Use of a Directional Spray System Design to Control Respirable Dust and Face Gas Concentrations Around a Continuous Mining Machine

Gerrit V.R. Goodman and Douglas E. Pollock

Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health,
Pittsburgh, Pennsylvania

A laboratory study assessed the impacts of water spray pressure, face ventilation quantity, and line brattice setback distance on respirable dust and SF_6 tracer gas concentrations around a continuous mining machine using a sprayfan or directional spray system. Dust levels were measured at locations representing the mining machine operator and the standard and off-standard shuttle car operators, and in the return airway. The results showed that changes in all three independent variables significantly affected log-transformed dust levels at the three operator sampling locations. Changes in setback distance impacted return airway dust levels. Laboratory testing also identified numerous variable interactions affecting dust levels. Tracer gas levels were measured on the left and right sides of the cutting drum and in the return. Untransformed gas levels around the cutting drum were significantly affected by changes in water pressure, face ventilation quantity, and setback distance. Only a few interactions were identified that significantly affected these concentrations. Gas levels in the return airway were grouped by face ventilation quantity. Return gas levels measured at the low curtain quantity were generally unaffected by changes in water pressure or curtain setback distance. At the high curtain quantity, return airway gas levels were affected by curtain setback distance. A field study was conducted to assess the impact of these parameters in an actual mining operation. These data showed that respirable dust levels may have been impacted by a change in water pressure and, to a lesser extent, by an increase in curtain setback distance. A series of tracer gas pulse tests were also conducted during this study. The results showed that effectiveness of the face ventilation was impacted by changes in curtain flow quantity and setback distance. Laboratory testing supported similar conclusions.

Keywords coal mine dust, engineering controls, exposure assessment, silica, underground mining

Address correspondence to: Gerrit V. R. Goodman, Pittsburgh Research Laboratory, NIOSH/Building–03, 626 Cochrans Mill Road, Pittsburgh, PA 15236; e-mail: gcg8@cdc.gov.

Federal regulations require that the concentration of respirable dust in the mine atmosphere not exceed 2.0 mg/m^3 for a working shift.(1) If the silica content on the dust filters exceeds 5% by weight, the 2 mg/m^3 dust standard is reduced according to the following expression: 10 divided by the percent silica. In either case, this maintains silica dust levels at or below 100 μg/m^3.

These regulations also require that methane gas levels in the face area be maintained below 1%. Methane readings obtained with a hand-held methane monitor are usually taken as close to the face as practical, although they cannot be taken closer than 0.3 m (12 inches) from the roof, face, ribs, and floor. Whenever methane readings are 1% or higher, mining must stop until concentrations drop below this level.

Many factors can affect respirable dust exposures and methane gas concentrations during coal mining. The impacts of face ventilation quantity are well documented in the literature and show that respirable dust levels around the mining machine drop significantly as exhaust face ventilation airflow increases.(2,3) A blowing face ventilation scheme generally is used with a mining machine equipped with a flooded-bed dust scrubber. Face ventilation in underground coal mining is typically provided by a curtain hung from the roof approximately 1 m from the left or right wall. The curtain mouth is the region defined by the seam height and the distance from the curtain to the wall.

Fresh air issuing from the curtain mouth and flowing toward the mining machine constitutes blowing face ventilation. Contaminated air flowing from the machine into the curtain mouth constitutes exhaust face ventilation. Studies have shown that increased blowing face ventilation flow above the flow rating of the scrubber unit sometimes led to excessive dust rollback.(4) However, exhaust face ventilation designs are generally preferred for dust control because dust-laden air does not pass over the machine operator. Higher airflow quantities further dilute face gas and result in decreased face gas concentrations.

A blowing ventilation design typically provides a higher rate of airflow to the mining face than a comparable exhausting design.(5)

Water sprays become effective movers of air as water spray pressure increases, and this airflow creates turbulence that can improve dilution of face gas.(6) However, this turbulence also can push dust toward the mining machine operator, and this can lead to higher respirable dust exposures for this person.(7)

Ventilation parameters, such as face airflow quantity, water spray pressure, and curtain setback distance (distance from curtain mouth to cutting head), must emphasize control and confinement and minimize dispersion of the dust cloud to improve suppression and capture of these particles. To control face gas levels, however, these parameters must be selected to provide turbulence to improve dilution of the gas. This suggests that ventilation airflows, spray pressures, and setback distances needed to control respirable dust concentrations may not effectively control methane gas at the face.

For this study, laboratory work assessed the effects of face airflow quantity, water spray pressure, and curtain setback distance on respirable dust exposures for the continuous miner and shuttle car operators. Dust levels also were monitored in the return airway. Corresponding tracer gas concentrations were measured at conventional methanometer locations and in the return airway. A similar study evaluated these factors in an underground mine environment. Due to concerns about worker health and safety, only changes in setback distance could be assessed. A series of tracer gas tests examined movement of the gas pulse into the return as curtain quantity and setback distance changed.

EXPERIMENTAL DESIGN

This laboratory work was conducted at a full-scale surface test gallery simulating a cut 12.2 m (40 ft) deep, 5.5 m (18 ft) wide, and roughly 2.0 m (6.4 ft) high. A full-scale mockup of a continuous mining machine used for this testing featured a 0.9 m (3 ft) diameter cutting drum rotating at 50 rpm. The machine was positioned at the end of the sump or box cut for testing. A coal slab measuring 2.4 m (8 ft) by 6.1 m (20 ft) remained to the right of the machine (Figure 1).

The mining machine was equipped with a directional spray system design (spray fan), which is a water-powered ventilation system originally designed for controlling methane gas levels. This system contained several spray manifolds placed on the continuous mining machine to direct fresh intake air to the cutting face, sweep contaminated air across the face, and direct this airflow into the return airway. The spray fan system was installed on the mockup of the continuous mining machine using established guidelines.(6) Thirty-one BD3-3 hollow cone nozzles (Spraying Systems, Wheaton, Ill.) were positioned above, below, and along the sides of the cutting boom of the mining machine (Figure 2). These sprays directed airflow to the face to sweep dust and gas toward the return.(8) Water spray pressures were 483 kPa (70 psi) or 1310 kPa (190 psi) measured in the line feeding the spray manifold. Measured water flow rates at low and high pressures were 78.1 L/min (20 gpm) and 124.7 L/min (33 gpm), respectively.

In practice, the spray fan system is used only with an exhaust face ventilation scheme. Exhaust curtain ventilation was created in the laboratory by drawing air via a main gallery fan through a curtain positioned on the left side of the test gallery. Exhaust curtain ventilation flows were 2.8 m^3/sec (6000 cfm) or 5.7 m^3/sec (12000 cfm), while curtain setback distances were 9.2 m (30 ft) or 15.4 m (50 ft). Airflow was measured at the mouth of the curtain using a conventional vane anemometer.

A mixture of silica dust in coal dust (average of 8.2% silica by weight) was introduced into the gallery at the miner cutting head via a compressed air/eductor system. Two LH-$^1/_2$ brass eductors (Penberthy, Prophetstown, Ill.) were connected to a 5 psi compressed air source. These eductors mixed the dust mixture with the compressed air to deliver the dust to the cutting head at a rate of 25 gpm. One eductor discharged along the left front side of the cutting drum, while the other discharged

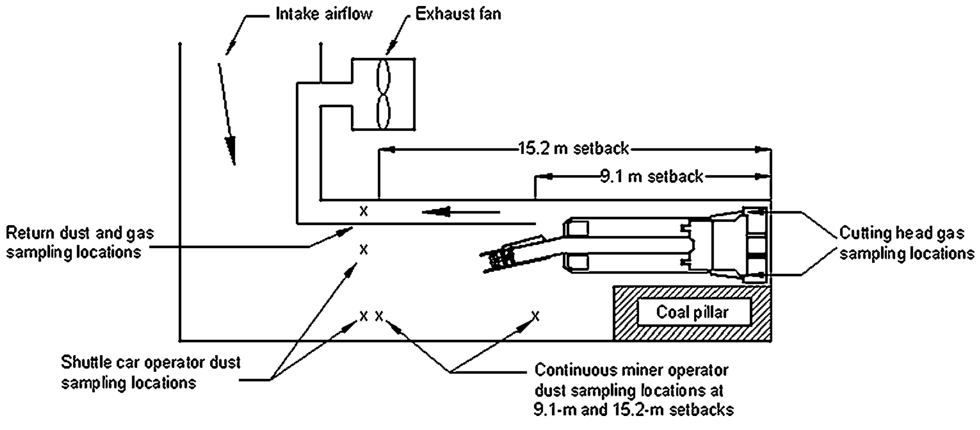

FIGURE 1. Full-scale test facility (plan view)

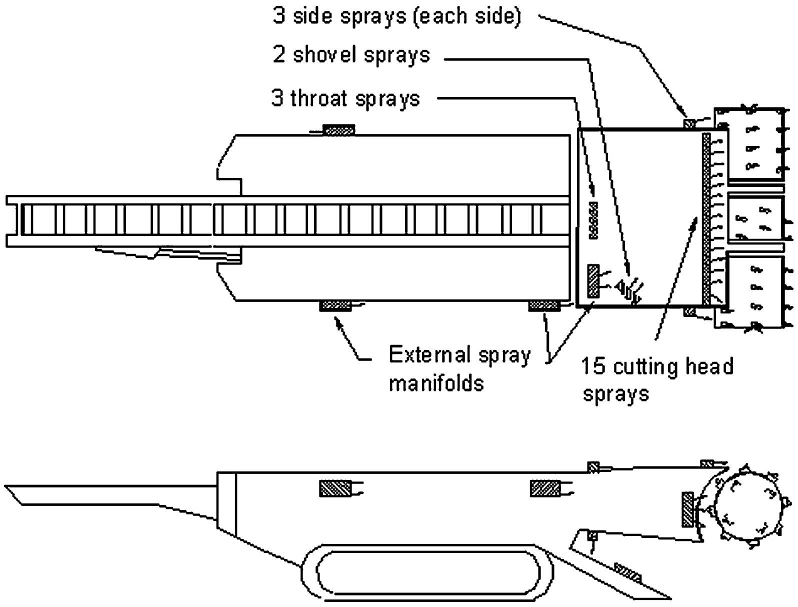

FIGURE 2. Spray locations on mining machine (plan view upper, side view lower)

along the right front of the drum. The rotating cutting head drum insured adequate mixing of the dust with the ventilation airflow.

For dust sampling, constant flow pumps pulled dust-laden air through 10-mm nylon cyclone separators at a rate of 2 L/min as specified by 30 CFR 70.205.(1) The respirable mass deposited onto preweighed 37-mm filters were subsequently postweighed. Dust levels were calculated from the net weight and the total airflow. Selected filters were sent to an independent and certified laboratory for silica analysis using XRD (X-ray diffraction) infrared method number 7500.(9) A pair of gravimetric samplers were placed on the off-curtain (right) side of the entry near the mouth of the exhaust curtain to represent the location of the remote mining machine operator. This location moved with curtain setback distance. Two pairs of samplers placed 7.6 m (25 ft) outby the rear of the mining machine on the left and right sides represented locations of the standard and off-standard shuttle car operators, respectively. A standard shuttle car operator sits on the left side of the car when traveling toward the dump point. The operator of an off-standard car sits on the right side when traveling toward the dump point. Finally, gravimetric samplers placed downwind of the mining machine monitored dust levels in that location (Figure 1).

A realtime aerosol monitor (RAM-1; Thermo Andersen Inc., Smyrna, Ga.) dust monitor measured pretest (baseline) conditions. Before each test, dust was introduced at the cutting head for 10 min with the cutting head rotating and only the exhaust curtain ventilation in operation. During this baseline period before operating the water sprays, the dust feed rate was adjusted to a level that produced uniform and visually stable dust concentrations.

Testing also evaluated the impact of face airflow quantity, water spray pressure, and setback distance on the removal and dilution of hazardous gas concentrations. Due to safety concerns, methane gas (CH_4), which is typically found in all underground coal mines, could not be used in this testing. Instead, sulfur hexafluoride (SF_6) was used as a surrogate or tracer gas. This gas is tasteless, odorless, not found naturally in the atmosphere, and is nontoxic in the amounts used in this testing. It is also detectable in the ppm concentration level. SF_6 was introduced at the cutting drum where the drum's rotation mixed the gas with the face airflow.

A model 1303 multipoint gas doser (California Analytical Instruments, Orange, Calif.) metered the SF_6 into the gallery at a rate of 6 mL/sec. Real-time measurement of the SF_6 gas levels was made with a model 1312 photoacoustic gas monitor (California Analytical Instruments). Gas sampling was conducted at locations representing typical methanometer locations on a continuous mining machine: on the left and right sides of the cutting boom approximately 0.6 m from the cutting drum. Gas levels were also measured in the return airway (Figure 1). For each test, gas was introduced into the gallery in a series of four evenly spaced pulses, each pulse lasting 12 min. These pulse durations were used to more accurately mimic a flow of methane gas into the underground mine environment.

The water sprays controlling the respirable dust cloud would not absorb sufficient quantities of either SF_6 or CH_4 to seriously impact gas levels. SF_6 and methane are soluble in water at a rate of 5.4 cc and 30.1 cc per liter of water, respectively.(10) This chemical property is typically measured in a closed system under equilibrium, whereas the full-scale test facility was neither closed nor at equilibrium. For this reason, the solubilities of these gases in water are less under test conditions. At the high water flow of 124.7 L/min, the absorption rate of SF_6 is less than 10^{-4} mL/sec compared with the dose rate of 6 mL/sec, a

TABLE I. Untransformed Respirable Dust Levels Measured During Full-Scale Testing (n = 3)

Water Spray Pressure (kPa)	Exhaust Curtain Flow (m^3/s)	Curtain Setback Distance (m)	Average Gravimetric Dust Concentration, mg/m^3 (Standard Deviation) Continuous Miner Operator	Standard Shuttle Car Operator	Off-Standard Shuttle Car Operator	Return
483	2.8	9.2	0.73 (0.12)	0.56 (0.21)	1.27 (0.71)	5.53 (1.17)
1310	2.8	9.2	1.33 (0.33)	0.36 (0.07)	0.46 (0.09)	7.87 (6.95)
483	5.7	9.2	0.12 (0.03)	0.11 (0.02)	0.11 (0.02)	6.63 (1.23)
1310	5.7	9.2	0.17 (0.06)	0.14 (0.04)	1.08 (0.78)	7.54 (3.18)
483	2.8	15.4	0.19 (0.05)	0.50 (0.18)	4.52 (1.21)	5.26 (1.49)
1310	2.8	15.4	0.88 (0.17)	1.79 (0.25)	3.52 (0.59)	3.03 (0.35)
483	5.7	15.4	0.24 (0.07)	0.26 (0.05)	4.60 (0.89)	3.80 (0.38)
1310	5.7	15.4	0.42 (0.32)	0.45 (0.45)	3.75 (0.64)	3.10 (0.45)

loss of less than 1%. At the same water flow, CH_4 is absorbed by the water sprays at a rate of 0.29 mL/sec. For a typical CH_4 dose rate of 1300 L/min,(11) less than 1% of the methane gas is absorbed. Neither SF_6 nor CH_4 levels are sufficiently affected through absorption by the water sprays.

Tracer gas release and sampling ran concurrently with dust sampling. Disposable filters, placed at the ends of the gas sampling tubes, prevented dust from entering the gas monitoring equipment.

Robust assessments of the effects of curtain quantity, water spray pressure, and setback distance on respirable dust and tracer gas concentrations were made by testing with the high and low values of these variables. A randomized full factorial design evaluated each combination of independent variables. Two replicates of each test were made to obtain a measure of the error associated with each combination.

The dust concentration at each sampling location was calculated using the average of the concentrations for each group of samplers. The tracer gas concentration at each location was the average of the concentrations recorded for each pulse. Respirable dust and tracer gas concentrations for each series of test conditions were calculated using the average concentration for each test comprising that set of conditions.

RESULTS AND DISCUSSION

Effects on Respirable Dust Exposures

The dust concentrations at each sampling location displayed a tendency toward a log-normal distribution. Following $\log_{10}$ transformations, Shapiro-Wilks statistics ranged from 0.86 to 0.96 (p-value from 0.004 to 0.48) for the laboratory data. This test rejected the assumption of normality for data collected at the off-standard shuttle car location. Levene's statistics for homogeneity of variances ranged from 1.40 to 4.55 (p-value from 0.27 to 0.01). This test rejected the null hypothesis of equality of variances across groups for data collected at the return sampling location. Although some sampling data showed departures from normality, the F tests used in analyses of variance (ANOVA) are robust and little affected by such departures. The balanced design used for these analyses also minimizes the impact of unequal variances within each grouping of curtain quantity, water pressure, and setback distance.(12) Analyses of data with a nonnormal distribution or with unequal variances may produce significance levels slightly higher than would be otherwise found.

The untransformed data in Table I show means and standard deviations for operator and return sampling locations. Analyses of variance were used to define the effects of the independent variables on $\log_{10}$ transformed respirable dust levels.

As shown in Table II, curtain quantity and water spray pressure significantly affected (at a 0.05 confidence level) the log transformed values of the respirable dust levels for the mining machine operator. Not surprisingly, increasing curtain quantity improved dilution of the dust cloud and led to the greatest reductions at this position. Although reductions occurred for all levels of water pressure, reductions were greatest when testing with the highest water pressure. The reductions were also high when increasing curtain airflow at the smaller curtain setback distance.

Increasing water spray pressure increased dust levels for the miner operator generally by increasing dust rollback levels. Increasing water pressure had the most adverse effect on operator dust levels with low return curtain quantity. This supports previous work regarding the importance of balancing airflow and water pressure to control dust levels.(13)

Log transformed dust levels at the standard shuttle car operator were affected by changes in curtain quantity and setback distance. Increasing the curtain quantity reduced dust levels by improving dust dilution at the face. This effect was constant at either setback distance. The 9.2 m setback distance produced lower dust levels due to improved circulation of fresh air around the mining machine.

Extending curtain setback distance produced statistically significant changes in the transformed dust levels at the

TABLE II. Summary of ANOVA Statistics from Log-Transformed Gravimetric Dust Data

Source of Variation	Sum of Squares	Degrees of Freedom	F-Ratio
$\log_{10}$(machine operator)			
A: water pressure	2.51	1	9.48^{A}
B: curtain quantity	8.57	1	32.43^{A}
C: curtain setback	0.08	1	0.29
Interactions			
AB	1.00	1	3.80
AC	0.27	1	1.03
BC	3.58	1	13.53^{A}
Error	4.49	17	
Total	20.55	23	
$\log_{10}$(standard shuttle car operator)			
A: water pressure	0.62	1	1.83
B: curtain quantity	9.25	1	27.36^{A}
C: curtain setback	3.49	1	10.33^{A}
Interactions			
AB	0.12	1	0.35
AC	0.87	1	2.58
BC	0.00	1	0.00
Error	5.74	17	
Total	20.09	23	
$\log_{10}$(off-standard shuttle car operator)			
A: water pressure	0.11	1	0.28
B: curtain quantity	1.04	1	2.67
C: curtain setback	27.78	1	71.57^{A}
Interactions			
AB	3.09	1	7.97^{A}
AC	0.75	1	1.92
BC	1.28	1	3.29
Error	6.60	17	
Total	40.65	23	
$\log_{10}$(return airway)			
A: water pressure	0.10	1	0.81
B: curtain quantity	0.00	1	0.01
C: curtain setback	1.76	1	13.91^{A}
Interactions			
AB	0.03	1	0.24
AC	0.33	1	2.60
BC	0.14	1	1.08
Error	2.16	17	
Total	4.52	23	

Note: Critical F-value: $F_{0.95,1,17} = 4.45$.

[A] Significant at 0.05 level of confidence.

off-curtain side shuttle car operator by placing the curtain mouth near this individual. Dust flowing near the curtain mouth may have contaminated these samples. The interaction of water pressure and curtain quantity produced significant changes in dust levels at the off-curtain side operator. Increasing water pressure at the higher curtain flow increased dust levels by blowing dust back to this individual. The analytical results in Table I show that dust levels at the off-standard shuttle car location were generally much greater than levels measured at the mining machine or standard shuttle car operator locations. The inability to effectively protect the operator of the off-standard shuttle car limits its use with a sprayfan-equipped mining machine.

Finally, changes in curtain setback distance resulted in statistically significant changes in transformed return airway dust levels, a fact that contradicts the sampling results for the off-standard shuttle car operator. However, standard deviations were sometimes very high when sampling in the return. This introduced considerable uncertainty into the analyses of variance at this location making it difficult to identify significant variations.

Silica dust levels at the mining machine and standard shuttle car operator sampling locations were generally below the 0.01 mg limit of detection or the 0.03 mg limit of quantification for NIOSH Method 7500. Even at the off-standard shuttle car location, silica dust levels were not detected for tests at the smaller setback distance of 9.2 m. At the larger distance of 15.2 m, the respirable dust samples contained from 3.2 ± 1.5% to 4.3 ± 1.9% silica by weight. Silica dust contents in the return varied from 2.4% to 5.0% by weight. However, analyses of silica contents versus changes in water pressure, curtain quantity, and setback distance showed no significant differences at a 95% level of confidence.

Ventilation airflow quantity and setback distance are largely ineffective for selective control of respirable silica dust. Previous work showed that high water pressure can provide added control of smaller sized silica particles.(14) However, water pressures recorded for that work were 17,250 kPa, much higher than the pressures reported in the current work.

Effects on SF_6 Levels

Although respirable dust concentrations were log transformed to improve normality and homogeneity of variances, similar adjustments were not necessary for the tracer gas data. Shapiro-Wilks statistics ranged from 0.86 to 0.94 (p-value from 0.004 to 0.17) with nonnormality discovered at the return sampling location. Homogeneity of variances was not a major concern with Levene statistics ranging from 1.46 to 1.54 (p-value from 0.25 to 0.22) for the gas concentrations.

Increases in curtain flow quantity and curtain setback distance significantly impacted SF_6 tracer gas concentrations on the off-curtain or right side of the cutting drum (Tables III and IV). The data generally showed lower gas levels with increasing curtain flow quantity suggesting improved dilution at this higher flow. Increasing curtain setback distance had an adverse effect on gas levels by reducing dilution airflow quantity to the face. The interaction of curtain flow quantity and water pressure significantly impacted off-curtain side gas levels. Increasing curtain flow produced the greatest drop in off-curtain side gas levels when coupled with high water pressure. No other interactions were statistically significant.

TABLE III. Untransformed SF_6 Tracer Gas Concentrations Measured During Full-Scale Testing ($n = 3$)

			Average SF_6 Tracer Gas Concentration, ppm (Standard Deviation)		
Water Spray Pressure (kPa)	Exhaust Curtain Flow (m^3/sec)	Curtain Setback Distance (m)	Cutting Drum, Curtain (left) Side	Cutting Drum, Off-Curtain (right) Side	Return
483	2.8	9.2	2.80 (0.24)	0.45 (0.15)	2.22 (0.08)
1310	2.8	9.2	2.07 (0.15)	0.60 (0.19)	2.37 (0.23)
483	5.7	9.2	2.51 (0.12)	0.20 (0.09)	1.10 (0.08)
1310	5.7	9.2	1.46 (0.02)	0.09 (0.04)	1.15 (0.05)
483	2.8	15.4	2.88 (0.09)	0.73 (0.11)	2.17 (0.17)
1310	2.8	15.4	2.38 (0.16)	1.03 (0.06)	2.29 (0.12)
483	5.7	15.4	2.79 (0.19)	0.44 (0.08)	1.03 (0.30)
1310	5.7	15.4	1.73 (0.07)	0.27 (0.03)	0.73 (0.18)

Water pressure, curtain quantity, and curtain setback distance all significantly impacted tracer gas concentrations on the curtain (left) side of the cutting drum. Tracer gas concentrations decreased as water spray pressure and exhaust curtain quantity increased, likely a result of improved dilution. This follows from previous work showing that higher water spray pressures create additional airflow and that this airflow can be used to dilute and remove harmful quantities of gas.(6,15) Gas levels were slightly higher at the larger curtain setback distance suggesting that dilution airflow quantities decreased. The interaction of water pressure and curtain airflow quantity significantly impacted gas levels on the left side of the cutting drum. Increases in curtain quantity had a slightly greater impact to reduce gas levels when water pressure was highest. Remaining interactions were not significant. This testing also showed that gas concentrations were highest on the curtain side of the cutting head, indicating that the sprayfan effectively "scoured-out" the right or off-curtain side. Similar results were reported by other researchers.(8)

Although return airway gas levels exhibited homogeneity of variance, the distribution of gas concentrations was nonnormal. The data in Table III show a distinct grouping of return gas concentrations at flow rates of 2.8 and 5.7 m^3/sec. Examining these two groupings of return gas levels individually improved the normality of the data. Shapiro-Wilks statistics improved to 0.93 (p-value $= 0.38$) for data at curtain flows of 2.8 and 5.7 m^3/sec. Levene statistics were only slightly affected (statistic $= 2.20$, p-value 0.16).

At a curtain flow of 2.8 m^3/sec, analyses of variance showed no statistically significant impacts of water pressure or curtain setback distance on return gas levels, suggesting that return gas levels were largely a function of this curtain quantity alone. At the larger curtain flow of 5.7 m^3/sec, changes in curtain setback distance produced statistically significant reductions in return gas levels, although this did not necessarily indicate improved ventilation at this larger setback distance. Rather, this showed that poor ventilation at the face likely caused a plug of gas to form between the cutting head and return curtain. This phenomenon also explains the increased gas concentrations at the cutting head sampling locations. The lower gas levels in the return were due to the ventilation airflow diluting the periphery of the gas plug.

Field Evaluation of Dust and Gas Concentrations

The effects of varying ventilation parameters on respirable dust and face gas levels also were assessed at an underground coal mining operation. Mining activity occurred in five entries that were an average of 2.7 m high and 5.5 m wide. Face ventilation was provided by an exhaust line curtain hung along the left rib. Curtain flow varied with entry location but averaged 3.3 m^3/sec (7200 cfm). The mining machine used 26 water sprays arranged in a spray fan pattern with each spray delivering 2.4 L/min at 689.5 kPa (0.63 gpm at 100 psi). Spray pressure varied from 621 kPa to 793 kPa (90 to 115 psi) as measured on the cutting drum of the mining machine.

Assessment of Respirable Dust Concentrations

A combination of gravimetric and continuous-recording instruments measured dust levels on and around the mining machine. While the gravimetric samplers were identical to those used in the laboratory phase of this study, the continuous-recording samplers were personal DataRam (pDR) dust monitors (Thermo MIE, Inc., Smyrna, Ga.). A permissible air sampling pump pulled dust-laden air through a 10-mm nylon cyclone at a rate of 2 L/min. This aerosol then passed through a light-scattering chamber where the amount of scatter represented a respirable dust concentration. This pDR device contained an internal data logger that recorded dust concentrations every 10 sec.

Two shifts of exposure data were collected during the underground phase of this work. For the two shifts, coal productions were 696 and 960 tons while actual operating times of the mining machine were 305 and 218 min, respectively. A third shift was invalidated due to excessive downtime spent repairing a bad trailing cable.

TABLE IV. Summary of ANOVA Statistics from SF_6 Tracer Gas Data

Source of Variation	Sum of Squares	Degrees of Freedom	F-Ratio
Off-curtain side location			
A: water pressure	0.01	1	0.99
B: curtain quantity	1.24	1	107.90[A]
C: curtain setback	0.47	1	41.2[A]
Interactions			
AB	0.21	1	18.22[A]
AC	0.003	1	0.27
BC	0.03	1	2.99
Error	0.20	17	
Total	2.16	23	
Curtain side location			
A: water pressure	4.20	1	203.47[A]
B: curtain quantity	1.02	1	49.39[A]
C: curtain setback	0.34	1	16.32[A]
Interactions			
AB	0.29	1	14.09[A]
AC	0.02	1	0.93
BC	0.01	1	0.49
Error	0.35	17	
Total	6.23	23	
Return airway—2.8 m^3/sec			
A: water pressure	0.05	1	2.05
C: curtain setback	0.01	1	0.51
Interactions			
AC	0.00	1	0.02
Error	0.50	8	
Total	10.35	11	
Return airway—5.7 m^3/sec			
A: water pressure	0.04	1	1.40
C: curtain setback	0.18	1	5.54[A]
Interactions			
AC	0.05	1	2.93
Error	0.50	8	
Total	10.35	11	

Notes: Citical F-value for off-curtain side and curtain side readings: $F_{0.95,1,17} = 4.45$. Critical F-value for return readings: $F_{0.95,1,8} = 5.32$.

[A] Significant at 0.05 level of confidence.

Dust sampling packages consisting of a pDR dust monitor and a gravimetric sampler were positioned together in the return airway and on a researcher shadowing the mining machine operator. This operator typically stood away from the machine on the right side of the entry. These sampling packages also were placed on the left and right rear corners of the mining machine. Two standard shuttle cars (no off-standard cars) were used to haul coal at this operation. However, dust levels were not measured on this equipment. Left rear and right rear corner sampling locations on the mining machine were used in lieu of shuttle car sampling locations.

The results given in Table V show that machine operator dust levels were fairly low. Dust levels at the left and right rear corners of the mining machine are potential indicators of dust rollback from the cutting drum. These concentrations were highest on the left side, not unexpected with the exhaust curtain hung on the left side of the entry.

Right rear corner dust levels can serve as an indicator of potential exposure for the machine operator; as this individual stands nearest to this corner. First and second shift data showed similarities between dust concentrations at the right rear corner and those measured around the operator. Intake dust levels for the first and second shifts were 0.26 mg/m^3 and 0.14 mg/m^3, respectively.

The percentage of silica dust on the samples increased from the machine operator sampling location to the return airway sampling location. Silica contents at each location were similar for the two sampling days.

A booster pump failed to operate the first shift, resulting in a water pressure of 621 kPa measured with a dial gauge on the cutting head. This pump operated during the second shift and water pressure increased to 793 kPa. Dust levels decreased from the first shift to the second shift, although the reductions at the machine operator and right rear corner sampling locations approximated the reduction in intake dust level (Table V). However, the reductions seen on the downwind side of the mining machine (left rear corner and return) far exceeded the reduction in intake dust. This suggests that perhaps even this small increase in water pressure on the second shift had a positive impact on downwind dust concentrations. Previous work showed that small increases in water pressure improved dust removal capabilities.(16) Although slightly smaller increases were noted at this operation, the prior work suggests that even this may be beneficial from a dust control standpoint.

However, it is understood that many factors can affect dust concentrations around a continuous mining machine. These include, but are not limited to, production rate, cutting technique, variations in seam geology, and so on. The aforementioned tonnages and operating times yield similar production rates for both shifts. Also, a majority of the development work for these two shifts occurred with the mining machine cutting straight-ahead, as opposed to this machine turning in the entry to create an air connection to the adjacent entry. This suggests that similar levels of dust generation may have existed during each shift.

Impact of Curtain Setback Change

Another facet of this study assessed the impacts of setback distance changes on respirable dust levels measured on and around the mining machine. This required the measurement of dust levels for discrete time periods corresponding to specific curtain setback distances. The pDR devices provided such a time-based output of dust levels at the left and right rear corners of the mining machine, in the return airway, and near the mining machine operator. The ratio of gravimetric concentration to average pDR dust level at each location provided a means to calculate equivalent gravimetric dust concentrations for these

TABLE V. Gravimetric Analysis of Field Data

Sampling Location	Sampling Time (min)	Respirable Dust Concentration (mg/m^3)	Silica Dust Content (%)
First shift			
Continuous miner operator (shadow)	484	0.39	4.0
Mining machine—right rear corner	481	0.56	4.0
Mining machine—left rear corner	481	1.26	6.3
Return airway	480	2.72	7.5
Second shift			
Continuous miner operator (shadow)	426	0.22	3.1
Mining machine—right rear corner	427	0.40	5.6
Mining machine—left rear corner	427	0.60	5.6
Return airway	380	1.75	7.2

time periods. Multiplying this ratio by the average pDR reading for the time period in question gave a weighted gravimetric dust level for that period.

Time study data compiled during this underground study showed that the average curtain setback distance was either 2.4 m (8 ft) or 4.9 m (16 ft), depending on the position of the machine within the cut. This analysis, therefore, examined the impact of these two curtain setback distances on pDR-adjusted respirable dust levels at the previously mentioned sampling locations.

Table VI shows that only slight increases in pDR-adjusted dust levels were seen with curtain setback distance. The largest increases in dust levels were found at the left and right rear corners, suggesting that the increase in curtain setback distance affected the amount of dust rollback from the cutting head. Increases in dust levels were similar at the machine operator sampling location suggesting that movements of this individual during mining were consistent for the two shifts.

Assessment of Face Gas Levels

This study also assessed the effects of varying curtain setback distance and return curtain quantity on face gas concentrations. A more precise measurement of these impacts was possible using sulfur hexafluoride tracer gas. Ten cubic centimeters of the gas were released on the right side of the mining machine about 1.5 m away from the cutting drum. Gas samples then were collected in small evacuated bottles at a location 4.5 m outby the mouth of the return curtain (Figure 3).

Gas samples were taken in the following manner: 6 samples at 5-sec intervals, 3 samples at 10-sec intervals, 4 samples at 15-sec intervals, and 2 samples at 3-sec intervals, resulting in 15 samples in 180 sec. This scheme was similar to that used in previous testing.(17) Frequent sampling at the beginning of the interval caught the rise and decay of the gas pulse as it traversed the face and entered the return airway. Less frequent sampling at the end caught the tail of the pulse.

The mining company stated that the most appropriate machine location for the tracer gas testing was at the end of a 3.0-m cut on the right side of the face (Figure 3). During these tests, the cutting drum of the machine rotated and all water sprays operated. Four different face ventilation configurations were then assessed with the machine at this location.

1. Baseline conditions with the curtain mouth 0.6 m from the face and 4.2 m^3/sec measured at the curtain mouth.
2. Curtain mouth 3.6 m from the face and 4.2 m^3/sec measured at the curtain mouth.
3. Curtain mouth 3.6 m from the face and 0.7 m^3/sec measured at the curtain mouth. This low curtain flow condition occurs when the roof bolters raised the ventilation

TABLE VI. Summary of pDR-Adjusted Dust Levels vs. Setback Distance

	2.4 m Curtain Setback Distance		4.9 m Curtain Setback Distance	
Sampling Location	Number of Samples	Average pDR-Adjusted Dust Concentration, mg/m^3 (Standard Deviation)	Number of Samples	Average pDR-Adjusted Dust Concentration, mg/m^3 (Standard Deviation)
Mining machine operator	2	0.26 (0.04)	2	0.31 (0.04)
Machine right rear corner	2	0.48 (0.08)	2	0.62 (0.01)
Machine left rear corner	2	1.08 (0.64)	2	1.20 (0.78)
Return airway	2	3.67 (0.14)	2	3.71 (0.19)

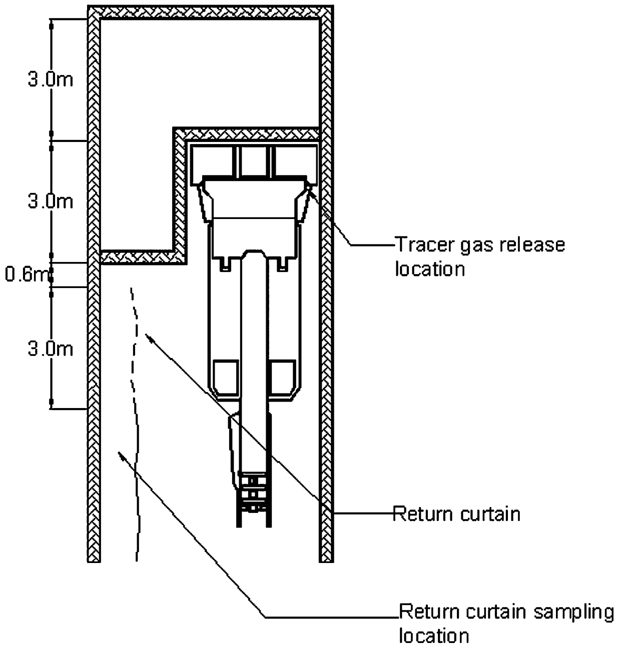

FIGURE 3. Gas release and sampling locations (plan view)

curtain to move their machine around the mining machine.

4. Curtain mouth 0.6 m from the face and 0.7 m^3/sec measured at the curtain mouth.

This release strategy differed from the laboratory evaluations, in that shorter term pulses were used. Given the highly dynamic nature of the underground mine environment, releasing longer pulses of tracer gas may not have provided additional insight. Given the shorter term pulses used in this underground testing, the ventilation could not be assessed in a conventional manner that is, by calculating and comparing average gas concentrations. Instead, other parameters were used.

Previous analyses of tracer gas data considered the time required for measurable gas levels to reach the return curtain sampling location. This time reflected the effectiveness of the face ventilation for moving gas from the cutting face to the return curtain.(16) Other measures include the duration or residence time of the gas pulse at the face as a gauge of face ventilation efficiency.

Previous work with residence time distributions is limited to analyses of chemical reactors where a pulse of nonreactive tracer material is injected into the reactor input stream and sampled in the effluent stream.(18) Residence time analyses calculated the lengths of time required to remove various elements of the SF_6 pulse from the face area. The distribution of these times is called the exit age distribution, E(t), or the residence time distribution of the tracer gas. By definition, the area under the E(t) curve is unity. The mean residence time (MRT) is defined as the first moment of the residence time distribution.(19) A well-ventilated face will not only show a quick arrival of measurable gas levels at the return sampling location but also will show a short MRT indicating quick removal of the gas from the face area.

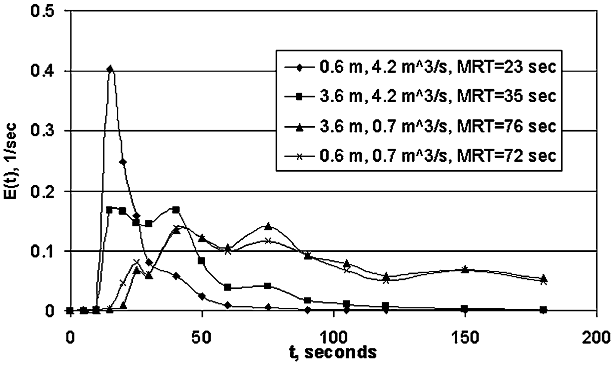

FIGURE 4. Residence time distributions and mean residence times (MRT) for the four test conditions

Residence time distributions for the four different ventilation conditions show that arrivals of measurable gas concentrations were similar for the four different ventilation conditions (Figure 4). This figure also shows that the shortest mean residence time of 23 sec occurred with a curtain setback of 0.6 m and a curtain flow of 4.2 m^3/sec. Increasing curtain setback distance to 3.6 m lengthened the MRT to 35 seconds, suggesting that the gas pulse resided longer at the face. Decreasing exhaust curtain flow to 0.7 m^3/sec dramatically increased the capture time to 76 seconds, showing that the gas pulse was being slowly removed from the face area. Re-extending curtain setback distance to 0.6 m reduced the MRT to 72 sec.

The shapes of the E(t) curves reflect the efficiency of the ventilation flow for removing tracer gas from the face area. The curve obtained with a setback distance of 0.6 m and a curtain flow of 4.2 m^3/sec shows a pronounced spike suggesting that the tracer was quickly removed. This shape is indicative of flow exhibiting little mixing where each portion of the tracer gas moves uniformly through the face area.(18) The two E(t) curves with curtain flows of 0.7 m^3/sec never reach zero on the vertical axis. This suggests that measurable quantities of tracer gas were still found behind the exhaust curtain at $t = 180$ sec. Because the tracer gas concentration will eventually reach zero at some time beyond 180 sec, the MRT analysis used earlier is a conservative estimate for these curves. The gas concentrations measured beyond $t = 180$ sec would extend the mean residence time beyond those values shown in Figure 4.

The data in Figure 4 show that curtain quantity had the most dramatic effect on the behavior of the tracer gas pulse, a result confirmed by the full-scale testing presented earlier. Curtain setback distance had a much less pronounced impact on the pulse curve. This also was evident from the full-scale laboratory results. In the laboratory testing, only a minor interaction was observed between curtain quantity and curtain setback distance at a curtain flow of 5.7 m^3/sec. The underground tests showed that varying curtain setback distance had a greater impact at the higher curtain flow rate of 4.2 m^3/sec than at a rate of 0.7 m^3/sec. At this flow rate, the effectiveness of the face ventilation to remove the tracer gas was marginal and changing curtain setback distance from 0.6 to 3.6 m produced little change in mean residence time.

CONCLUSIONS

The laboratory study showed that increases in water spray pressure led to increased levels of dust rollback, particularly at the lower return curtain quantity. This resulted in higher exposures at the mining machine operator and standard shuttle car operator. Increases in curtain quantity generally led to reductions in dust levels, although some increases were noted at the off-standard shuttle car operator. Increases in curtain setback distance resulted in significant increases in dust exposures at all sampling locations. Exposures for the mining machine operator were also impacted by the interactions of water pressure and curtain quantity and curtain setback distance. The standard shuttle car operator was impacted by the interaction of curtain quantity and curtain setback distance. No interactions were found for the off-standard shuttle car operator or return airway.

Tracer gas testing showed that increased curtain flow and reductions in curtain setback distance provided additional dilution to reduce SF_6 gas concentrations at the two cutting head sampling locations. The benefits of higher spray pressure were evident only at the curtain side sampling location. Interactions between spray pressure and curtain flow quantity led to statistically significant effects at the curtain and off-curtain locations only.

Return gas levels were grouped according to face ventilation flow. Those gas levels measured at the low ventilation were not affected by any changes in water pressure or setback distance. Curtain setback distance affected gas levels measured at the higher airflow.

Underground testing showed that a small increase in water pressure may have reduced dust levels on the downwind side of the mining machine and in the return airway. The study showed that increases in setback distance also led to slight increases in gravimetric dust levels for the miner operator. Dust levels measured on the left and right rear corners of the machine also increased. The laboratory data showed similar results.

Tracer gas tests showed that increases in setback distance and decreases in curtain quantity both negatively impacted the effectiveness of the face ventilation to remove the gas pulse. However, reductions in curtain quantity impacted the ventilation much more seriously than increases in curtain setback distance.

ACKNOWLEDGMENTS

The authors would like to thank Emery Chilton for his assistance in quantifying the solubilities of the SF_6 and CH_4, and the coal company and its mine workers for assisting with the underground portion of the study.

REFERENCES

1. "Mineral Resources," *Code of Federal Regulations.* Title 30, Parts 70 and 75. 1999.
2. **Colinet, J.F., J.J. McClelland, and R.A. Jankowski:** *Interactions and Limitations of Primary Dust Control for Continuous Miners*. Report of Investigations, No. 9373. Pittsburgh, Pa.: U.S. Bureau of Mines, 1991.
3. **Divers, E.F., and N.I. Jayaraman:** Coal mine face ventilation systems: New concepts and underground results. In *Proceedings of the First U.S. Mine Ventilation Symposium*, pp. 33–42. H.L. Hartman (ed.). Society of Mining, Metallurgy, and Exploration, Littleton, Colo., 1982.
4. **Schultz, M.J., and K.G. Fields:** *Dust Control Considerations for Deep Cut Mining Sections*. Preprint 99-163. Society for Mining, Metallurgy, and Exploration, Annual Meeting, Denver, Colo., 1999.
5. **Luxner, J.V.:** *Face Ventilation in Underground Bituminous Coal Mines*. Report of Investigations, No. 7223. Pittsburgh, Pa.: U.S. Bureau of Mines, 1969.
6. **Foster-Miller, Inc.:** *Improved Diffuser and Sprayfan Systems for Ventilation of Coal Mine Working Faces*. Contract J0113010. Pittsburgh, Pa.: U.S. Bureau of Mines, 1985.
7. **Jankowski, R.A., N.I. Jayaraman, and C.A. Babbitt:** Water spray systems for reducing the quartz dust exposure of the continuous miner operator. In *Proceedings of the 3rd U.S. Mine Ventilation Symposium*, University Park, PA, pp. 605–611. R.V. Ramani (ed.). Society of Mining, Metallurgy, and Exploration, Littleton, Colo., 1987.
8. **Ruggieri, S.K., J.C. Volkwein, F.N. Kissell, et al.:** Extended advance face ventilation systems. In P. Mousset-Jones (ed.), *Proceedings of 2nd U.S. Mine Ventilation Symposium*, University of Nevada–Reno, 1985. pp. 543–549. Society of Mining, Metallurgy, and Exploration, Littleton, Colo. (1985).
9. **Schlecht, P.C., and P.F. O'Connor (eds.):** *NIOSH Manual of Analytical Methods (NMAM®)*, 4th ed. Method 7500. Cincinnati, Ohio: NIOSH, 1994.
10. **Braker, W., and A.L. Mossman:** *Matheson Gas Data Book*. Secaucus, N.J. Matheson Gas Products, 1980.
11. **Taylor, C.D., and J.A. Zimmer:** Effects of water sprays and scrubber exhaust on face methane concentrations. In S. Wasilewski (ed.), *Proceedings of the Seventh International Mine Ventilation Congress*, Cracow, Poland, 2001, pp. 466–470. Electrical & Engineering and Automation in Mining (EMAG), Cracow, Poland (2001).
12. **Neter, J.:** *Applied Linear Statistical Models,* 2nd ed. Homewood, Ill.: R.D. Irwin, 1985.
13. **Volkwein, J.C.:** Sprayfans combined with reverse sprays ventilate 40-foot cuts. *Technology News* No. 319. Pittsburgh, Pa.: U.S. Bureau of Mines, 1988.
14. **Jayaraman, N.I., and R.A. Jankowski:** Atomization of water sprays for quartz dust control. *Appl. Ind. Hyg. 3*:327–331 (1988).
15. **Foster-Miller, Inc.:** *Development of Optimized Diffuser and Spray Fan System for Coal Mine Face Ventilation*. Contract H0230023. Pittsburgh, Pa.: U.S. Bureau of Mines, 1977.
16. **Jayaraman, N.I., W.E. Schroeder, and F.N. Kissell:** Studies of dust knockdown by water sprays using a full-scale model mine entry. *Transactions, Society of Mining, Metallurgy, Exploration 278*:1875–1882 (1986).
17. **Foster-Miller, Inc:** *Deep Cut Mine Face Ventilation*. Contract H0348039. Pittsburgh, Pa.: U.S. Bureau of Mines, 1988.
18. **Aris, R:** *Elementary Chemical Reactor Analysis*, pp. 215–223. Englewood Cliffs, N.J.: Prentice-Hall, 1969.
19. **Levenspiel, O.:** *The Chemical Reactor Omnibook*, pp. 63.1–63.11. Corvallis, Ore.: OSU Bookstores, Inc., 1989.