Factors impacting respirable dust entrainment and dilution in high-velocity air streams

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Abstract
In conjunction with steady increases in production levels, longwall operators have applied greater quantities of ventilating air to control respirable dust and methane gas. As a result, air velocities greater than 7.6 m/s (1,500 fpm) have been measured on longwall faces. Operators have expressed concern over the potential entrainment of respirable dust at these high-velocities, especially during shield advance, as dust falls from the shield canopy directly into the air stream. Laboratory tests to simulate dust liberation by shield movement were conducted at the Pittsburgh Research Laboratory of NIOSH in a wind tunnel designed to study dust entrainment in high-velocity airstreams. Dust was introduced into the tunnel to determine dust concentration as it relates to entrainment, dilution, air velocity and particle adhesion. Airborne dust samples were obtained by isokinetic sampling using BGI cyclones to quantify respirable dust concentration at the various air velocities. Laboratory tests were conducted at velocities ranging from 2.0 to 10.1 m/s (400 to 2,000 fpm), and significant differences in airborne respirable dust levels were measured. This research is being conducted to provide fundamental information on the entrainment characteristics of respirable dust at high air velocities, which will subsequently lead to solutions for shield dust control. A discussion of the test procedures and results are presented.

Introduction
Substantial gains in longwall production levels have occurred in the past decade, with longwall mining now accounting for more than 50% of the underground coal produced in the United States (Energy Information Administration, 2000). Increased production has put greater demand on longwall dust-control systems, and many operations still have difficulty maintaining consistent compliance with federal dust standards. Reducing longwall respirable dust generation remains a primary health concern of industry, regulators and researchers involved with worker pneumoconiosis and silicosis.

During the 1980s and 1990s, dust-control technology concentrated on reducing dust generated by the two largest sources: the shearer and the stageloader (Colinet and Jankowski, 1997). During the early 1980s, face air velocities ranged from 0.6 to 3.3 m/s (125 to 650 fpm), while average production was 810 t/shift (890 st/shift) (Jankowski and Organiscak, 1983). The shearer and stageloader accounted for 82% of the total respirable dust generated. During the early 1990s, the range of air velocities increased from 1.0 to 7.6 m/s (195 to 1,500 fpm), while the average production increased nearly four-fold to 3,180 t/shift (3,500 st/shift) (Niewadomski, 2000). Despite increased production, the total dust contribution of the shearer and stageloader decreased to 68% as a result of improved controls. Increased ventilation, improved water spray application at the shearer, the enclosing of the stageloader and the addition of water sprays throughout the stageloader were the primary modifications that led to this reduction.

However, during the 1980s and 1990s, research also showed that shield dust was beginning to emerge as a significant contributor to airborne dust concentrations. Dust attributed to shield movement almost doubled from 12% to 23% (Colinet and Jankowski, 1997). The primary factors that have led to this increase are most likely a combination of higher production and lack of effective control technology. Higher production rates have led to increased shearer speeds, which require that shields be moved faster and in greater numbers. As shield supports are lowered and advanced, broken coal and/or rock fall from the top of the shield canopy directly into the air stream ventilating the longwall face. In addition, it has been noted that the air velocities being found on longwall faces have significantly increased. These factors combine to increase the potential for entraining greater quantities of dust during shield advance.

Successful dust control utilizes water as a primary means to suppress, direct, and/or capture respirable dust. Moisture, either as a film on the particle or as higher humidity in the airflow, increases particle adhesion (Whitehead, 1993). In continuous mining operations where water is a primary tool used to suppress dust, studies have shown that the amount of

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airborne dust is a very small percentage of that which is generated (Cheng and Zukovich, 1973; Ramani et al., 1987). These studies show that for typical run-of-mine coal, approximately 0.5% to 1.0% (by weight) of the sample consists of respirable dust (<10 μm). The studies also show that a very small percentage of this respirable dust, less than 0.4%, became airborne. A significant portion (99.6%) of the respirable dust was adhering to the oversize coal in the ROM, primarily due to the high moisture content (>10%) resulting from the quantity of water used.

Other research has studied the electrostatic charging characteristics of the coal vs. the inherent moisture content of the coal and the air-dry loss (ADL) moisture. Inherent moisture is defined as water that is chemically bound in coal or is otherwise so contained that it cannot be driven off at 100°C (212°F). ADL moisture is any moisture that can be removed through evaporation. It can come from the in situ nature of the coal (coalbed moisture), water added during mining or processing or adsorption from air humidity. The research found that both types of moisture could impact airborne respirable dust levels (Organiscak and Page, 2000; Page, 2000; Page and Organiscak, 2002).

In the same research, underground dust samples obtained in a variety of coal seams with inherent moisture contents ranging from 0.5% to 4.5% suggest that significant particle adhesion exists for the 0.5% coal, but adhesion appears to decrease for coals greater than 1.3% inherent moisture. Similar trends were observed for ADL moisture. These studies show that each coal may have its own dust charge and generation characteristics that can influence airborne dust levels. Both laboratory and underground studies showed a general trend of decreasing dust levels as electrostatic charges increase. Conversely, as moisture increases, the electric charge dissipates and dust levels begin to increase. Depending on coal type, dust levels do not begin to decrease until a specific moisture content is achieved, in some cases over 7% for some of the coals tested. This research suggests that electrostatic charges have a significant role in adhesion between particles <10 μm. Research is continuing to better define this relationship.

Dilution is another method used to control dust and often the face airflow is increased as a means to further dilute the dust generated by all sources. A minimum longwall face air velocity of 2.0 to 2.3 m/s (400 to 450 fpm) is recommended for proper dilution of dust along the face (Breuer, 1972; Foster-Miller Associates, 1982), but due to the presence of methane, higher air velocities are often required for dilution of gas. Currently, some U.S. longwall operations are using face velocities in excess of 7.6 m/s (1,500 fpm). Studies have shown (Breuer, 1972; Tomb et al., 1991) that with adequate moisture on the coal, airflow may be increased beyond 5.1 m/s (1,000 fpm), without significantly increasing the dust entrainment on the face. In these studies, the shearer and stageloader were shielded from the face airflow by physical barriers and/or water spray systems were used to increase ADL moisture and promote particle adhesion. Conversely, earlier studies (Hall, 1956; Hodkinson, 1960) showed that, for low ADL moisture coals, velocities in excess of about 2.3 m/s (450 fpm) can cause dust concentrations to rise. Dust sampling on these longwalls clearly indicates that if moisture content is adequate, increasing air velocity does not promote dust generation from controlled sources such as the shearer or stageloader.

However, the relationship between adequate moisture and dilution to control dust may not be representative of shield dust. What differentiates shield dust from shearer and stageloader dust is the mechanism of entrainment. As shields are advanced, material drops off of the shield canopy directly into the air stream, which facilitates entrainment of respirable dust. Shield spray systems that wet material on top of the shield canopy are available, but the effectiveness of these systems has not been documented.

Two factors determining the effectiveness of shield spray systems are the uniformity with which and the degree that sprays wet or add moisture to the material on the canopy. The addition of water from the shield sprays may not adequately wet the coal and may actually decrease adhesion as the electrostatic charges begin to dissipate. This can lead to higher dust levels, especially in high-velocity airstreams.

In an effort to better understand the effects of high air velocity on the entrainment associated with shield dust, a test facility capable of entraining dust in a wind tunnel was designed and constructed at the NIOSH Pittsburgh Research Laboratory. The wind tunnel enabled laboratory studies to be conducted under controlled conditions that simulated dust entrainment similar to that created by shield movement. This research was conducted to provide fundamental information on the entrainment characteristics of dust at high air velocities, which will subsequently lead to solutions for shield dust control.

Test facility

The test facility consisted of thefollowing four main components, as shown in Fig. 1: a wind tunnel, a variable speed axial vane fan, two types of dust feeders and a dust sampling station.

Wind tunnel. The tunnel provided an enclosed and controlled area in which to entrain the dust. It was constructed of 12.7-mm (1/2-in.) plywood and 50.8 x 101.6-mm (2 x 4-in.) wood framing. The dimensions of the tunnel were 0.6 x 1.2 m (2 x 4 ft), providing an area of 0.7 m^2 (8 sq ft). The length of the wind tunnel was 12.2 m (40 ft) with a 1.5-m (5-ft) long evasé at the open end to reduce head loss and turbulence as air entered the tunnel. The interior of the tunnel was waterproof painted, and all seams were sealed with caulking. A clean-out was provided in the tunnel to wash accumulated dust from the interior surface with water after each test. Two observation windows were built into the tunnel at the material dump point and at the sampling station to observe conditions during testing.

Variable speed axial vane fan. The 0.6-m- (2-ft-) diameter fan provided a means to adjust air velocity in the tunnel. Air velocity was controlled with a 29.7-kW (40-hp) Joy axial vane fan capable of producing air velocities in the tunnel in excess of 10.2 m/s (2,000 fpm). This was coupled with an Allen-Bradley variable-speed controller to adjust fan rpm as needed. A 1.2-m- (4-ft-) long reducer duct between the tunnel and fan was used to transition the round fan opening to the rectangular tunnel; this served to reduce shock loss and turbulence on the intake side of the fan. The exhaust side of the fan was connected by duct to a bag house (not shown) that filtered the dust from the air for environmental reasons.

Material feeders. Two types of feeders were used in this study. The Eriez Model FBV-513 vibratory material feeder provided a controlled means to introduce the material (dust and coarser coal) into the tunnel for each test. The unit was positioned on top of the tunnel as shown in Fig. 1. It was equipped with a 0.12-m^3 (4-cu ft) hopper and dual controls to adjust vibration and feed rate. The original pan was retrofitted

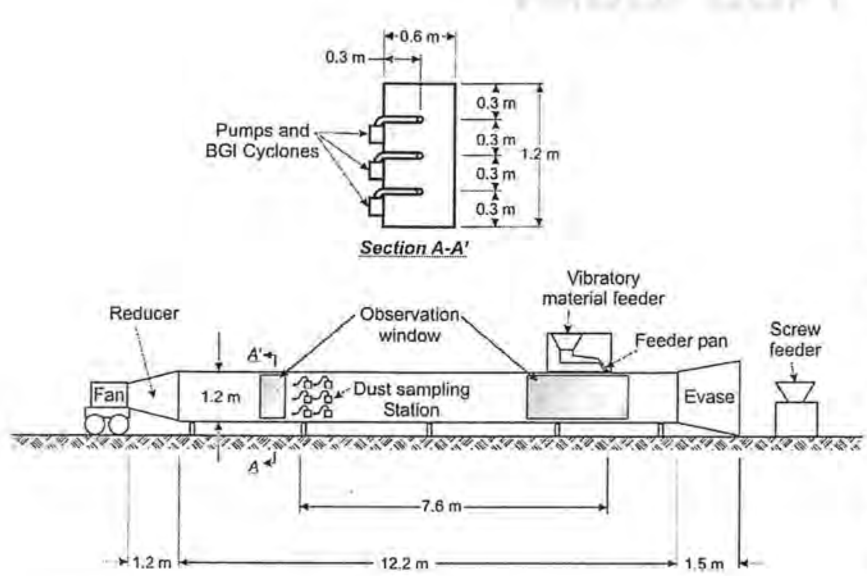

Figure 1 — Schematic of dust entrainment test facility.

with a 560-mm- (22-in.-) wide feeder pan that distributed the material across the entire width of the tunnel. The second feeder, a Vibra Screw Model SCR-20 screw feeder was used to introduce only dust into the tunnel. The unit was positioned to inject dust at the opening of the evase, as shown in Fig. 1. It was equipped with a 12.7-mm. (1/2-in.-) diameter stainless steel screw feed and a 0.04-m^3 (1.5-cu ft) hopper. Compressed air with a mini-eductor operated at 206.8 kPa (30 psi) was used to inject the dust into the air stream.

Dust-sampling station. The sampling station provided a means to collect dust samples for each test. Dust samples were collected using SKC sampling pumps and BGI GK2.69 cyclone samplers through three ports located in the sides of tunnel. Sampling probes were inserted into each port, which allowed the sampling pumps and cyclones to be located on the outside of the tunnel. The distance between the material dump point and the location of the downstream sampling probes was 7.6 m (25 ft), as shown in Fig. 1.

Sampling method

The BGI GK2.69 cyclone sampler combined with isokinetic sampling was used to measure respirable dust concentrations in the tunnel. The sampling pumps are run at 4.2 L/m and the resulting respirable D_{50} cut point of 4 μm and size distribution curve are similar to that of the Dorr-Oliver cyclone run at 2.0 L/m. The primary attribute of this instrument is its capability of gathering sufficient mass on the filter for short duration sampling. The respirable sample is collected on a 37-mm PVC filter.

Another favorable characteristic of the BGI sampler is the design of the intake port, which allows tubing to be attached for isokinetic sampling. Isokinetic sampling is a method by which dust-laden air is drawn into a sampling nozzle at a velocity equal to the velocity of the air being sampled (Brockmann, 1993; Quilliam, 1994). The nozzle diameter required to match the velocity in the wind tunnel is a function of the sampling pump air volume. Pumps were operated at 4.2 L/m, and tests were performed at five velocities — 2.0, 4.1, 6.1, 8.1 and 10.1 m/s (400, 800, 1,200, 1,600 and 2,000 fpm).

To match these velocities, nozzle diameters of 6.7, 4.7, 3.8, 3.3 and 3.0 mm (0.261, 0.184, 0.151, 0.130 and 0.117 in.), respectively, were used. Figure 1 inset shows a cross-sectional view of the arrangement of isokinetic probes in the tunnel. Three probes were placed on 0.3-m (1-ft) spacings in relation to each other and the sides of the tunnel. The use of a three-point sampling grid to calculate an average concentration over the area of the tunnel minimized the variation in dust levels that could occur due to dust gradients in the tunnel.

Fan settings at the five selected air velocities were established using a pitot tube and manometer through a cross-sectional traverse. Settings were established by averaging the velocity over 16 quadrants within the tunnel. Air-velocity profile measurements were conducted at the sampling station to determine fan settings for the test velocities. According to Guffey and Booth (1999), velocity measurements should be made at least 7.5 duct diameters away from any major upstream disturbances, in this case the material dump point. The distance between the material dump point and the sampling station is 7.6 m (25 ft), which is approximately 7.5 duct diameters for a round duct of equivalent area of 0.7 m^2 (8 sq ft). It is important that turbulent flow exits to ensure a satisfactory dispersion and removal of dust (Hartman, 1961). The critical velocity for this tunnel was calculated and the test velocities exceed the velocity necessary for turbulent flow.

Summary of previous research

Previous research by NIOSH, which reported the entrainment of dust as a function of air velocity, was presented in a paper by Listak et al. (2001). The test apparatus was the same as that in Fig. 1, with the only difference being that Marple cascade impactors were used as the primary sampling instrument. The two objectives of these tests, as they relate to air velocity, were to study the entrainment characteristics of both total dust (< 50 μm) and respirable dust (< 10 μm) and to study the change in dust concentration and size distribution of the dust. The studies showed that both total and respirable dust concentrations increased as air velocity increased in a linear relationship, indicating that particle entrainment was greater than dilution effects. Total dust concentration increased from 18.6 mg/m^3 at 2.0 m/s (400 fpm) to 117.1 mg/m^3 at 8.1 m/s (1,600 fpm). Similarly, respirable dust concentrations increased from 1.47 mg/m^3 at 2.0 m/s (400 fpm) to 19.84 mg/m^3 at 8.1 m/s (1600 fpm). Statistical analysis of the concentrations measured at each velocity resulted in significant differences at a 95% confidence interval.

Analysis of the size distribution of the sampled dust showed an inverse relationship between velocity and mass median diameter of the dust. As velocity increased, the mass median diameter of the entrained dust particles decreased in a near linear manner. The mass median diameter was found to be 10.8 μm at 2.0 m/s (400 fpm) and decreased to 7.7 μm at 8.1 m/s (1,600 fpm). Higher concentrations and finer particle size distributions suggest that at a moisture content of approximately 1%, a portion of the dust particles were adhering to each other at the 2.0 m/s (400 fpm) velocity. As the velocity increases, the adhering forces are overcome by the increased energy supplied to the system, resulting in higher concentrations and smaller particle sizes in the air stream. Although the particle size decreased with increased velocity, dilution was not observed in any of the tests.

In summary, the tests showed that adhesion of respirable dust to larger material and to other respirable particles plays an important role in dilution (or as shown in this study, the lack of dilution) as the air velocity increases.

Table 1 — Mix proportions used in tests.

Sample*	9.5 to 4.75 mm (0.37 to 0.18 in.) weight, kg (lbs)	4.75 to 1.18 mm (0.18 to 0.05 in.) weight, kg (lbs)	Mineral black weight, kg (lbs)	Respirable Dust in sample, kg (lbs)	Respirable dust in sample, %
1	8.6 (19)	8.6 (19)	0.9 (2.0)	0.6 (1.3)	3.3
2	8.0 (17.5)	8.0 (17.5)	2.2 (5)	1.4 (3.3)	8.2
3	6.8 (15)	6.8 (15)	4.6 (10)	3.0 (6.5)	16.1
4	4.5 (10)	4.5 (10)	9.2 (20)	6.0 (13.0)	32.5

*The total weight for each sample was 18.2 kg (40 lbs).

Table 2 — Respirable dust concentrations for mixed feed at both test velocities.

Percent respirable in sample	Average respirable concentration, mg/m³ 4 tests at 2.0 m/s (400 fpm)				Mean	Standard deviation	95% confidence interval
3.3	0.91	0.69	0.63	0.29	0.63	0.25	0.40
8.2	0.96	1.06	0.85	0.43	0.82	0.28	0.44
16.1	2.53	2.48	2.91	1.91	2.46	0.41	0.66
32.5	2.52	3.56	2.73	2.07	2.72	0.62	0.99
Percent respirable in sample	**Average respirable concentration, mg/m³ 4 tests at 8.1 m/s (1600 fpm)**				**Mean**	**Standard deviation**	**95% confidence interval**
3.3	3.85	2.79	2.44	2.88	2.99	0.60	0.96
8.2	7.48	8.35	5.89	5.11	6.71	1.47	2.34
16.1	13.43	12.05	12.13	13.33	12.74	0.75	1.19
32.5	22.26	22.26	23.81	20.98	22.33	1.16	1.84

Sampling protocol to study entrainment and dilution. Based on the results from the previous research, a new set of tests was designed to further study entrainment and dilution in the wind tunnel. This was achieved through a series of tests that introduced dust into the tunnel by two different methods to evaluate particle adhesion with respect to velocity.

The first method of introducing dust into the tunnel used the Eriez Model FBV-513 vibratory material feeder. As in previous research (Listak et al., 2001), the feeder was used to drop a prepared mix of fine and coarse particles that simulates material accumulating on the canopies of the shields. This series of tests was designed to represent the coarser debris and respirable dust that falls into the air stream and becomes entrained as face supports are advanced. The feed material consisted of coarser crushed coal and respirable coal dust in the form of Keystone Mineral Black 325BA. Keystone Mineral Black 325BA is a commercially available material, manufactured by Keystone Filler and Manufacturing Company. The physical properties of this material are consistent, having a maximum particle size of 50 μm, 65% of which is <10 μm and a moisture content of <1%. The air-dry loss moisture on the feed samples, coarse and fine material, was also <1%.

Table 1 shows the mix weights of the four different feed samples used in the tests that were designed to study air velocity effects on changing amounts of respirable dust in the sample. Therefore, the percentage of respirable dust in the feed material was reduced in successive tests. However, assuming that the size distribution of material on top of the support canopy and ROM coal are similar, the percentages of respirable dust in these tests are still much higher than in actual mining conditions. There are two reasons for this: First, the sampling time for these tests was 30 min, so high percentages of respirable dust had to be introduced into the tunnel to yield sufficient weight gains on the filters. Second, by starting with a high percentage of respirable dust in the sample (32.5%) and reducing this by half in consecutive tests, a wide range of size distributions was available to study general trends related to entrainment. As in earlier tests by Listak et al., test duration was 30 minutes for consistency in calculating and comparing concentrations.

The second method of dust introduction used only the mineral black using the Vibra Screw Model SCR-20 screw feeder and a compressed air-eductor with an injection nozzle. The dust passed from the screw feeder into a compressed air-eductor, causing particle separation and thereby minimizing adhesion between respirable particles. This method is similar to dust introduction methods used in the NIOSH full-scale longwall facility (Rider et al., 2001), which is designed to simulate shearer-generated dust. The time duration of each test was kept consistent at 15 minutes. At a feed rate of 0.27 g/s (0.035 lb/min), approximately 240 g (0.53 lbs) of mineral black was introduced into the tunnel. Sixty-five percent of this weight is respirable dust (<10 μm), approximately 144 g (0.31 lbs).

Test velocities and the number of individual tests varied depending on the introduction method used. For tests using the vibratory feeder, only the two end-point velocities were selected — 2.0 and 8.1 m/s (400 and 1,600 fpm), the reason being that initial tests by Listak et al. found that the entrainment curves were linear. Four tests were run at each velocity for each of the four sample types shown in Table 1, for a total of 32 tests. For the tests using the screw feeder and eductor, all five velocities listed above were selected. Six tests at each velocity were conducted at two different humidity levels, resulting in a total of 60 tests.

Data analysis and results

Vibratory feeder respirable dust and coarse material mix. Table 2 shows the results for the first series of tests using the vibratory feeder. The table indicates the respirable dust concentrations for each of the four tests conducted at 2.0 m/s (400 fpm) and 8.1 m/s (1,600 fpm). The table also shows the mean and standard deviation of the concentrations, and the 95% confidence interval using a t-distribution.

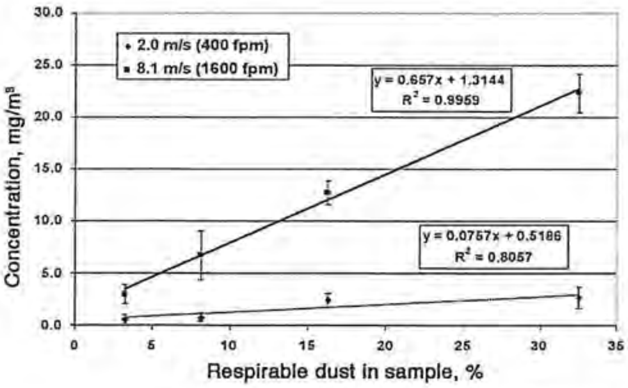

Figure 2 — Dust concentration at the two test facilities vs. the percentage of respirable dust in the sample.

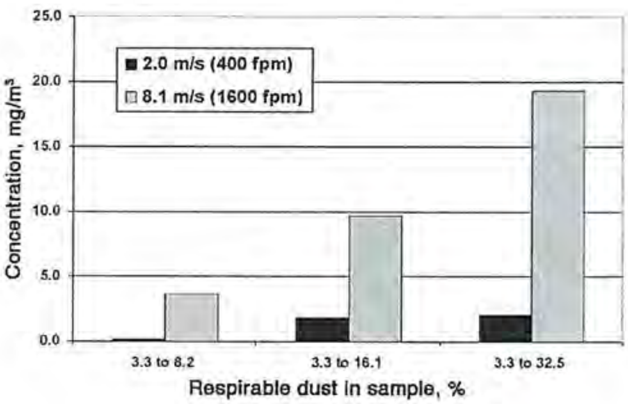

Figure 3 — Increase in respirable dust concentrations using 3.3% respirable content as the baseline.

The data in Table 2 clearly show that increasing the percentage of respirable dust in the sample also causes the concentration to increase for the two test velocities. Figure 2 plots these data showing the mean and the 95% confidence interval for the respirable dust at the two test velocities vs. the percentage of respirable dust in the sample. The graphs show the effects of velocity on the entrainment of respirable dust as the percentage of dust in the feed material was changed. At 2.0 m/s (400 fpm) the average concentration increased from 0.63 to 2.72 mg/m^3 when the respirable portion of the feed material changed from 3.3% to 32.5%, respectively. The same relationship is quite dramatic at 8.1 m/s (1,600 fpm) as concentrations rise from 2.99 to 22.33 mg/m^3. Becasue dust concentration is a function of mass and air quantity, increasing air velocity would increase air volume in the test structure and should dilute the dust cloud and result in lower concentrations for a constant dust feed. However, in this case the higher velocity resulted in higher dust concentrations regardless of the percentage of respirable dust in the sample. The adhesion of respirable particles to larger material, and respirable particles to each other, affects the entrainment, transport and deposition of dust. These tests indicate that, as the air velocity increases the higher energy overcomes the forces of adhesion, negating the effects of dilution and resulting in the entrainment of more dust. Increasing the percentage of respirable dust in the sample and increasing velocity results in increased dust concentration. Again, these results were obtained with a dust mixture consisting of less than 1% ADL moisture.

As stated above, the percentage of respirable dust in the sample for these tests was much higher than in actual mining conditions (ROM). This was to achieve sufficient filter weight gains for the short sampling time and also to provide enough respirable dust to study general trends related to adhesion and dilution at low versus high velocities. In Fig. 2, the two graphs begin to converge as the percentage of respirable dust in the sample is reduced. Based on this, the data suggest that if tests were conducted at the lower range of respirable in ROM coal (between 0.5% and 1.0% of the sample by weight) similar trends would be observed. Also, the concentrations values for the 32.5% respirable dust samples were very similar to concentration values in a previous test by Listak et al., as shown in Table 4. Sampling with the BGI cyclone resulted in concentrations of 2.72 and 22.23 mg/m^3 at 2.0 m/s (400 fpm) and 8.1 m/s (1,600 fpm), respectively. Impactor sampling gave concentrations of 1.47 and 19.84 mg/m^3 at 2.0 m/s (400 fpm) and 8.1 m/s (1,600 fpm), respectively, showing that the two sampling methods produced similar results.

Figure 2 also suggests, based on the slope of the two lines, that as respirable content is increased, the entrainment capacity at 8.1 m/s (1,600 fpm) is much greater than 2.0 m/s (400 fpm). Figure 3 shows the increase in respirable dust concentration using the 3.3% respirable content as the baseline. The 8.1-m/s (1,600-fpm) chart shows a near linear increase, suggesting the dust entrainment capacity at this velocity (or air volume) has not been reached. The 2.0-m/s (400-fpm) chart shows that this capacity was reached at 16.1% respirable in the sample, as there is very little increase in concentration from 16.1% to 32.5%. The data indicate that particle adhesion is greater than the energy at 2.0 m/s (400 fpm) and has most likely reached the limit of entrainment for the velocities tested and percentage of respirable dust in the sample.

Screw feeder/eductor — respirable dust only. Based on these tests, it was suspected that dust particles being separated as they fell into the air stream was leading to higher concentrations in the tunnel rather than dilution. Because dilution was not being observed in the tunnel, a series of baseline or control tests was necessary to determine if dilution would occur as velocity was increased. In this series of tests, the Keystone Mineral Black 325BA passed from the screw feeder into the compressed air-eductor operated at 206.8 kPa (30 psi), then through an injection nozzle before being introduced into the tunnel. This system provided a high-velocity jet that likely separated particles, thereby reducing particle adhesion. This approach is similar to dust introduction methods used in the NIOSH full-scale longwall facility (Rider et al., 2001), which is designed to simulate shearer-generated dust. Tests were conducted between 2.0 m/s (400 fpm) and 10.5 m/s (2,000 fpm) at 2.0-m/s (400-fpm) intervals. In the large bay that houses the wind tunnel, the seasonal weather results in changes in the relative humidity. In the winter months, relative humidity is low, but increases in the summer months. During shakedown tests, it appeared that the humidity impacted the airborne dust levels in the tunnel. As a result, tests were conducted at two different relative humidity ranges — 30% to 35% and 15% to 18%.

Table 3 gives the results of the tests and shows the mean and standard deviation of the concentrations, with a 95% confidence interval using a t-distribution. The data in the table show that as velocity increases, the concentrations decrease.

Table 3 — Respirable dust concentration for the five test velocities and two humidity ranges.

Velocity m/s (fpm)	Average respirable concentration, mg/m³ 6 tests at 30% to 35% relative humidity						Mean	Standard deviation	95% confidence interval
2.0 (400)	15.64	14.98	15.23	15.47	16.68	12.38	15.06	1.44	1.51
4.1 (800)	9.19	10.14	9.83	10.93	11.93	9.04	10.18	1.10	1.15
6.1 (1,200)	6.73	5.93	6.72	7.72	7.28	5.41	6.63	0.85	0.89
8.1 (1,600)	6.01	6.16	5.12	6.02	7.04	4.12	5.75	1.00	1.05
10.1 (2,000)	2.67	3.27	3.44	2.78	3.33	3.09	3.10	0.31	0.33

Velocity m/s (fpm)	Average respirable concentration, mg/m³ 6 tests at 15% to 18% relative humidity						Mean	Standard deviation	95% confidence interval
2.0 (400)	13.87	13.27	10.52	11.38	11.11	9.92	11.68	1.56	1.64
4.1 (800)	7.15	7.30	6.79	6.91	7.23	9.04	7.40	0.83	0.87
6.1 (1,200)	5.14	4.54	5.37	4.81	5.87	4.92	5.11	0.47	0.49
8.1 (1,600)	4.12	3.12	3.14	4.27	3.74	3.69	3.68	0.48	0.50
10.1 (2,000)	3.09	2.34	2.69	2.73	2.47	2.75	2.68	0.26	0.27

Figure 4 plots the concentrations showing the mean and the 95% confidence interval for the respirable dust at each test velocity and the two different relative humidity ranges. The graphs clearly show two trends: dilution results when respirable particles are introduced into the air stream in a manner that reduces particle adhesion and higher relative humidity results in higher dust concentrations.

As discussed above, electrostatic charge and moisture appear to play an important role in airborne respirable dust levels. Page and Organiscak (2002) showed, in both laboratory and underground studies, the basic relationship of electrostatic charge, i.e., that dust levels decrease as electrostatic charges increase. However, as ADL moisture increases, the electric charge dissipates and dust levels begin to increase initially. Dust levels do not begin to decrease until a specific moisture content is achieved (some cases >7%). Figure 4 supports this observation, with ADL moisture represented as relative humidity in the air. The higher relative humidity levels produced increased dust concentration at all test velocities. It is hypothesized that the higher humidity helps to dissipate electrostatic charge, reducing particle adhesion and thus leading to higher dust levels.

Note that the two curves in Fig. 4 are not linear. The data indicate that when the amount of dust is kept constant (as in these tests) the capacity of dilution to lower dust concentration begins to diminish as the velocity increases. This relationship suggests that even though the dust is being introduced in a manner to reduce particle adhesion, the higher-velocity air may still be promoting particle separation, overcoming the favorable effects of the increased air volume.

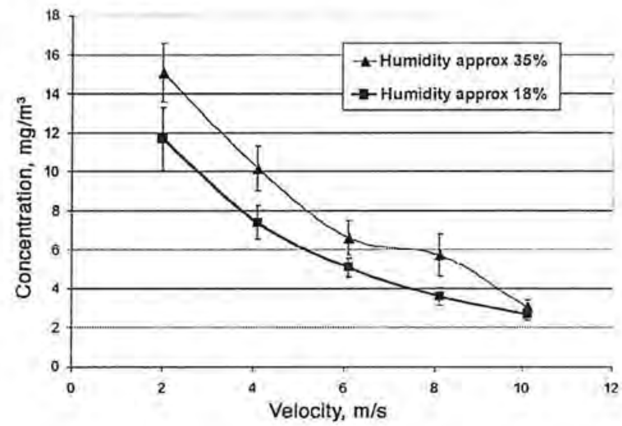

Figure 4 — Dust concentrations at the five test velocities and two relative humidity ranges.

Discussion

The section "Summary of previous research" reviewed tests conducted by Listak et al. (2001), where the sampling was conducted with impactors. Also, the test samples were all the same mixtures of coarse and fine material as that in Sample 4 in Table 1, containing 32.5% respirable dust. The mix was dropped into the tunnel using the Eriez Model FBV-513 vibratory material feeder. The studies showed that the respirable dust concentrations increased as air velocity increased in a near linear relationship, indicating that particle entrainment was greater than dilution effects for these tests. Table 4 shows the respirable dust concentrations at the four velocities for the tests reported by Listak et al. (2001). The concentrations for the high and low humidity mean values from the current tests in Table 3 were averaged and included in Table 4 for comparison.

Figure 5 graphs the respirable dust concentrations in Table 4. It needs to be noted that the data being compared in these graphs resulted from different methods of introducing the dust, as well as different amounts of respirable dust in the feed. However, the results of these tests show a potential trend. Where the curves intersect, dust concentrations from the mixed dust that is dropped into the tunnel increase rapidly and outweigh the favorable effects of dilution represented by dust injected into the tunnel. The data suggest that there may be a velocity where airborne dust concentrations from material that falls into the air stream, as is the case with shield dust, are kept to a minimum and yet still maintain a beneficial level for diluting dust from controlled sources such as the shearer and stageloader. The results of these tests indicate that this velocity may be approximately 4.6 m/s (900 fpm) for coal with low moisture contents. If there were a critical air velocity, as the trends in these curves indicate, more data would have to obtained under controlled conditions to determine its value.

Table 4 — Comparison of tests by two different feed methods.

Velocity, m/s (fpm)	Respirable dust concentration, mg³ Tests by Listak et al., respirable dust 32.5% of sample	Average of humidity tests from Table 3
2.0 (400)	1.47	13.37
4.1 (800)	5.65	8.79
6.1 (1,200)	12.95	5.87
8.1 (1,600)	19.84	4.68

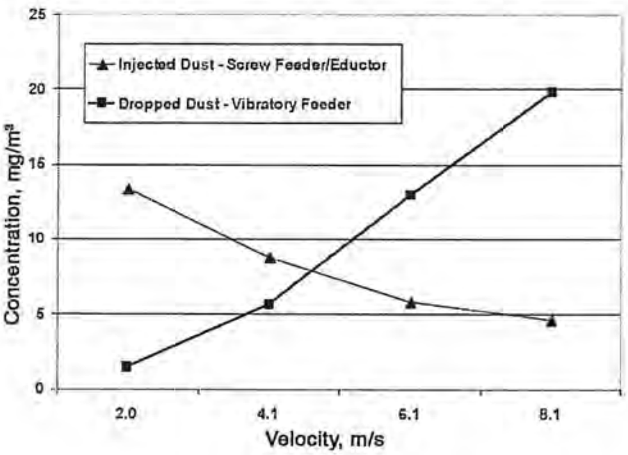

Figure 5 — Comparison of different feed methods and the impact of velocity on dust concentrations.

Summary

Substantial gains in longwall production levels have occurred and longwall operators have increased the levels of air and water applied in an effort to control dust generation and worker exposure. Research and application of control technologies have focused on the shearer and stageloader/crusher, which were the two highest sources of respirable dust as characterized by a U.S. Bureau of Mines study in the 1980s (Jankowski and Organiscak, 1983). A similar study by the U.S. Bureau of Mines in the 1990s (Colinet and Jankowski, 1997) indicated that dust liberation during shield movement has emerged as a significant contributor to dust generation on longwalls. As shields are advanced, material drops off of the shield canopy directly into the air stream, which facilitates entrainment of dust into the air stream. Higher production levels have resulted in faster shield advance, greater numbers of shields being moved, and air velocity increases. These factors combine to elevate the dust problems associated with shield advance.

Results from the laboratory tests at NIOSH indicate that increased air velocities have the potential to raise the level of airborne respirable dust liberated by shield advance. Tests were conducted with varying percentages of respirable dust in the feed material. For both test velocities (2.1 m/s and 8.1 m/s), regardless of the percentage of respirable dust in the test samples, increases in air velocity still resulted in higher levels of respirable dust. It is important to note that these results were obtained with dry dust (<1% ADL) dropped directly into the air stream without any method of dust control in use. Dilution or decreasing levels of airborne respirable dust were achieved with increasing air velocity only when the dust was introduced with the screw feeder/eductor to minimize particle adhesion.

These tests suggest that dust levels are influenced by a relationship between electrostatic charge and moisture. With ADL moisture represented as relative humidity in the air, the higher relative humidity levels produced increased dust concentration at all test velocities. It is hypothesized that the higher humidity helps dissipate electrostatic charge, reducing the potential for particle adhesion and thus leading to higher dust levels. Both series of tests suggest that particle adhesion, moisture content, air velocity and exposure to the ventilating air stream interact to determine the concentration of the respirable dust that becomes airborne. It appears that increased air velocities have the potential to entrain greater quantities of respirable dust during shield advance, when the crushed material on top of the canopy has a low ADL moisture. To further study this relationship, future tests will evaluate the effects of increased moisture on dust concentration.

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