Administration, 2015). The regional concentration of the study sites also limits the study's generalizability to other regions of the United States. 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 other 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 PMRD study investigates the respirable dust exposures associated with these continuous mining arrangements by reviewing dust surveys performed at 10 U.S. mines.

Dust measurements taken during 167 continuous miner cuts show that face ventilation schemes can significantly influence both continuous miner operator and shuttle-car operator exposures, with exhausting faces resulting in higher continuous miner operator exposures than blowing faces. Shuttle-car operators experienced the opposite effect, with higher dust exposures on blowing faces than on exhausting ventilation. Comparisons between continuous miner operator and shuttle-car operator dust measurements show that in headings ventilated with exhaust curtain, continuous miner operators were exposed to significantly higher dust concentrations than shuttle-car operators. In blowing headings, the difference in exposures was not found to be significant, although continuous miner operator positioning at the mouth of the curtain should provide clean intake air while shuttle-car operators must work on the wide side of the entry in potentially contaminated return air.

Mining extended or deep cuts did not result in statistically significant differences in continuous miner operator and shuttle- car operator exposures when compared with 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 continuous miner operator did not show a significant difference. The same comparison made for shuttle-car operators shows that crosscuts were significantly lower than headings. Comparisons of continuous miner exposures made at the intra-mine level indicate that a significant difference exists with crosscut exposures being higher than headings at three of the 10 survey locations. The same comparison made for shuttle-car 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 continuous miner operators and shuttle-car operators than similar cuts made in the direction of the ventilation.

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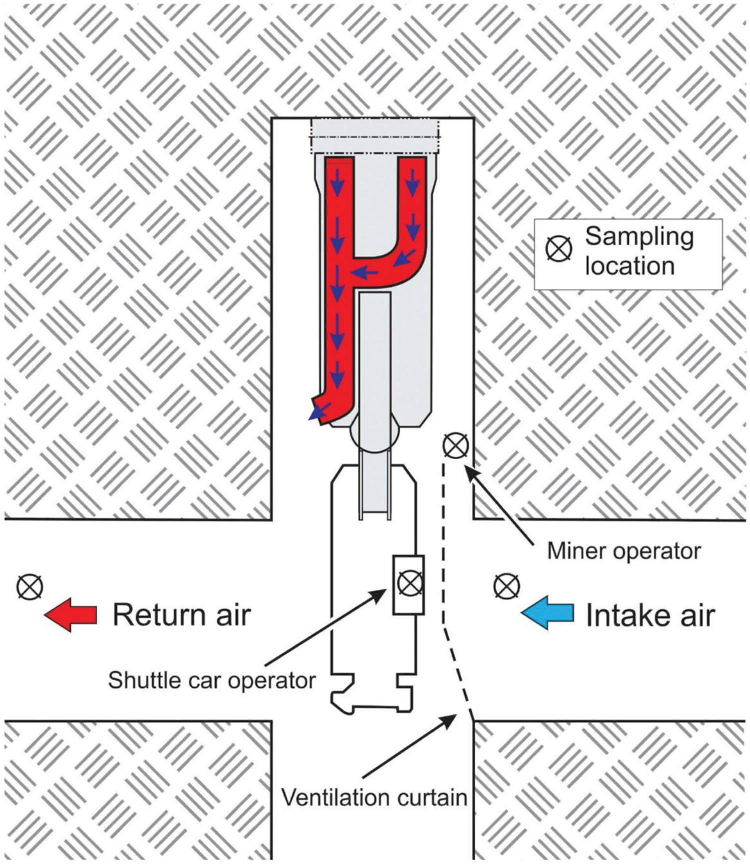

Figure 1.

Layout of a blowing curtain face ventilation system.

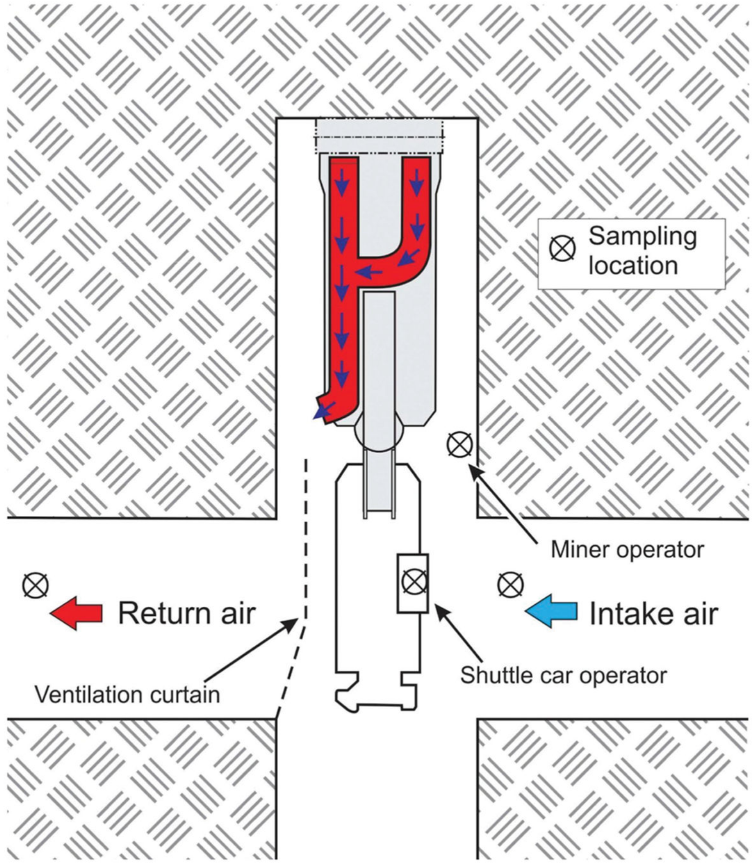

Figure 2.
Layout of an exhausting curtain face ventilation system.

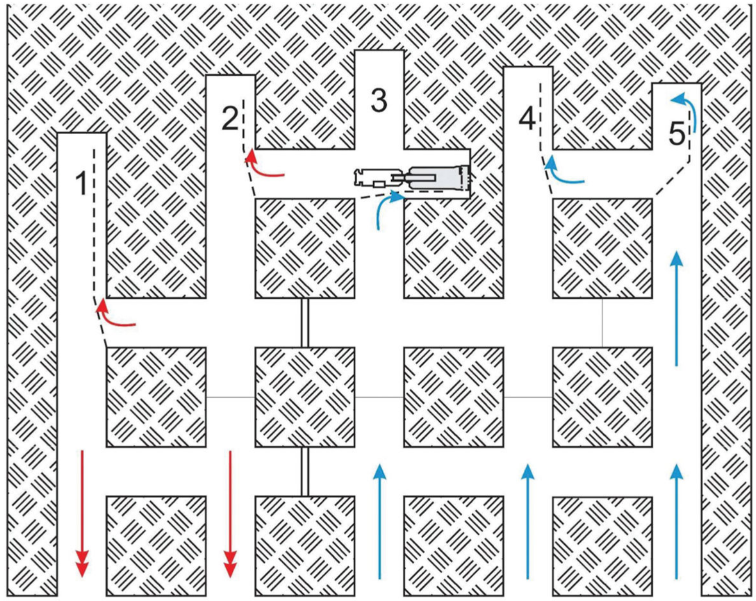

Figure 3.
Layout of a five-entry section with the continuous mining machine working the 3–4 Right crosscut.

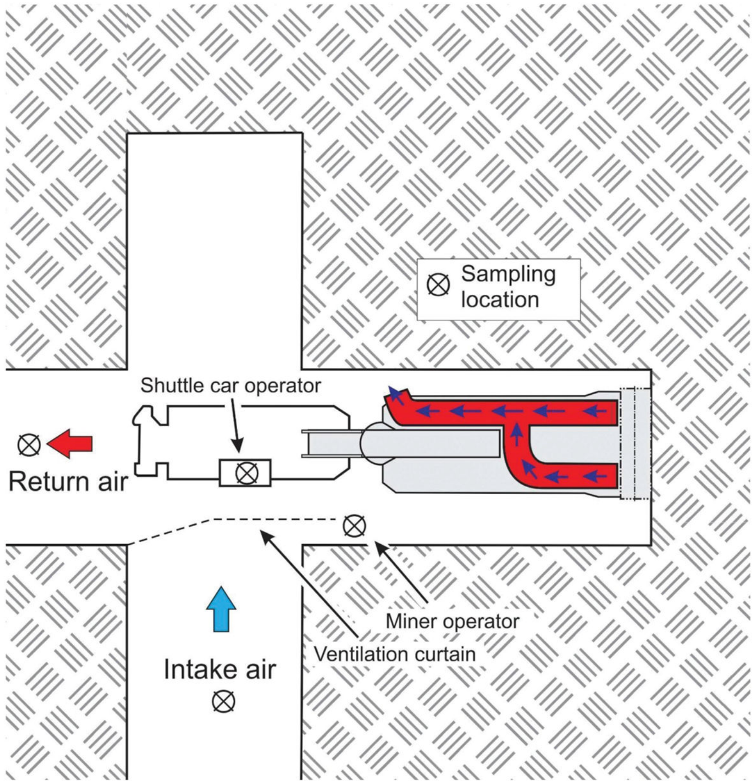

Figure 4.
Continuous mining machine and shuttle car positioned in a typical crosscut entry.

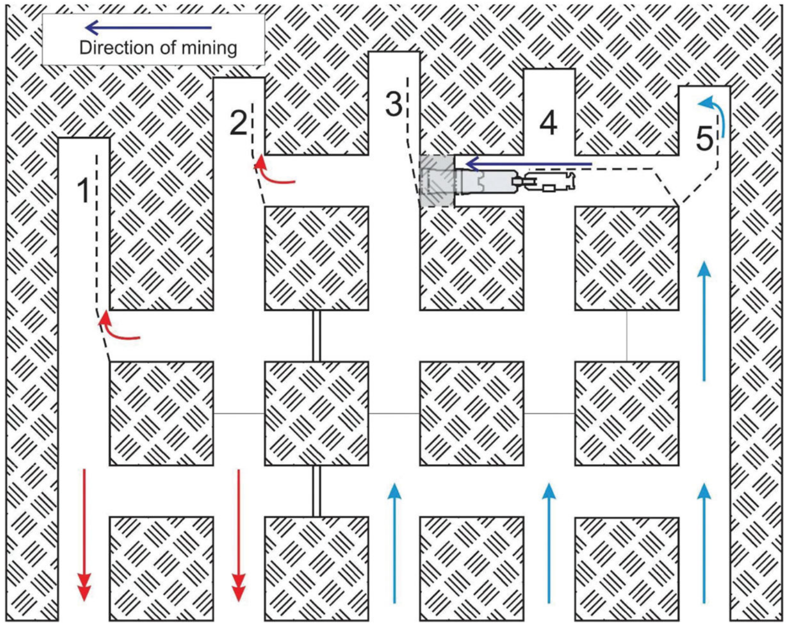

Figure 5.
Mining the 4-3 Left crosscut in the same direction as the section airflow (with airflow) from Entry 4.

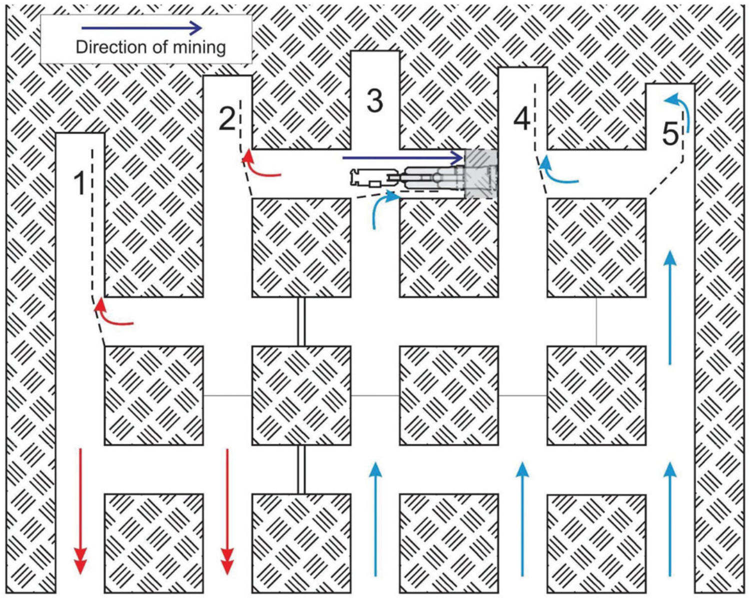

Figure 6.
Mining the 3–4 Right crosscut in the opposite direction as the section airflow (against airflow) from Entry 3.

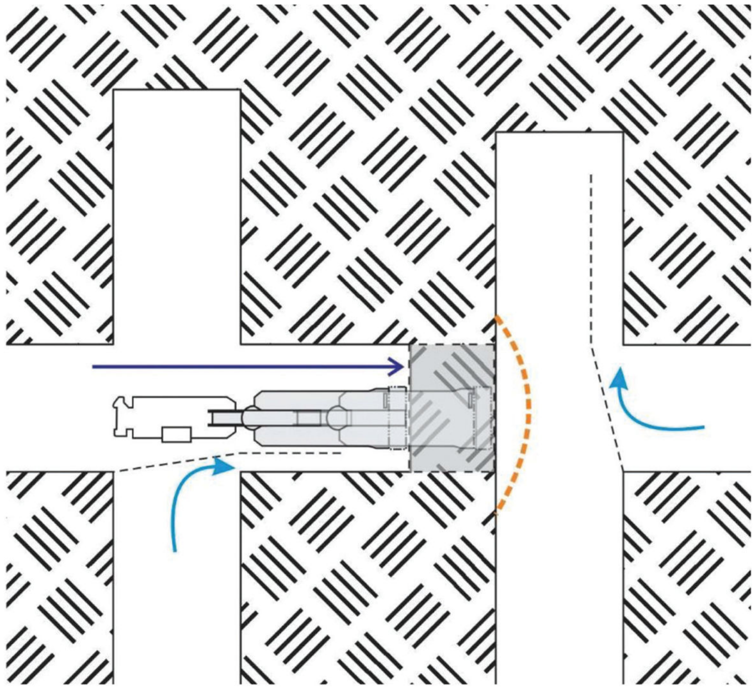

Figure 7.

Diagram showing the placement of ventilation curtain on the upwind side of a crosscut to prevent the passage of contaminated air upon breakthrough.

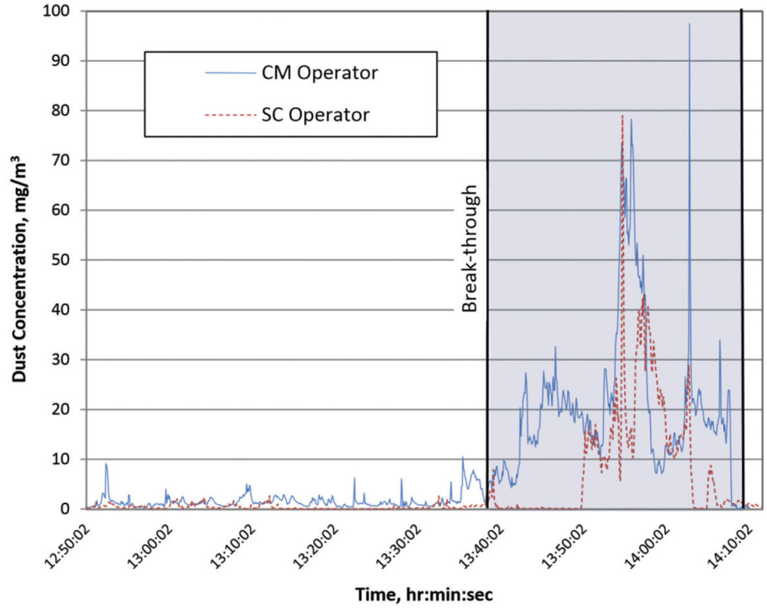

Figure 8.

Instantaneous dust concentrations at Mine J while mining the final portion of a crosscut against airflow.

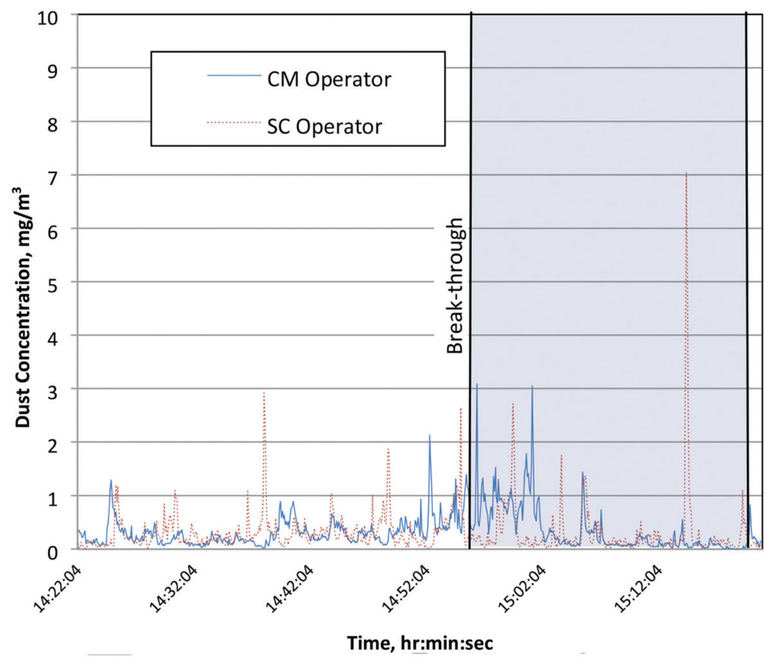

Figure 9.

Instantaneous dust concentrations at Mine J while mining the final portion of a crosscut with airflow.

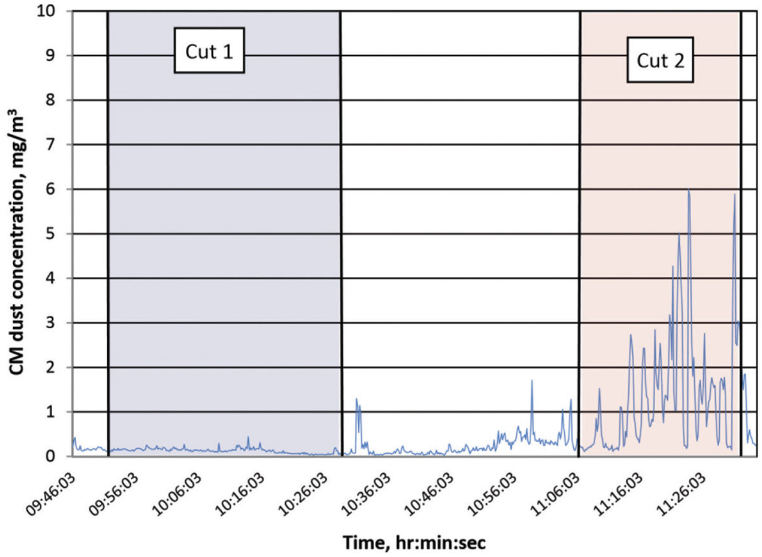

Figure 10.

Instantaneous continuous-miner operator dust concentrations at Mine I while mining two headings showing the effect of proper positioning (Cut 1) and operator movements into a contaminated atmosphere (Cut 2).

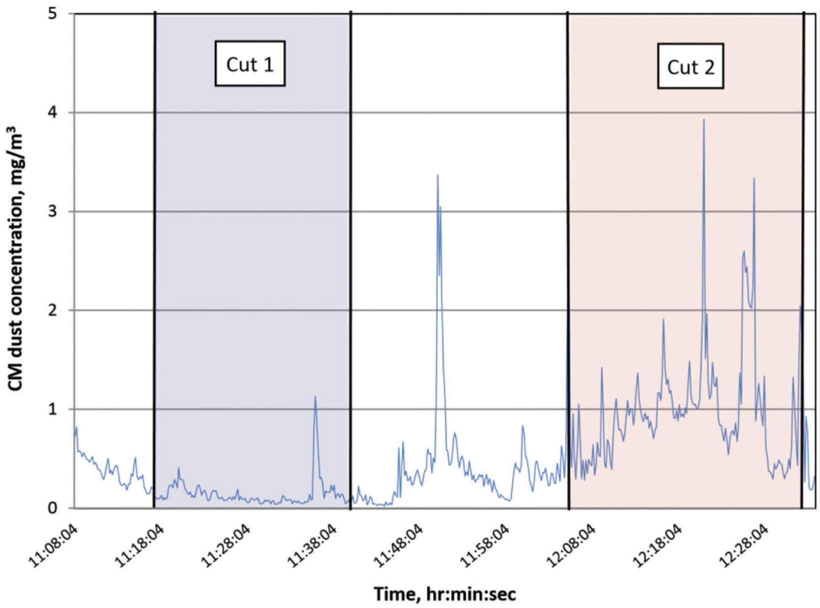

Figure 11.

Instantaneous continuous-miner operator dust concentrations at Mine I while mining a full face of coal (Cut 1) and mining 30–36 in. of rock (Cut 2).

Table 1

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

Study characteristic	Value
Number of mines.	10
Mining height, mean ± SD (minimum, maximum).	162.8 ± 42.4 in. (107, 213) 64.1 ± 16.7 cm (42, 84)
Ventilation rate, mean ± SD (minimum, maximum).	3.935 ± 1.354 m^3/s (1.536, 9.366) 8,338 ± 2,870 cfm (3,255, 19,845)
No. of cuts sampled.	167
No. of headings sampled.	106
No. of crosscuts sampled.	61

Table 2

Types of cut sampled and the resulting area and occupational dust concentrations (CM = continuous miner, SC = shuttle car, SD = standard deviation).

Cut description (no. of CM operator cases, no. 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 miner, SC = shuttle car.)

Mine ID (no. 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 (4,168)	0.03	14.04	5.63	NA[a]	14.01
B (12)	Exhaust.	107 (42)	6.1 (20)	3.304 (7,000)	0.20	4.81	5.75	1.02	4.61
C (10)	Exhaust.	107 (42)	6.1 (20)	4.012 (8,500)	0.25	5.54	1.40	0.66	5.29
D (15)	Exhaust.	188 (74)	7.6 (25)	4.512 (9,560)	0.17	4.33	1.52	0.48	4.16
E (22)	Exhaust.	114 (45)	6.1 (20)	2.454 (5,200)	0.16	1.17	0.73	0.44	1.01
F (24)	Blowing.	198 (78)	9.8 (32)	3.194 (6,768)	0.26	2.64	0.98	1.04	2.38
G (28)	Mixed.	183 (72)	6.1 (20)	3.407 (7,219)	0.10	1.22	1.68	0.86	1.12
H (7)	Exhaust.	152 (60)	12.2 (40)	4.684 (9,925)	0.13	2.29	0.70	0.32	2.16
I (21)	Blowing.	213 (84)	11.0 (36)	4.188 (8,874)	0.24	1.87	0.52	1.41	1.63
J (14)	Exhaust.	152 (60)	11.0 (36)	4.900 (10,383)	0.37	5.80	1.21	0.71	5.43

[a] No sample available for this occupation.

Table 4

Occupational dust concentrations for individual mines and Mann–Whitney *U* test results comparing headings to crosscuts. (Values in bold indicate significant differences at α = 0.15. CM = continuous miner, 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[a]	NA[a]	–
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	1.0000

[a]No sample available for this occupation.