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Examination of redirected continuous miner scrubber discharge configurations for exhaust face ventilation systems

J.A. Organiscak and **T.W. Beck**

Mining engineers, National Institute for Occupational Safety and Health, Pittsburgh, PA

Abstract

The U.S. National Institute for Occupational Safety and Health (NIOSH) Office of Mine Safety and Health Research (OMSHR) has recently studied several redirected scrubber discharge configurations in its full-scale continuous miner gallery for both dust and gas control when using an exhaust face ventilation system. Dust and gas measurements around the continuous mining machine in the laboratory showed that the conventional scrubber discharge directed outby the face with a 12.2-m (40-ft) exhaust curtain setback appeared to be one of the better configurations for controlling dust and gas. Redirecting all the air toward the face equally up both sides of the machine increased the dust and gas concentrations around the machine. When all of the air was redirected toward the face on the off-curtain side of the machine, gas accumulations tended to be reduced at the face, at the expense of increased dust levels in the return and on the curtain side of the mining machine. A 6.1-m (20-ft) exhaust curtain setback without the scrubber operating resulted in the lowest dust levels around the continuous mining machine, but this configuration resulted in some of the highest levels of dust in the return and gas on the off-curtain side of the mining face. Two field studies showed some similarities to the laboratory findings, with elevated dust levels at the rear corners of the continuous miner when all of the scrubber exhaust was redirected toward the face either up the off-tubing side or equally up both sides of the mining machine.

Keywords

Dust control; Air quality; Health and safety; Silica; Coal

Introduction

Coal mine worker overexposure to coal and quartz dust continues to be a problem at underground coal mining operations in the United States. The current U.S. Mine Safety and Health Administration (MSHA) standard for coal mine worker respirable dust exposure is limited to a 2-mg/m^3 average during an eight-hr shift (30 *CFR* 70-72, 74, 2010). If more than 5% quartz mass is found in the coal mine worker dust sample with MSHA's P7 infrared method, the applicable respirable dust standard is reduced to the quotient of 10 divided by

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the percentage of the quartz in the sample (Parobeck and Tomb, 2000). More than 90% of the mechanized mining units operating in U.S. underground coal mines are continuous mining machines (MSHA, 2011). MSHA inspector dust samples from 2008 to 2011 showed that 4.5% of continuous miner operators exceeded the 2 mg/m^3 dust standard, while 11.7% of their dust samples exceeded the reduced silica standard, thereby indicating that many continuous mining machine operators continue to be overexposed to coal and quartz dust (U.S. Department of Labor, 2011).

The primary means of dust control for continuous miner units are water sprays, good ventilation practices, machine-mounted scrubbers and worker positioning (Colinet et al., 2010; Kissell et al., 2003). Approximately 75% of continuous miner units at any time use scrubbers and radio remote control to extract extended mining cuts of up to 12.2 m (40 ft) (referred to as “deep cut mining” throughout this paper)(MSHA, 2012). MSHA's policy regarding the use of deep cut mining practices is described in its procedure instruction letter entitled, *Procedures for Evaluation of Requests to Make Extended Cuts with Remote Controlled Continuous Mining Machines* (PIL No. I12-V-11). The following factors are considered when evaluating extended-cut approval requests: 1) coal seam characteristics; 2) roof falls; 3) remote-control machinery accidents; 4) ignitions; 5) face methane liberation and 6) ventilation, noise and respirable dust compliance. MSHA only permits deep cut mining while it is performing the onsite evaluation of the requested mining plan and after the district manager approves the mining plan. At all other times, the standard mining practice is 6.1-m (20-ft) cuts with ventilation curtain/tubing maintained not more than 6.1 m (20 ft) from the deepest point of penetration that the face has been advanced.

NIOSH recently examined scrubber applications during deep cut mining at six mines and found that there were no significant differences in dust levels when comparing the first and last 6.1 m (20 ft) of deep cut mining (Potts et al., 2011). However, NIOSH showed in this study that, for 22% of the extended cuts sampled, scrubber airflow decreased by 20% to 35% and recommended that scrubber screens be cleaned more frequently than the common manufacturer recommendation of twice per shift. For blowing face ventilation, it was illustrated that maintaining an ideal curtain-to-scrubber airflow ratio of 1:1 was beneficial to controlling dust levels at the face, and that face airflow should be measured before scrubber activation, since curtain airflow increased by as much as 40 to 54% with the scrubber operating. On exhaust ventilation systems, the shuttle car sampling locations had lower dust levels than measured on the blowing face ventilation systems, because they were located on the intake side of the face ventilation, as opposed to the return side with blowing ventilation. However, with exhaust face ventilation systems, the curtain setback should be great enough to prevent the scrubber exhaust from blowing the line curtain against the rib. This curtain setback distance is generally greater than 9.1 m (30 ft) from the face.

When using deep cut mining in exhaust face ventilation systems, the curtain/tubing setback distance permitted by MSHA with the conventional scrubber configuration discharge is generally limited to 12.2 m (40 ft) from the mining face, allowing the maximum mining entry advance distance of up to 12.2 m (40 ft) inby the permanently installed roof support (roof bolts). The standard 6.1-m (20-ft) curtain/tubing ventilation setback practice prevents the conventional scrubber discharge configuration to be used with exhaust ventilation systems, since it would discharge its exhaust air outby and upstream of the return air split (curtain/tubing), recirculating back into the face intake air. In several rare cases, MSHA has granted a ventilation plan variance to redirect the scrubber discharge direction back toward the working face during deep cut mining, given a proven history of very low methane emissions at specific sites.

NIOSH recently examined redirected scrubber exhaust methods in its full-scale continuous miner gallery and through two mine case studies. The full-scale continuous miner laboratory experiments studied respirable dust and sulfur hexafluoride gas levels around the mining machine with a conventional scrubber exhaust configuration and several redirected scrubber exhaust configurations at a 12.2-m (40-ft) exhaust curtain setback distance. The standard exhaust face ventilation practice of no scrubber with a 6.1-m (20-ft) exhaust curtain setback was also examined for comparison with the scrubber tests. Two underground field survey case studies were also conducted to examine the in-mine usage of redirected scrubber methods. One mine redirected all of the scrubber exhaust air up the off-exhaust tubing/ curtain side of the continuous mines when using 3- to 12.2-m (10- to 40-ft) setbacks from the face. Another mine redirected the scrubber exhaust air toward the face up both sides of the continuous miner when using 4.6-to-12.2-m (15-to-40-ft) exhaust tubing setbacks from the face. This report primarily describes the controlled laboratory experiments conducted and briefly discusses the results from the two underground case studies.

Experimental design

Laboratory experiments were conducted within a full-scale continuous miner gallery, as shown in Fig. 1. The gallery entry dimensions were 5.5 m (18 ft) wide by 2 m (6.5 ft) high with a full-scale plywood mockup of a Joy CM14 continuous mining machine positioned at a simulated mining face. This mining machine was equipped with a flooded-bed scrubber, ductwork of several scrubber discharge configurations, several banks of external spray nozzles, and a 0.91-m- (36-in.-) diameter cutting drum that rotated at 50 rpm. The flooded-bed scrubber used a 20-layer pleated stainless steel filter wetted by three Spraying System QPH-6.5 full-cone nozzles (Spraying Systems, Wheaton, IL) and was powered by a variable frequency ac drive speed controlled fan. Scrubber inlets were located under each side and the center of the cutter boom near the hinge point. The scrubber exhaust could be discharged from three different locations (1, 2 and 3) in Fig. 1 at various airflow proportions. The redirected scrubber discharge locations 2 and 3 were angled 22.5° away from the machine body toward the face and located approximately 6.1 and 7.6 m (20 and 25 ft) outby the face, respectively. The scrubber discharge location 1 was angled 45° away from the machine body outby and toward the curtain side of the entry. External water sprays were Spraying Systems 3/8-BD-3 hollow cone nozzles (77° spray angle at 550 kPa or 80 psig) comprised of 15 top-mounted boom sprays directed at the top of the rotating drum, three under-boom throat sprays directed at the loading pan and three sprays on each side of the cutter boom directed at the drum's end rings.

Coal dust and sulfur hexafluoride (SF_6) gas were introduced in front of and along the length of the rotating cutting drum. Pulverized coal dust (Keystone mineral black 325BA, Keystone Filler & Manufacturing Co., Muncy, PA) was fed into the gallery at 25 g/min with a screw feeder (Vibra Screw, Inc., Totowa, NJ) and two LH-1/2 brass eductors (Penberthy, Prophetstown, IL) operated with 30 kPa (4 psig) of compressed air. One eductor discharged dust through a hose along the left front side of the drum and the other eductor discharged dust through a hose along the right front side of the drum. SF_6 gas was also released from tubing at each end of the dust discharge hoses to mix in the gas with the dust. An Innova model 1303 multipoint gas doser (California Analytical Instruments, Orange, CA) released the SF_6 gas at a flow rate of 7 mL/sec. The rotating drum ensured their mixing to simulate dust and gas emissions from the face during testing.

Respirable dust and SF_6 gas concentrations were measured at several locations around the mining machine (Fig. 1). Respirable dust concentrations were measured with coal mine dust personal sampling units (CMDPSU), comprised of an ESCORT-Elf constant flow air sampling pump pulling dust-laden air at 2 L/min through a 10-mm nylon cyclone (respirable dust classifier) and depositing the respirable fraction onto a preweighed 37-mm filter cassette (Zeffon International, Ocala, FL). A pair of samplers (CMDPSU) were placed and operated at the remote continuous miner operator (CM Oper) position, the right rear corner (RRC) of the mining machine, the left rear corner (LRC) of the mining machine, and the return (Return) air course. The pairs of dust concentrations measured were averaged to determine the dust concentration at each sampling location. SF_6 gas measurements were made using a California Analytical Instruments Innova model 1312 photoacoustic gas monitor, which sequentially drew gas samples through tubing from the off-curtain side (OCS) of the cutting boom, the curtain side (CS) of the cutting boom, inside the scrubber exhaust (Scrubber) and the return (Return) air course. This data was collected with a computer-based data acquisition system and the gas concentrations at each location were averaged for the test.

Other operating parameters measured and recorded were water spray pressure, machine water flow, face return airflow and scrubber airflow. Water pressure and flow were measured with electronic instruments and recorded with a computer data acquisition system. Face return airflow was measured at the inlet end of the ventilation curtain with a handheld vane anemometer (moving traverse) with the scrubber off at the beginning and end of each test. Scrubber airflow was also measured with a handheld vane anemometer at the scrubber discharge locations (moving traverse) at the beginning and end of each test. The moving traverse airflow measurements at the scrubber discharge locations were adjusted (corrected) to airflows previously determined from fixed point traverse measurements taken inside the scrubber duct for the various scrubber discharge configurations studied.

The experimental test plan conducted is shown in Table 1. Four different scrubber discharge configurations were studied in these laboratory experiments at a 12.2-m (40-ft) curtain setback distance while using two levels of face ventilation airflow quantities. One scrubber configuration and no scrubber operating were also studied at a 6.1-m (20-ft) curtain setback distance for the two levels of face ventilation airflow quantities. Figure 1 illustrates the scrubber discharge locations with a 12.2-m (40-ft) exhaust curtain setback from the face during 6.1-m (20-ft) deep box cut. The scrubber exhaust discharge configurations examined were: 1) 100% redirected on the off-curtain side of the mining machine toward the face (OCS-100%); 2) 50% redirected up each side of the mining machine toward the face

(50%-50%), 3) 15% redirected on the off-curtain side of the mining machine toward the face (OCS-15%) with 85% directed outby and on the curtain side of the face; and 4) 100% of the air directed outby and on the curtain side of the face (Conv. Exhaust). Only the scrubber discharge redirected on the off-curtain side of the mining machine toward the face (OCS-100%) and no scrubber operating configurations were conducted at a 6.1-m (20-ft) curtain setback distance. Scrubber airflow was targeted at a constant 3.3 m^3/s (7,000 cfm) for the various exhaust configurations tested at two return face airflows of 3.78 and 5.66 m^3/s (8,000 and 12,000 cfm). The average scrubber airflow during all experiments was 3.24 m^3/s (6,868 cfm), and the face airflows for the experiments averaged 3.77 and 5.59 m^3/s (7,993 and 11,837 cfm), respectively. The dust and gas feed rates into the gallery were consistently controlled at 25.4 g/min and 7.1 mL/sec. External water sprays were consistently operated at 550 kPa (80 psig) during all experiments.

Each experimental factor combination in Table 1 was replicated for at least three tests. Experimental tests were blocked or separately conducted within the box and slab cuts for experimental practicality. The box cut for these experiments is when the mining machine is advanced or positioned 6.1 m (20 ft) into the confined area of the mining face on the curtain side of the entry, as shown in Fig. 1. The slab cut in these experiments is when the mining machine is advanced or positioned on the off-curtain side entry wall of the face with the slab section removed (see Fig. 1). Experimental tests were also separately conducted or blocked with respect to curtain setback. The scrubber configurations at two face return airflows were randomly conducted once within each experimental test block before another block of experiments were conducted. All experimentally controlled test factors were precisely maintained and had relative standard deviations (RSD = (standard deviation/average) × 100%) less than 2.5% of their measured average. All dust testing results are limited to examining airborne dust capture around a continuous mining machine and do not represent dust suppression from coal wetting. All SF_6 test results are limited to comparing gas level changes around the continuous mining machine for the different scrubber configurations and are not reflective of actual methane emissions at any particular mine.

Experimental results

Test replicate averages and standard errors were determined for respirable dust and SF_6 gas concentrations at multiple locations around the mining machine during these experiments. The averages and standard errors for the box cut are illustrated in Figs. 2 and 3 and for the slab cut in Figs. 4 and 5. The tests conducted near the 3.78 m^3/s (8,000 cfm) face airflows are presented on the left side of these figures, and the tests conducted near the 5.66 m^3/s (12,000 cfm) face airflows are presented on the right side of these figures. Their *x*-axes are successively labeled from 100% of the scrubber exhaust redirected toward the face on the off-curtain side of the mining machine, to the conventional exhaust configuration with 100% of the airflow directed away from the face on the curtain side of the mining machine for the 12.2-m (40-ft) curtain setback distance. The two 6.1-m (20-ft) curtain setback configurations are labeled in descending order, shown to the right of the 12.2-m (40-ft) curtain setback configurations.

Regression analysis was also conducted on the experimental data to determine the significant dust and gas relationships (at the 95% confidence levels) with respect to the scrubber configurations and face airflows tested. Table 2 shows the significant dust and gas concentration changes (positive or negative) measured for the scrubber configurations tested with respect to no scrubber operating, as illustrated in Figs. 2-5. The scrubber configurations were modeled with qualitative binary indicator variables of 0 and 1 compared to the 6.1-m (20-ft) curtain setback configuration without the scrubber operating (designated as 0 for the X_1 indicator variable). Because a continuous mining machine without a scrubber would not have an inside scrubber exhaust location, the regression analysis at this particular location was remodeled with respect to the scrubber operating with all of the scrubber exhaust redirected up the off-curtain side toward the face for the 6.1-m (20-ft) curtain setback position (redesignated as 0 for the X_1 indicator variable, with one less indicator variable in the model). The face airflow was included as a quantitative variable in the regression model. Shown below is the first order linear response function used for this regression analysis (Neter et al., 1996).

$$\widehat{Y}=\underbrace{\beta_0+\beta_1X_1+\ldots+\beta_nX_n}_{\text{Indicator variable terms}}+\underbrace{\beta_{n+1}X_{n+1}+\ldots+\beta_{n+q}X_{n+q}}_{\text{Quantitative variable terms}} \quad (1)$$

where: $\hat{Y}$ = Regression model concentration estimate

X_1 = 1 if scrubber configuration 1; or 0 otherwise (no scrubber)

X_n = 1 if scrubber configuration n; or 0 otherwise

X_{n+1} = 1st quantitative variable (face airflow)

X_{n+q} = qth quantitative variable (no additional quantitative variables used in model)

β_0 = Model constant or intercept parameter

β_n = nth scrubber configuration regression parameter

β_{n+q} = Quantitative variable regression parameter

Stepwise regression analyses were separately conducted for all of the dust and gas sampling locations of the box and slab cut experiments to identify the statistically significant regression variable parameters in the linear response model. Since several of the experimental dust and gas sampling locations exhibited an extensive data range, non-normality and unequal variances, the square root or natural logarithms of their concentrations were used to stabilize regression model variance (Neter et al., 1996). Table 2 illustrates the significant dust and gas concentration regression relationships for the scrubber configurations tested in the box cut (*B*) and slab cut (*S*) with a + symbol, illustrating a significant positive relationship, and a − symbol, illustrating a significant negative relationship in the regression models.

Box cut

Figure 2 shows how the two scrubber configurations that substantially increased dust concentrations in the box cut were redirecting all of the scrubber airflow back toward the face on the off-curtain side of the face (OCS-100%) and equally on both sides of the face (50%-50%) for the 12.2-m (40-ft) curtain setback position. These two redirected scrubber exhaust configurations significantly increased the dust concentrations at the rear corners of the CM (RRC and LRC), ranging from 4 to 11.7 mg/m^3, compared to less than 1.5 mg/m^3 for the other experimental configurations. They also increased the remote CM operator position dust concentration to above 1 mg/m^3 for the lower face airflow (3.78 m^3/s or 8,000 cfm) condition, as compared to less than 0.4 mg/m^3 for the other experimental configurations. However, redirecting all the scrubber exhaust back toward the face did reduce the return dust concentrations below the 2.3 to 8.6 mg/m^3 range measured for the other experimental configurations tested. Redirecting all of the scrubber exhaust back toward the face at the12.2-m (40-ft) curtain setback resulted in face air recirculation and increased dust concentrations inby the exhaust curtain, but the recirculation of this face air through the scrubber lowered the return dust concentrations.

The 6.1-m (20-ft) curtain setback with the scrubber operating (OCS-100%, 6.1-m) and without the scrubber operating (No Scrubber, 6.1-m) resulted in some of the lowest dust concentrations, below 0.2 mg/m^3 at the CM Operator and below 1.5 mg/m^3 at the rear corners of the CM (RRC and LRC), because the exhaust curtain was inby these sampling locations, which kept them in cleaner intake air. However, the return dust concentrations were greater than 6.2 mg/m^3 with the 6.1-m (20-ft) curtain setback, because most of the dust at the face directly enters into the face return with (OCS-100%) and without the scrubber. The dust concentrations at the RRC and LRC of the CM with the redirected off-curtain side scrubber discharge (OCS-100%, 6.1-m) notably increased from less than 1.4 and 1.5 mg/m^3, respectively, to greater than 5.7 and 3.9 mg/m^3, respectively, by increasing the curtain setback from 6.1 m (20 ft) to 12.2 m (40 ft) (OCS-100%). The conventional scrubber exhaust (Conv. Exhaust) and redirecting 15% of the airflow on the off-curtain side (OCS-15%) of the face for the 12.2-m (40-ft) curtain setback appeared to be a good compromise for controlling dust (as shown in Fig. 2) at all the sampling locations at the face and return.

Figure 3 shows how the scrubber configurations that significantly increased SF_6 gas concentrations in the box cut were without the scrubber operating (No Scrubber) at the 6.1-m (20-ft) curtain setback position and with all of the air redirected back toward the face on the off-curtain side of the face (OCS-100%) and equally on both sides of the face (50%-50%) at the12.2-m (40-ft) curtain setback position. These experimental configurations resulted in notably higher SF_6 gas concentrations near the continuous miner cutter head (OCS and CS locations), ranging from 4.7 to 14.7 ppm compared to 0.8 to 8.04 ppm for the other experimental configurations. Redirecting the scrubber exhaust back toward the face (OCS-100% and 50%-50%) with the 12.2-m (40-ft) curtain setback resulted in the most air recirculation through the scrubber, with gas concentrations inside the scrubber greater than 5.8 ppm, compared to gas concentrations of less than 3.6 ppm for the other scrubber configurations. The larger curtain setback apparently allowed the redirected scrubber exhaust to be recirculated at the face, increasing the SF_6 gas concentrations in the scrubber exhaust and near the face (OCS and CS).

The highest SF_6 gas concentrations measured at the OCS and CS locations near the cutting drum were 14.7 and 10.4 ppm, respectively, without the scrubber operating at the 3.78 m^3/s (8,000 cfm) face airflow and the 6.1-m (20-ft) curtain setback configuration. These gas concentrations were the highest because the intake airflow was not being drawn by the scrubber inlets closer to the face to help dilute this gas (Taylor et al., 1996). Although increasing face ventilation air quantity significantly reduced gas levels at all sampling locations (see Table 2), the largest change in gas concentrations at the face was a result of the scrubber configurations studied (see Fig. 3). The conventional scrubber exhaust and redirecting 15% of the airflow on the off-curtain side of the face for the 12.2-m (40-ft) curtain setback appeared to be good compromises for controlling gas at the face (as shown in Fig. 3). The lowest gas concentrations on the curtain side of the face (CS) and intermediate gas concentrations on the off-curtain side of the face (OCS) were observed with these two scrubber configurations. Return gas levels were only significantly reduced by increasing the face airflow quantity, regardless of the scrubber configuration (see Table 2).

Slab cut

Figure 4 shows how the two scrubber configurations that significantly increased dust concentrations in the slab cut were redirecting all the scrubber airflow back toward the face on the off-curtain side of the face (OCS-100%) and equally on both sides of the face (50%-50%) for the 12.2-m (40-ft) curtain setback position. These two redirected scrubber configurations had some of the highest dust concentrations at the rear corners of the CM (RRC and LRC), ranging between 2.7 and 10.8 mg/m^3, compared to 0 to 3.4 mg/m^3 for the other experimental conditions. The operator location had dust concentrations as high as 0.6 mg/m^3, with all of the exhaust redirected toward the face, compared to less than 0.2 mg/m^3 for the other experimental configurations.

The 6.1-m (20-ft) curtain setback without the scrubber operating (No Scrubber, 6.1-m) again resulted in some of the lowest dust concentrations, below 0.1 mg/m^3 at the CM Oper and rear corners of the CM (RRC and LRC), because the exhaust curtain was inby these sampling locations, which kept them in the cleaner intake air. However, operating without the scrubber (No Scrubber, 6.1-m) again resulted in some of the higher return dust concentrations equal to or greater than 6.0 mg/m^3, because the airborne dust was directly transported into the return without being removed by a scrubber. Return dust concentrations were also greater than 6 mg/m^3 for the scrubber discharge redirected up the off-curtain side of the continuous mining machine (OCS-100%) at the 6.1-m (20-ft) and 12.2-m (40-ft) curtain setbacks, because the discharged airflow swept the face, pushing some of the dust away from the scrubber inlets before it could be captured. Again, the dust concentrations at the RRC and LRC of the CM with the redirected off-curtain side scrubber discharge increased from less than 0.4 and 3 mg/m^3, respectively, to greater than 2.6 and 10.2 mg/m^3, respectively, by increasing the curtain setback from 6.1-m (20 ft) to 12.2-m (40 ft). The conventional scrubber discharge (Conv. Exhaust) and redirecting 15% (OCS-15%) of the airflow on the off-curtain side of the face for the 12.2-m (40-ft) curtain setback appeared to be a good compromise for controlling dust (as shown in Fig, 4) at all the sampling locations at the face and return.

Figure 5 shows how the scrubber configurations that significantly increased face SF_6 gas concentrations in the slab cut were the test condition without the scrubber operating (No Scrubber) at the 6.1-m (20-ft) curtain setback position and the test condition with the scrubber redirecting all of the air back toward the face equally on both sides of the face (50%-50%) at the 12.2-m (40-ft) curtain setback position. These experimental configurations had notably higher SF_6 gas concentrations near the continuous miner cutter head (OCS and CS locations), ranging from 4.9 to 16.2 ppm, compared to a range of 0.6 to 6.4 ppm for the other scrubber configurations. Redirecting all of the scrubber exhaust air equally back toward the face (50%-50%) with the 12.2-m (40-ft) curtain setback resulted in the largest amount of air recirculation through the scrubber, with gas concentrations inside the scrubber greater than 6.8 ppm, compared to gas concentrations less than 3.5 ppm for the other scrubber configurations. Redirecting all of the scrubber airflow on the off-curtain side of the face for the 6.1-m (20-ft) curtain setback (OCS-100%, 6.1-m) and 12.2-m (40-ft) curtain setback (OCS-100%) maintained gas levels near the face (OCS and CS) below 3.4 ppm, because the scrubber exhaust air effectively swept the gas away from the face into the return. One of the best scrubber configurations observed for the 12.2-m (40-ft) curtain setback in the slab cut was redirecting only 15% of the scrubber exhaust up the off-curtain side of the face (OCS-15%), maintaining gas levels at or below 2.2 ppm near the face (OCS and CS). The partial scrubber recirculation or scrubber “push-pull” arrangement appeared to assist scrubber gas capture and removal from the face, in similar fashion to using blocking sprays with the conventional scrubber discharge during the slab cut (Organiscak and Beck, 2010).

The highest SF_6 gas concentrations measured at the OCS and CS locations near the cutting drum were 16.2 and 8.6 ppm, respectively, without the scrubber operating at the 3.78 m^3/s (8,000 cfm) face airflow and the 6.1-m (20-ft) curtain setback configuration. These gas concentrations were the highest because the intake airflow was not being drawn by the scrubber inlets closer to the face to help dilute this gas (Taylor et al., 1996). Although increasing face ventilation air quantity significantly reduced gas levels at nearly all of the sampling locations (Table 2), the largest change in gas concentrations at the face were a result of the scrubber configurations studied (Fig. 5). The return gas levels were only significantly reduced by increasing the face airflow quantity, regardless of the scrubber configuration (see Table 2).

Mine case studies

Field case studies were conducted at two mines to examine the dust control effectiveness of redirecting the scrubber exhaust back toward the face. Table 3 shows the dust concentrations measured at the mining face for these two mines only during the production cuts. Note that these dust concentrations were not converted to an MRE instrument equivalent concentration as required for full-shift MSHA dust compliance purposes (30 CFR 70, 2010). The first mine (Mine 1) was part of a study to evaluate the dust concentrations at mines using deep cut practices, and the details of this study are identified as Mine C in another report (Potts et al., 2011). This particular mine used a Joy 12 CM continuous miner to advance a five-entry development section with its entire scrubber exhaust redirected on the off-tubing side toward the face at approximately a 45° angle from the rear corner of the mining machine. The mining height varied from 2.7 to 3 m (8.8 to 10 ft) with the entry width averaging 6.1 m (20 ft). Exhaust tubing (sometimes curtain) was primarily used on the left side of the entry to ventilate the face and was maintained from a 3- to 12.2-m (10- to 40-ft) distance from the face at the beginning to the end of the extended cut. The extended cut sequence comprised of advancing a 6.1-m (20-ft) box cut on the tubing/curtain side of the entry, advancing a 6.1-m (20-ft) slab cut on the off-tubing/curtain side of the entry, advancing a 6.1-m (20-ft) box cut on the off-tubing/curtain side of the entry, and advancing a 6.1-m (20-ft) slab cut on the tubing/curtain side of the entry. Respirable dust concentrations were measured with a Thermo Scientific Model 1000 AN personal DataRam (pDR) and 2 CMDPSUs at each of the sampling locations shown in Table 3, except for one case—the continuous miner operator who wore a Thermo Scientific Model 3600 personal dust monitor (PDM) (Volkwein et al., 2006). The PDR continuous light-scattering data output was calibrated or adjusted to the respirable dust mass measured by the adjacent CMDPSUs (Listak et al., 2007). The PDM provided continuous mass measurements that were analyzed per cut. Dust concentrations were analyzed for the first 6.1 m (20 ft) of entry advance and the second 6.1 m (20 ft) of entry advance, normalized for production or mining rate. The five extended cuts driven up the heading (not cross-cuts) that were studied had an average face airflow quantity of 8.59 m^3/s (18,200 cfm) and a scrubber airflow quantity of 6.3 m^3/s (13,340 cfm).

The Table 3 dust concentration results showed that most of the sampling locations for the second 6.1 m (20 ft) of face advance were only slightly higher than for the first 6.1 m (20 ft) of advance (not statistically significant at the 95% confidence level). Only the off-standard cab shuttle car (shuttle car 2) located on the left or exhaust tube side of the entry had a statistically significant increase in dust concentrations from 0.07 to 0.31 mg/m^3 when the face advanced from the first 6.1 m (20 ft) to the second 6.1 m (20 ft) of the extended cut. The higher dust concentration was likely a result of the off-standard shuttle car cab being on the same side and closer to the return tubing inlet in the deeper part of the extended cut. This dust concentration increase is similar to the increase observed at the left rear corner of the CM (LRC) in the laboratory when the curtain setback distance was increased from 6.1 m (20 ft) to 12.2 m (40 ft).

The second mine (Mine 2) used a Joy 12 CM continuous miner to advance a three-entry development section, but redirected the scrubber exhaust equally from both sides of the mining machine at a 45° degree angle toward the face. The mining height was about 2.9 m (9.5 ft) with the entry width 6.1 m (20 ft). Exhaust tubing was used on the right side of two entries and on the left side of the other entry to ventilate the face. The exhaust tubing was maintained from 1.5 to 12.2 m (5 to 40 ft) from the face at the beginning to the end of the extended cut. The extended cut sequence was similar to Mine 1's, except that the scrubber was not turned on until the face was advanced 6.1 m (20 ft) into the extended cut. Respirable dust concentrations were measured with a PDR and two CMDPSUs at each of the sampling locations shown in Table 3. A NIOSH researcher carried the dust samplers and stood next to the continuous miner operator to measure concentrations at his position. The PDR continuous light-scattering data output was calibrated or adjusted to the respirable dust mass measured by the adjacent CMDPSUs (Listak et al., 2007). Two recording methane monitors (Industrial Scientific Model M40M with sampling pumps) were also located on both sides of the cutter boom inside the motor encasements and indicated that no methane was present during this study. A comparative dust control study was conducted at this particular mine between cuts using the scrubber for only the last 6.1 m (20 ft) of the extended cut compared to cuts running the scrubber for the whole 12.2-m (40-ft) cut. Dust concentrations were examined between six cuts with the scrubber operating during the last 6.1 m (20 ft) of the cut compared to three cuts with the scrubber operating during the whole cut. These comparative cuts were normalized for face air quantity and time in the cut. Face airflow ranged from 7.07 and 9.45 m^3/s (14,980 and 20,018 cfm) during this study with a scrubber airflow quantity of 3.61 m^3/s (7,649 cfm).

The Table 3 dust concentration results show that the dust concentrations at the CM Operator, shuttle car operators and return locations were slightly lower when running the scrubber during the whole cut as compared to the last half of the cut (not statistically significant at the 95% confidence level). Only the off-standard cab shuttle car (shuttle car 2) had a statistically significant decrease in dust concentration from 0.21 to 0.05 mg/m^3 when the scrubber was operated during the whole cut. Dust concentrations increased from 1.49 to 1.64 mg/m^3 at the LRC location and from to 1.32 to 2.08 mg/m^3 at the RRC location on the continuous mining machine when the scrubber was run during the entire cut. Although these dust level increases at the rear corners of the continuous miner were not statistically significant at the 95% confidence level, they do indicate that using the redirected scrubber running for the entire cut caused some dust rollback to these locations.

Discussion

The smaller dust concentration changes observed in the underground case studies as compared to the laboratory studies were likely a result of multiple key differences between the test conditions. These key differences include:

1. Underground seam thickness in the mines of at least 0.61 m (2 ft) or more than the test gallery.
2. Ventilation tubing primarily used at mines compared to the curtain in the test gallery.
3. Rough rib surface in the mines compared to smooth walls in the test gallery.
4. No shuttle car behind the continuous miner in the laboratory test gallery.
5. Ventilation curtain setbacks are dynamic in the mine compared to static 6.1- and 12.2-m (20- and 40-ft) curtain setbacks used in the test gallery.
6. The 12.2- m (40-ft) curtain setback used in the test gallery tends to be the worst-case scenario for air reaching the mining face in an exhausting face ventilation system.
7. Dust sampling locations were not identical between laboratory and mine studies.

The higher coal seam thickness, rough rib surface, shuttle cars and dynamic ventilation tubing setbacks in the mine most likely reduced the redirected scrubber rollback effect observed in the laboratory test gallery at the 12.2-m (40-ft) curtain setback condition. The dynamic face ventilation effects in underground mining can be observed from some of the laboratory tests (Figs. 2-5) with all scrubber airflow redirected up the off-curtain side of the CM (OCS-100%, 6.2-m and OCS-100%) for the 6.2-m (20-ft) and 12.2-m (40-ft) setback conditions. The dust concentrations around the machine (CM Oper, RRC and LRC) and the gas concentration at the face (OCS, CS and scrubber) significantly increased from the 6.1- to 12.2-m (20- to 40-ft) increase in curtain setback distance. The underground dust concentration effects measured around the continuous mining machine during the field studies represent the averaging of the dynamic face ventilation changes that occurred during the mining sequence. Finally, the higher coal seam, rougher ribs and shuttle cars in the coal mine could have reduced the redirected scrubber exhaust air velocity reaching the face, thereby reducing some of the rollback effects of the redirected scrubber exhaust observed in the laboratory.

Conclusions

Dust and gas measurements around the continuous mining machine in the laboratory showed that the conventional scrubber discharge with the 12.2-m (40-ft) exhaust curtain setback appeared to be one of the better configurations for controlling dust and gas. Redirecting 15% (OCS-15%) of the scrubber discharge toward the face on the off-curtain side of the CM helped to further reduce the gas concentrations at the face in the slab cut compared to the conventional scrubber discharge. Redirecting all of the scrubber exhaust air toward the face equally up both sides of the machine increased the dust and gas concentrations around the machine, while redirecting all the scrubber air toward the face on the off-curtain side of the machine tended to reduce gas accumulations at the face at the expense of increased dust levels in the return and on the curtain side of the mining machine. The 6.1-m (20-ft) exhaust curtain setback without the scrubber resulted in the lowest dust levels around the continuous mining machine, but this configuration resulted in some of the highest dust levels in the return and gas levels on the off-curtain side of mining face.

The two mine case studies showed some similarities with the laboratory tests of elevated dust levels at the rear corners of the continuous miner when all of the scrubber exhaust was redirected toward the face either up the off-tubing-curtain side or equally up both sides of the mining machine. At Mine 1, the off-standard shuttle car operator's cab, located on the exhaust tubing/curtain side of the entry, had a significant dust level increase from 0.07 to 0.31 mg/m^3 when the face advanced from the first 6.1 m (20 ft) to the second 6.1 m (20 ft) of the extended cut. At Mine 2, dust concentrations increased from 1.49 to 1.62 mg/m^3 at the LRC location and increased from 1.32 to 2.08 mg/m^3 at the RRC location on the continuous mining machine when the redirected scrubber was run during the entire cut compared to the last half of the cut. The low methane emissions at these particular mines made it prudent to allow complete scrubber exhaust recirculation back toward the face, since notable increases in SF_6 gas concentrations (OCS, CS and scrubber) were observed for these scrubber configurations in the corresponding laboratory tests at the 12.2-m (40-ft) curtain setback.

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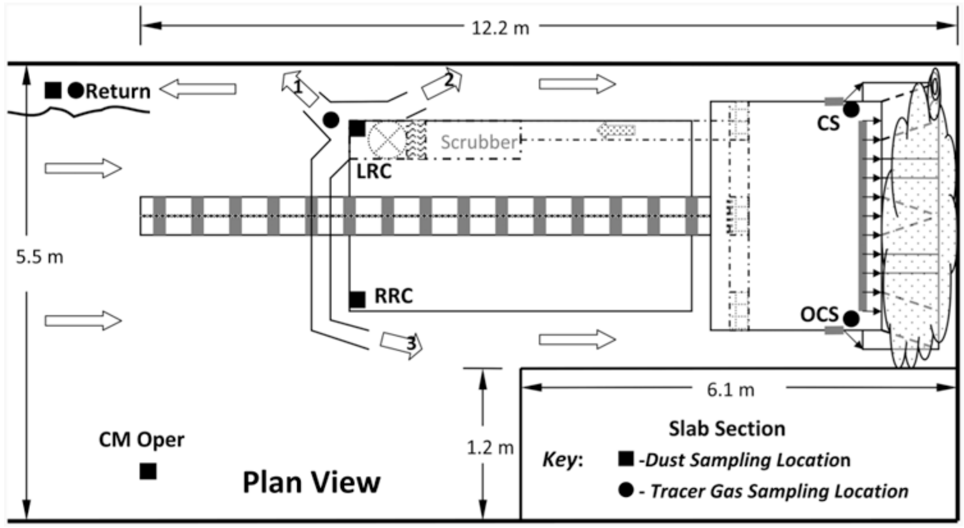

Figure 1.

Face ventilation layout with dust and gas sampling locations (not to scale; CM oper – continuous miner operator, RRC – right rear corner, LRC – left rear corner, OCS – off curtain side, CS – curtain side).

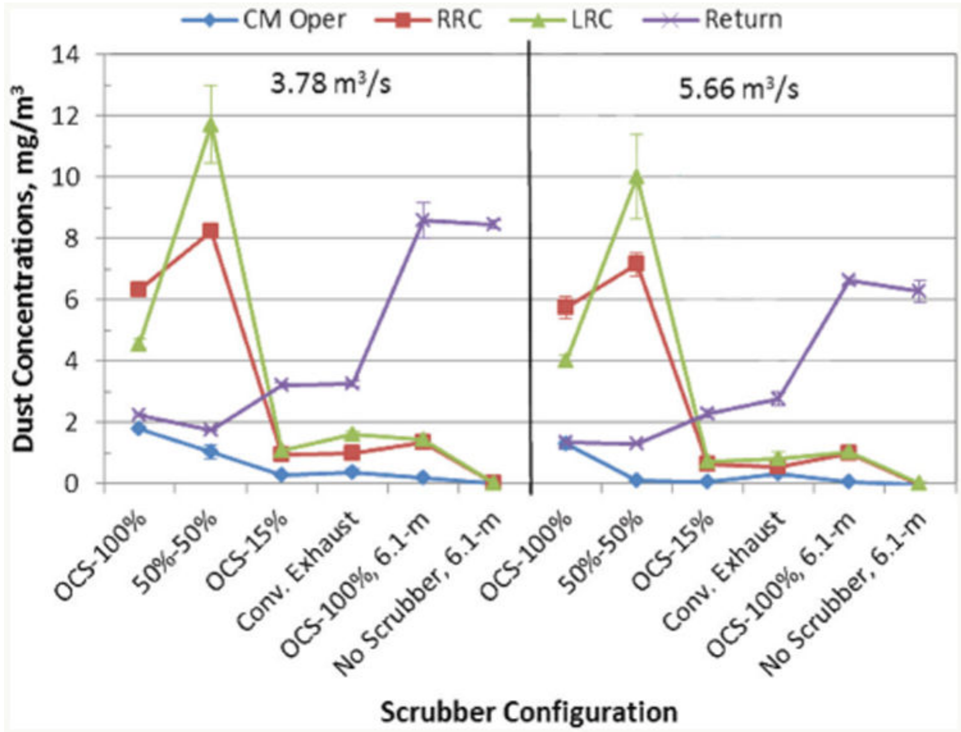

Figure 2.
Box cut dust concentrations measured for the various scrubber configurations tested.

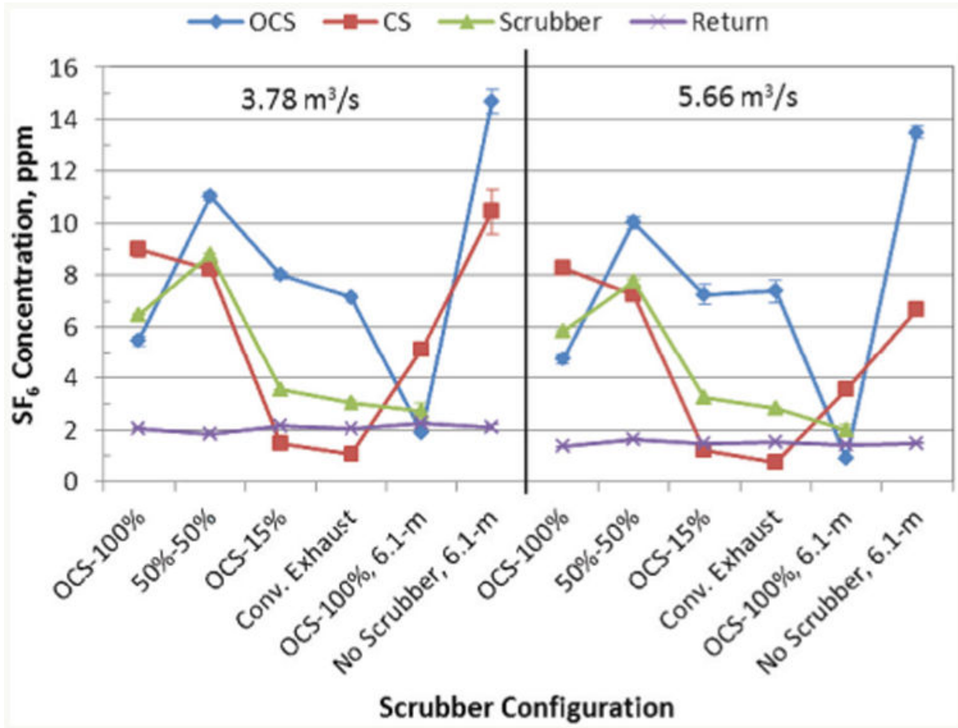

Figure 3.

Box cut SF_6 gas concentrations measured for the various scrubber configurations tested.

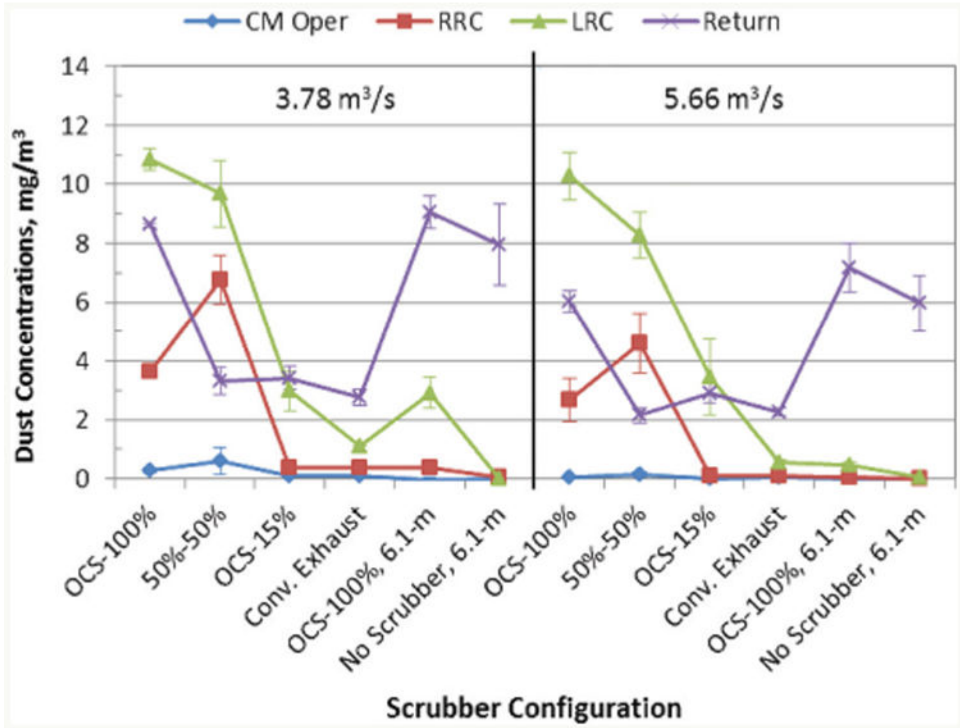

Figure 4.
Slab cut dust concentrations measured for the various scrubber configurations tested.

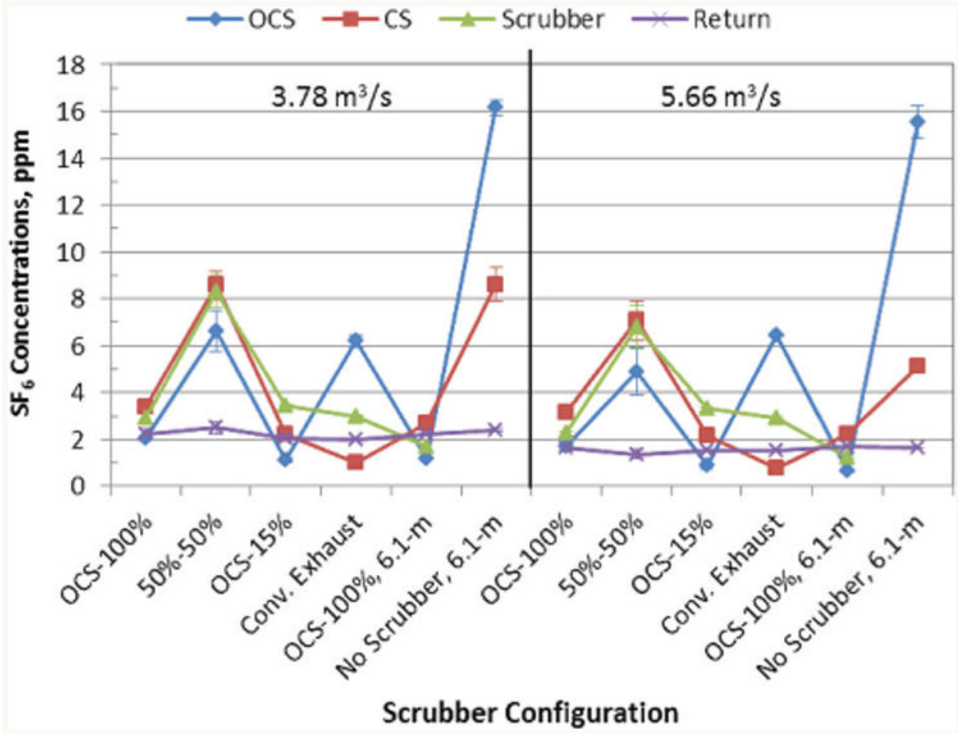

Figure 5.

Slab cut SF_6 gas concentrations measured for the various scrubber configurations tested.

Table 1

Experimental test conditions for both box and slab cuts.

Ventilation Factors		Scrubber Configurations				
Curtain setback	**Face ventilation**	**OCS-100% redirected scrubber (3-100%)**	**50%-50% redirected scrubber (2-50%, 3-50%)**	**OCS-15% redirected scrubber (1-85%, 3-15%)**	**Conv. exhaust scrubber (1-100%)**	**No scrubber**
6.1-m	3.78 m^3/s	X				X
	5.66 m^3/s	X				X
12.2-m	3.78 m^3/s	X	X	X	X	
	5.66 m^3/s	X	X	X	X	

Table 2

Significant dust and gas concentration relationships with respect to no scrubber with 6.1-m setback.

Sample Location	OCS-100% 12.2-m	50%-50% 12.2-m	OCS-15% 12.2-m	Conv. exhaust 12.2-m	OCS-100% 6.1-m	Ventilation
Dust-CM Oper	+B	+B, +S		+B		-B
Dust-RRC	+B, +S	+B, +S			+B	-B, -S
Dust-LRC	+B, +S	+B, +S	+S	+S	+S	
Dust-Return	-B	-B, -S	-B, -S	-B, -S		-B, -S
Gas-OCS	-B, -S	-B, -S	-B, -S	-B, -S	-B, -S	-B
Gas-CS	-S	-B	-B, -S	-B, -S	-B, -S	-B, -S
*__Gas-scrubber__	+B, +S	+B, +S	+B, +S	+B, +S		-B, -S
Gas-return						-B, -S

Key: + and − symbols refer to the positive and negative significant regression model parameter relationships, respectively, at the 95% confidence level for both the box cut (B) and slab cut (S) experiments performed.

*The scrubber gas concentration relationships were remodeled, excluding the no scrubber tests with a 6.1-m curtain setback, and compared the scrubber gas levels at the 12.2-m setback configurations to the OCS-100% configuration with a 6.1-m setback.

Table 3

Average of extended cut mining dust concentrations with redirected scrubber exhaust (bold numbers indicate significant differences between averages).

Dust sampling location	± Mine 1 dust concentrations with OCS-100% redirected exhaust		± Mine 2 dust concentrations with 50%-50% redirected exhaust	
	First 6.1 m of cut	Second 6.1 m of cut	Used for 2nd half of cut	Used for full cut
CM operator	0.42 mg/m^3	0.69 mg/m^3	0.14 mg/m^3	0.08 mg/m^3
Shuttle car 1 (standard cab)	0.06 mg/m^3	0.12 mg/m^3	**0.21 mg/m^3**	**0.05 mg/m^3**
Shuttle car 2 (off-standard cab)	**0.07 mg/m^3**	**0.31 mg/m^3**	0.30 mg/m^3	0.14 mg/m^3
CM right rear corner (RRC)	NA	NA	1.32 mg/m^3	2.08 mg/m^3
CM left rear corner (LRC)	NA	NA	1.49 mg/m^3	1.64 mg/m^3
Return	1.77 mg/m^3	2.19 mg/m^3	1.91 mg/m^3	1.51 mg/m^3

+Dust concentrations are normalized for production rate; normalized dust concentration = dust concentration for a cut × (average number of shuttle cars per minute for all cuts ÷ number of shuttle cars per minute for the cut).

±Dust concentrations are normalized for ventilation and production time; normalized dust concentration = dust concentration for a cut × (face airflow for the cut ÷ average face airflow for all cuts) × (cut time ÷ average cut time).