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Thoracic Dust Exposures on Longwall and Continuous Mining Sections

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Past data on the prevalence of symptoms of chronic bronchitis and decreases in pulmonary function indicate a potential problem due to deposition of coal mine dust in the bronchial airways. Difficulty with dust control in certain jobs indicates that chronic bronchitis may continue to be a problem.

Compliance with the respirable dust standard does not equally limit the thoracic dust exposure of all miners. Coal mine dust size distributions indicate that thoracic dust levels may be as high as five times respirable dust levels in some work areas on continuous mining sections and seven times respirable dust levels in some work areas on longwall mining sections. The largest thoracic dust generating sources are the longwall shearer, shield support advancement, and the continuous miner. The worst case scenario for thoracic dust exposure occurs on bidirectional cutting longwall mining sections where some mine personnel are very likely to work downwind of the shearer and/or support advancement for a significant portion of the shift. Continuous miner operators who are not utilizing remote control and roof bolter operators working downwind of the continuous miner may also be exposed to relatively high concentrations of thoracic dust.

Future thoracic dust control techniques will differ from respirable dust control techniques by paying more attention to the > 5 μm particles present in the airstream. Potts, J.D.; McCawley, M.A.; Jankowski, R.A.: Thoracic Dust Exposures on Longwall and Continuous Mining Sections. Appl. Occup. Environ. Hyg. 5:440–447; 1990.

Introduction

Coal miners are known to suffer from a higher incidence of bronchitic symptoms (cough and sputum production) and a lower mean forced expiratory volume (FEV_1) than comparable populations of nonminers.[1,2] Previously, researchers argued that these symptoms could be attributed to the miners' smoking habits. However, a recent survey[2] of British coal miners showed that the incidence of both conditions in nonsmokers with intermediate and high respirable dust exposure (174 and 348 gh/m^3, respectively) approached the incidence of smokers with hypothetical zero dust exposure. Reduced pulmonary function is of particular importance[3] because it is strongly correlated to an increased risk of death from chronic obstructive pulmonary disease.

Bronchitic symptoms[3] most commonly arise from changes in the large airways of the bronchial tree, whereas reductions in pulmonary function arise from changes in the small airways. Previous work[4] indicated that the mass fraction of dust that penetrates beyond the larynx (thoracic mass fraction) and deposits primarily in the bronchial airways of the respiratory tract may be as much as 4–5 times the respirable mass fraction. Since bronchitis and reduced pulmonary function both originate in the bronchial airways, dust deposition in that region may be associated with these conditions.

The objective of this study was to determine whether compliance with the respirable dust standard equally limits the thoracic dust exposure of all miners. This objective was accomplished by measuring the size distributions of dusts on longwall and continuous mining sections. Size distribution data and the American Conference of Governmental Industrial Hygienists (ACGIH) definitions of respirable and thoracic dust were then used to determine the thoracic/respirable dust ratio at each sampling location.

Sampling Equipment and Data Analysis for Mine Surveys

Andersen Model 298 (eight-stage) personal cascade impactors and DuPont P-2500B pumps were used to collect dust samples at various locations on longwall and continuous mining sections. Impactors were selected because they fractionate airborne dust by aerodynamic diameter, which is directly related[5] to the deposition of dust in specific regions of the respiratory tract. A sampling flow rate of 2 L/min was used in all tests. Cut-point diameters[6] for each impactor stage are shown in Table I. DuPont pumps were selected because they provide a constant flow rate, independent of battery voltage and pressure drop across the sampler. All pumps were calibrated with a Kurz 541S flow meter (accuracy ± 2%) before each dust survey. Dust samples were collected on Mylar substrates, which were coated with Dow Corning 316 silicone release spray to prevent[6] particle bounce. Polyvinyl chloride media

TABLE I. Impactor Stage Information for Andersen Model 298 Personal Cascade Impactor at a Sampling Flow Rate of 2 L/min

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Final Filter
Cut-point diameters	21.3	14.8	9.8	6.0	3.5	1.55	0.93	0.52	0.0
Correction factors	0.52	0.61	0.78	0.89	0.95	0.96	0.97	0.99	1.0
Thoracic fraction	0.005	0.084	0.32	0.71	0.96	1.0	1.0	1.0	1.0
Respirable fraction	0	0	0	0.029	0.24	0.77	1.0	1.0	1.0

with a 5-μm pore size was used for the final filters. All substrates and filters were vacuum dried immediately before weighing. A Mettler M3 balance (accuracy ± 0.011 mg) was used to weigh the samples. Correction factors for sampling efficiency and internal loss[6] for each impactor stage are shown in Table I. The corrected mass on each stage was calculated by dividing the measured mass on the stage by the correction factor for that stage. In this report, the terminology "total dust" represents the summation of the corrected masses on the impactor stages and final filter. Reference to specific products and the ACGIH criteria does not imply endorsement by the Bureau of Mines or the National Institute for Occupational Safety and Health (NIOSH).

Cascade impactor data and the ACGIH definitions[7] of the respirable and thoracic mass fractions were used to calculate[8] the respirable and thoracic exposures at each sampling location. The respirable mass fraction represents those particles penetrating beyond the terminal bronchioles with a collection efficiency described by a cumulative lognormal function, with a median aerodynamic diameter of 3.5 μm (± 0.3 μm) and a geometric standard deviation of 1.5 μm (± 0.1 μm). The thoracic mass fraction represents those particles penetrating beyond the larynx with a collection efficiency described by a cumulative lognormal function, with a median aerodynamic of 10 μm (± 1.0 μm) and a geometric standard deviation of 1.5 μm (± 0.1 μm). The respirable and thoracic mass fractions on each impactor stage were calculated using a procedure[8] based on Simpson's rule. Using this rule, the average thoracic fraction for each stage is:

$$TF = \frac{TF_{LL} + 4(TF_{MP}) + TF_{UL}}{6}$$

where: TF = the average thoracic fraction for the stage
TF_{LL} = the thoracic fraction at the stage lower size limit (cut-point of the stage)
TF_{UL} = the thoracic fraction at the stage upper size limit (cut-point of the previous stage)
TF_{MP} = the thoracic fraction of the stage midpoint size

The values TF_{LL}, TF_{MP}, and TF_{UL} were all interpolated[7] from the thoracic dust criteria curve. Respirable fractions were calculated using the same procedures. Average thoracic and respirable fractions for each impactor stage are shown in Table I. The thoracic mass fraction on each stage was then calculated by multiplying the average thoracic fraction for the stage (TF) by the total mass collected on the stage. The respirable mass fraction was calculated using the same procedure.

This study and several previous studies[4,5] have observed multimodal dust size distributions in the underground mine environment. Mass frequency plots were preferred to log-probability plots because mass frequency plots are better suited for modeling multimodal distributions. A maximum diameter of 50 μm was used for the first impactor stage and a minimum diameter of 0.25 μm was used for the final filter because these values were recommended in the instruction manual provided with the impactors. Cumulative size distribution plots were used to determine the mass median aerodynamic diameters of the dust samples. All particle diameters presented in this article are aerodynamic equivalent diameters, unless otherwise noted.

Sampling Procedures

Dust surveys were conducted on three longwall and three continuous mining sections. Three to five sampling days were devoted to each survey. The longwall mining dust sources isolated for this study included the intake airway, beltway, stageloader/crusher (crusher), supports, and shearer. Dust concentrations in the intake airway and beltway were averaged over the entire sampling period. Crusher, support, and shearer dust contributions were adjusted for downtime. The continuous mine sampling plan was designed to isolate the intake airway, feeder/breaker area, shuttle car loading, continuous miner, and roof bolting machine. Dust concentrations in the feeder/breaker area were averaged over the entire sampling period. Shuttle car loading, miner, and bolter dust contributions were adjusted for downtime. A sampling time was selected[9] for each location to prevent substrate overloading and underloading.

Figure 1 shows the dust sampling locations on the longwall mining sections. Two impactors were used at each location and approximately three sets of data were collected at each longwall mine. Impactors were placed in the intake airway (location 1) and beltway (location 2), and air direction and velocity were measured at both locations with a hand-held vane anemometer. Velocities were measured using the continuous-traversing technique. The air flow and impactor data collected at locations 1 and 2 were used to determine the quality of air upwind of the crusher. Impactors placed downwind of the crusher (location 3) and data collected at locations 1 and 2 were used to isolate crusher-generated dust. Mobile impactors were kept immediately upwind (location 4) and downwind (location 5) of the shieldmen to isolate support-generated

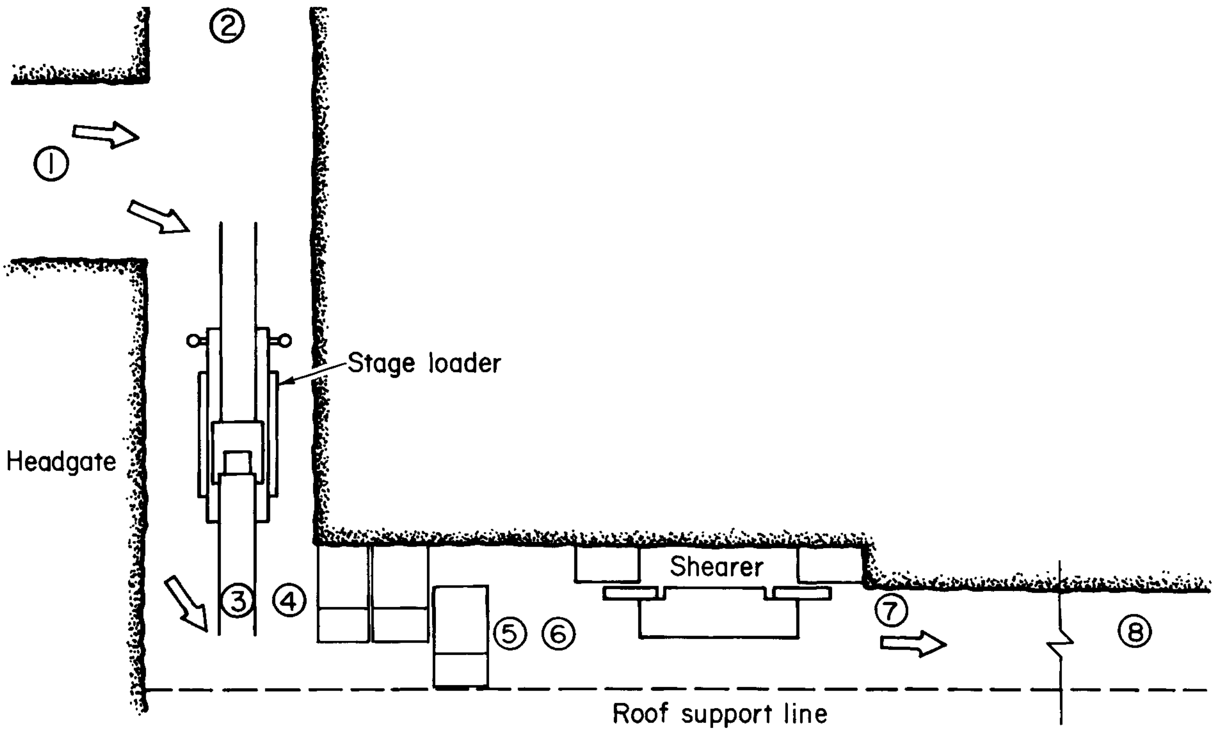

FIGURE 1. Dust sampling locations on the longwall mining sections.

dust. Mobile impactors were kept 9.1 m (30 ft) upwind (location 6) and downwind (location 7) of the shearer to isolate shearer-generated dust. Finally, impactors were used to measure tailgate area (location 8) dust levels.

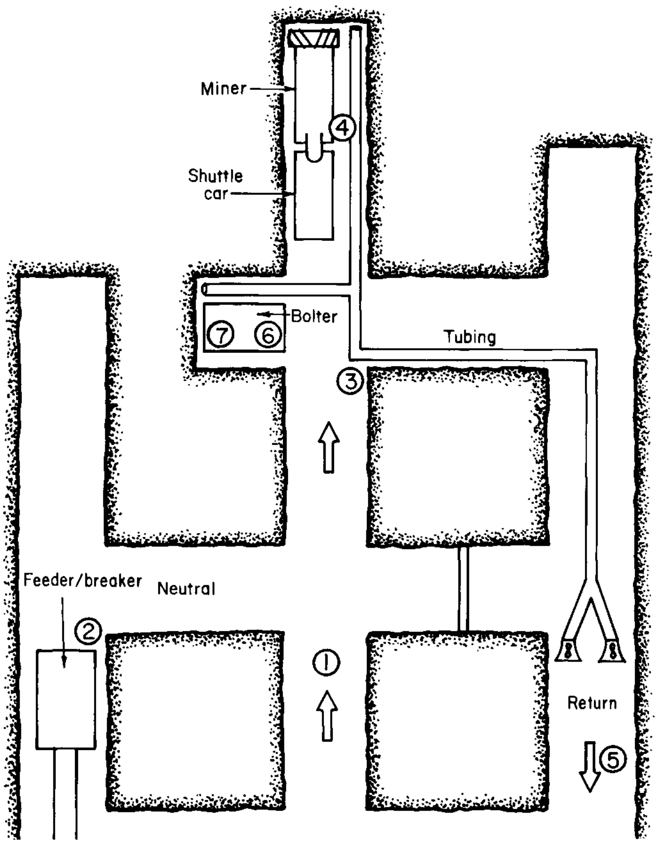

FIGURE 2. Dust sampling locations on the continuous mining sections.

Figure 2 shows the dust sampling locations on the two continuous mining sections using exhausting face ventilation. Similar sampling locations were used on the blowing face. Two impactors were used at each location and approximately three sets of data were collected on each continuous mining section. Impactors were placed in the intake airway (location 1), feeder/breaker area (location 2), and immediately upwind of the shuttle car loading area (location 3). Impactors placed in the miner cab (location 4) and location 3 were used to isolate dust generated during shuttle car loading. Impactors placed in the return airway (location 5) and location 3 were used to isolate total miner-generated dust. Impactors placed on the intake side (location 6) and return side (location 7) of the bolter were used to isolate bolter-generated dust. Shuttle cars on the blowing face section were also equipped with impactors.

Results of Longwall Mine Surveys

Mine 1 used a bidirectional cut sequence on a 2.4 m (8 ft) by 180 m (600 ft) coal face. Face air velocities averaged 1.7 m/s (340 fpm). Mine 2 used a unidirectional (head-to-tail) cut sequence on a 2.4-m (8-ft) by 190-m (630-ft) coal face. Face air velocities at mine 2 averaged 1.3 m/s (250 fpm). Mine 3 used a unidirectional (tail-to-head) cut sequence on a 2.1-m (7-ft) by 180-m (600-ft) coal face. Face air velocities at mine 3 averaged 1.3 m/s (250 fpm). All mines used a double-drum shearer and two-legged shields.

The shearer was the largest source of thoracic dust on each of the sections surveyed. Shearer cutting generated between 28 and 84 mg/m^3 of thoracic dust and accounted for 75 percent of the total thoracic dust generated on the sections employing unidirectional cuts. A bidirectional cut sequence and manual roof support advancement represents the worst case scenario for thoracic dust exposure because personnel are required downwind of the shearer. Supports were also a significant source of dust. Support advancement generated between 13 and 16 mg/m^3 of thoracic dust and accounted for 22 percent of the total thoracic dust generated on the sections employing unidirectional cuts. This statistic is important for both unidirectional and bidirectional cutting sections because personnel are required downwind of support advancement in both cases. The crusher generated between 1 and 2 mg/m^3 of thoracic dust and accounted for less than 3 percent of the total thoracic dust generated on the unidirectional sections.

The particle size distribution of airborne dust influences the mass of dust that deposits in a particular region of the respiratory tract. A number of factors affect the particle size distribution to which a miner is exposed, including source dust characteristics, rates of deposition, air velocity, and distance from the source(s). Reentrainment of deposited dust may also affect the particle size distribution of airborne dust(10) at velocities greater than 2.5 m/s (500 fpm). However, velocities above 2.5 m/s (500 fpm) are uncommon on longwall mining sections.

Longwall dust sources had a dramatic effect on the particle size distributions measured at various locations on the sections. Each dust source had an associated particle size distribution that remained quite consistent for all sections surveyed. Figure 3 shows the average cumulative size distributions of dusts contributed by the various longwall dust sources. The mass median aerodynamic diameters of dusts contributed by the intake airway, beltway, crusher, and shearer were 7.5, 9.1, 12, and 18 μm, respectively. The mass median diameter of support-generated dust was greater than 21 μm. In general, as the mass median diameter increased, the thoracic/respirable exposure ratio increased.

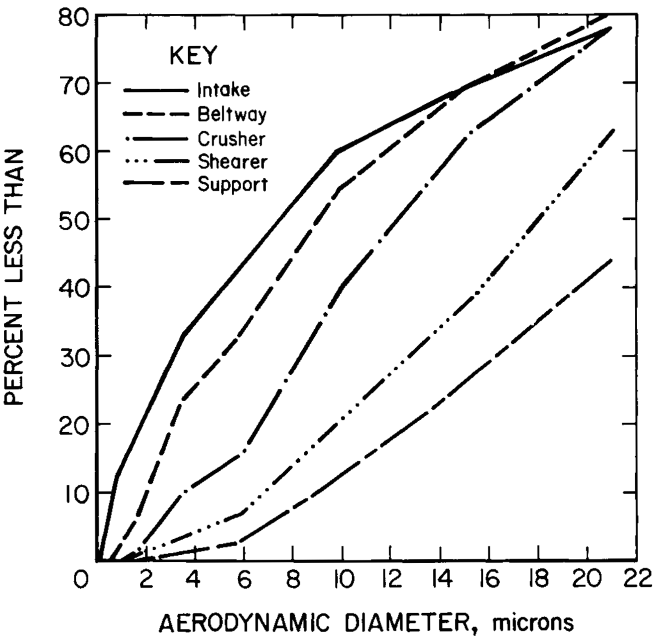

FIGURE 3. Average cumulative size distributions of dusts contributed by the various longwall dust sources.

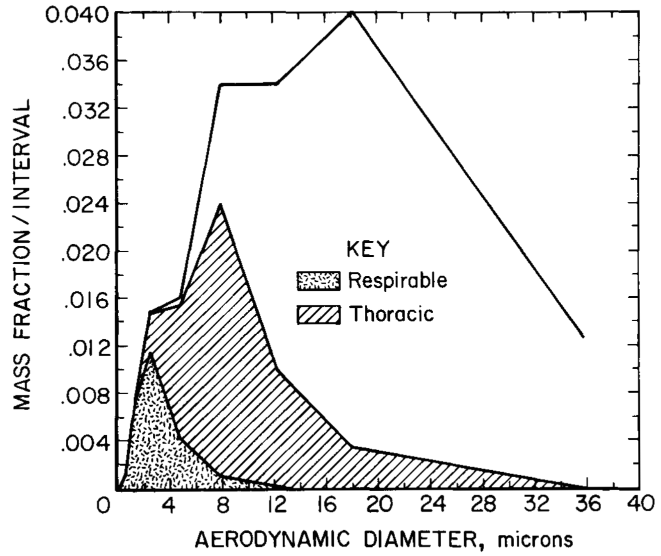

FIGURE 4. Average mass frequency distribution of shearer-generated dust showing the thoracic and respirable mass fractions.

Sources of dust associated with the transport of men, supplies, and coal in the airways and beltways are radically different than the crushing and grinding sources in the face area. This at least partially explains the measured size difference between entry and face dusts. The crusher, shearer, and supports all generate dust by crushing and grinding the coal; however, crusher-generated dust was much finer than dust generated by the other two sources. In all of the mines surveyed, the crusher was covered and hollow-cone sprays were used in the enclosed area to knock down dust. These scrubber-like dust control characteristics are most effective on larger dust particles, resulting in a finer crusher dust product.

The particle size distribution of a dust cloud changes continuously due to the mechanisms of particle deposition. The main mechanisms(11) of deposition in mine airways (turbulent flow) include sedimentation and Brownian and eddy diffusion. Rate of deposition is most dependent on particle size, coagulation, and airway characteristics.

Previous research(12) has found that the rates of deposition for < 5 μm particles do not follow a simple Stokes-type sedimentation relationship in turbulent flow. Deposition of these particles appears to be influenced by a diffusion effect that depends greatly on wall roughness. Conversely, the rates of deposition for > 5 μm particles do appear to follow a Stokes-type sedimentation relationship. Figure 4 shows the average mass frequency distribution of shearer-generated dust. The > 5 μm particles accounted for only 15 percent of the respirable dust generated by the shearer, whereas they accounted for 80 percent of the thoracic dust generated by the shearer. Thus, most of the airborne thoracic dust mass should exhibit a

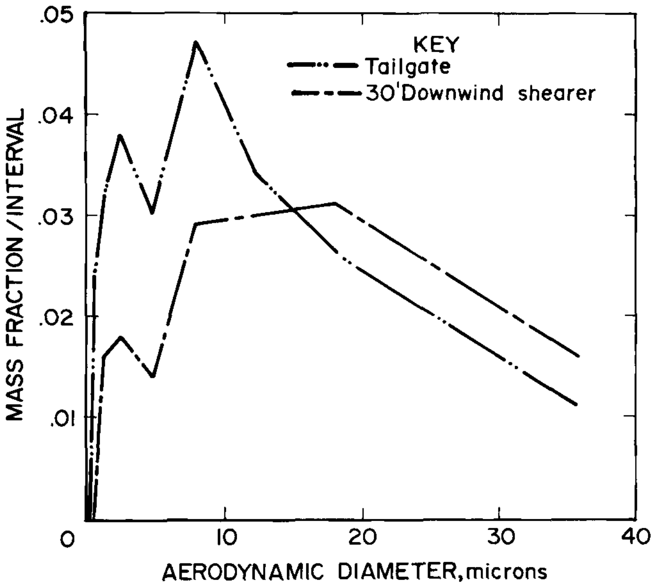

FIGURE 5. Average mass frequency distributions of dusts collected 30 ft downwind of the shearer and in the tailgate area.

Stokes-type sedimentation relationship. This relationship is important for assessing the thoracic dust exposure of operations conducted downwind of a thoracic dust source.

In the Stokes regime, larger particles settle out of the airstream at a much faster rate than smaller particles because the settling rate[13] is proportional to the square of the particle diameter. Thus, the mass median particle diameter of a dust cloud decreases as it moves further from the source. This phenomenon was observed on the longwall mining sections. Figure 5 shows the average mass frequency distributions of dusts collected 9.1 m (30 ft) downwind of the shearer and in the tailgate area. The shift towards finer particles in the tailgate area is very pronounced. The average mass median diameters of dusts collected 9.1 m (30 ft) downwind of the shearer and in the tailgate area were 20 and 15 μm, respectively. Very few of the < 5-μm particles deposited out of the airstream. Dust deposition between the shearer return and tailgate area reduced the total, thoracic, and respirable dust concentrations by about 60, 35, and 10 percent, respectively.

Differences in sampling procedures and the relative heights of the areas of dust generation were probably responsible for the measured size difference between shearer-generated and support-generated dusts. For safety reasons, a greater distance was maintained between the shearer and downwind samplers than the distance maintained between the shieldman and downwind samplers, allowing larger dust to settle out of the airstream. Also, most support dust is generated near the mine roof; therefore, larger dust particles remain in the sampling zone at greater distances from the source. Deposition may also have accentuated the measured size difference between entry and face dust sources because the distance between the entry sources and sampling locations was much greater than the distance between the face sources and sampling locations.

When one particle collides with another particle, the two particles may adhere (coagulation) and act as a single particle. Coagulation affects the rates of deposition because it affects the particle size distribution of airborne dust. The mechanisms and magnitude of coagulation in mine airways are not clearly understood. However, rates of coagulation did not appear to be site-specific because each longwall sampling location had an associated particle size distribution that remained consistent for all sections surveyed. Airway bends, obstructions, and roughness factors can also affect dust deposition rates; however, these characteristics vary only slightly between most longwall mining faces.

As reported earlier, each particle requires a certain amount of time to settle from the airstream (rate of deposition). Therefore, an increase in air velocity increases the distance that a particle will be carried before settling. Because larger particles settle at a faster rate than smaller particles, an increase in velocity results in a greater mass fraction of larger particles in the airstream at a fixed distance from the source. Average air face velocities on the sections surveyed for this study were typical for longwall operations and ranged from 1.3 to 1.7 m/s (250–340 fpm). This variation seemed to have only a minimal effect on respirable and thoracic dust deposition.

Many factors can affect the size distribution of dust to which a miner is exposed. However, these factors are predictable and remain constant between most longwall operations. In fact, current dust control technology and variations in longwall operating parameters seemed to have little effect on the size distributions of airborne dusts. Therefore, it is possible to estimate thoracic dust exposures on longwall operations from respirable dust information. Changes in air velocity probably produce the largest variations in particle size distributions between longwall operations. An increase in air velocity would increase the thoracic/respirable dust exposure ratios on longwall mining sections.

All of the data collected during this study showed that worker location drastically affects the size distribution of dust to which the worker is exposed. Longwall operations require workers in specific locations. A headgate operator works in the vicinity of the crusher and controls the power to the equipment. Two or three shieldmen advance the shields and panline after a cut pass. On a unidirectional cutting section, the shieldmen usually work between the crusher and the shearer. On a bidirectional section, the shieldmen work between the crusher and the shearer on the head-to-tail cut pass, and they work between the shearer and the tailgate area on the tail-to-head cut pass. Two shearer operators work in the vicinity of the shearer throughout the shift. A mechanic and a foreman work anywhere along the face that they are needed. The thoracic/respirable dust exposure ratios on the longwall sections averaged: 1.8 in the intake airway, 2.7 in the beltway, 3.1 in the headgate area, 6.7 downwind of support and panline advancement activities, 5.4 immediately downwind of the shearer during a cut pass, and 3.6 in the tailgate area during a cut pass (coefficients of variation were 8, 17, 23, 16, 15, and 7 percent, respectively). Clearly, compliance with the respirable dust standard would not equally limit the thoracic dust exposures of all longwall face workers.

Results from Continuous Mining Section Surveys

Mine A's continuous miner extracted coal from a 2.9-m (9.5-ft) high by 4.9-m (16-ft) wide room at a rate of 145 t/hr during production. Two section fans and exhausting tubing were used to move 7.6 m^3/s (16,000 cfm) of air through the active room. Mine B's miner drove a 2.3-m (7.5-ft) by 5.8-m (19-ft) room at a rate of 180 t/hr; exhausting curtain directed 11.3 m^3/s (24,000 cfm) of air through the active room. Mines A and B used electric-powered shuttle cars. Mine C's miner drove a 2.7-m (9-ft) by 4.9-m (16-ft) room at a rate of 163 t/hr; a fan and blowing tubing were used to move 2.8 m^3/s (6000 cfm) of air through the active room. Mine C used diesel-powered shuttle cars.

Miner cutting and loading generated between 14 and 22 mg/m^3 of thoracic dust on the exhausting faces. Bolter operators may be exposed to these high thoracic dust levels when working downwind of the miner. However, implementing a mining cycle that proceeds in the same direction as air flow will minimize the number of rooms that must be bolted downwind of the miner. Using a tubing bypass system[14] or a double-split ventilation system will eliminate the need to bolt in return air. Thoracic dust levels in the miner cabs ranged from 8.8 to 11.3 mg/m^3 on the exhausting faces. Miner cab dust on exhausting faces frequently consists of dust rollback from the active face and dust generated during shuttle car loading operations. However, mines A and B both moved large quantities of air (16,000 and 24,000 cfm, respectively) through the active face area, and no dust rollback was apparent. The mining machines at mines A and B were operated with remote control, allowing the miner operators and helpers to avoid loading dust. On the blowing face, thoracic dust levels in the miner cab averaged 10 mg/m^3. Thoracic dust levels downwind of the miner and shuttle car loading operations also averaged 10 mg/m^3. Most of the face workers were exposed to these dust levels during production. Bolting operations generated between 1.9 and 2.8 mg/m^3 of thoracic dust. Thoracic dust levels in the feeder/breaker areas ranged from 2.8 to 4.1 mg/m^3.

Figure 6 shows the cumulative size distributions of dusts contributed by the various continuous mining dust sources. The mass median aerodynamic diameters of dusts in the intake airway and feeder/breaker area were 6.5 and 10 μm, respectively. The size distributions of miner-generated dusts varied significantly between the blowing face and the exhausting faces. Miner dust consisted of dusts generated by miner cutting and shuttle car loading operations. The mass median aerodynamic diameters of miner dusts on the blowing face and exhausting faces averaged 8.5 and 14 μm, respectively. Miner dust on the blowing face was much finer than miner dusts on the exhausting faces because much of the cutting dust on the blowing face was drawn through a miner-mounted scrubber. The efficiency of a

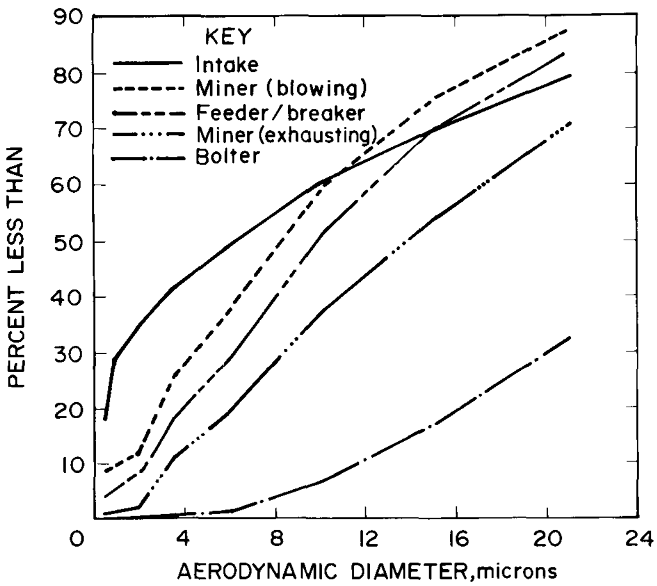

FIGURE 6. Average cumulative size distributions of dusts contributed by the various continuous mining dust sources.

scrubber improves with increasing particle size, thus, dust entering a scrubber will have a coarser particle size distribution than dust exiting a scrubber. Also, the blowing face surveyed for this study used diesel shuttle cars. Diesel engines generate submicron particles, resulting in a finer return dust product.

The size distributions of bolter-generated dusts varied between mines and sampling days. Air flow was low in all of the bolter rooms and the size distribution of collected dust was very dependent on the sampling location. Figure 6 shows an interesting size distribution collected in the bolter operator zone at mine A. In this instance, the bolter operator was positioned between the drill rod and the exhausting tubing. All of the larger dust that was falling from the ceiling was pulled through the bolter operator's breathing zone. About 67 percent of the mass collected at this position deposited on the first impactor stage.

Miner cab dust characteristics also varied between the blowing face and the exhausting faces. The miner cab on an exhausting face is downwind of loading and upwind of cutting, whereas the miner cab on a blowing face is downwind of cutting and upwind of loading. Figure 7 shows the average mass frequency distributions of miner cab dusts. The average particle size distribution of miner cab dust on the exhausting faces was relatively coarse because the cab was extremely close to the loading dust source.

Results from this study showed that blowing face ventilation and the use of diesel-powered shuttle cars can affect the particle size distributions of dusts at various locations on continuous mining sections. However, most continuous mining operations use exhausting face ventilation and electric-powered shuttle cars. This study and a previous study[5] found that the size distributions of dusts associated with the intake airway, feeder/breaker area, miner cab, and the immediate face return remained consistent

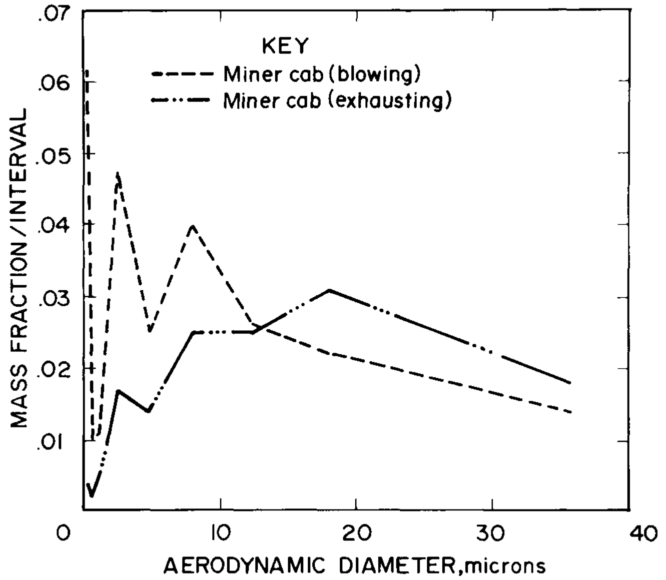

FIGURE 7. Average mass frequency distributions of dusts collected in the miner cabs.

between exhausting face sections using electric-powered shuttle cars. The effects of deposition, air velocity, and airway characteristics are more pronounced on operations conducted downwind of the active face. Therefore, it is impractical to propose a specific dust size distribution for these operations.

Like longwall mining operations, continuous mining operations require workers in specific locations. A miner operator and a helper work in the vicinity of the miner cab. Two or three shuttle car operators move between the active face and feeder/breaker area. Two bolter operators primarily work upwind of the active face. A mechanic, a foreman, and a supply man work anywhere on the section that they are needed. The thoracic/respirable dust exposure ratios on the exhausting faces averaged 1.5 in the intake airway, 3.0 in the feeder/breaker area, 3.2 downwind of miner cutting and loading operations, and 4.1 in the miner cab (coefficients of variation were 9, 23, 25, and 12 percent, respectively). Ratios on the blowing face averaged 2.4 in the feeder/breaker area, 2.3 downwind of miner cutting and loading operations, 3.2 in the miner cab, and 2.8 in the shuttle car cabs (coefficients of variation were 3, 29, 20, and 17 percent, respectively). As with longwall mining sections, compliance with the respirable dust standard would not equally limit the thoracic dust exposures of all continuous mining section workers.

Conclusions and Recommendations

Data collected for this study show that compliance with the respirable dust standard would not equally limit the thoracic dust exposure of all mine workers. Assuming a respirable dust level of 2 mg/m^3, the thoracic dust level in the same area would range from approximately 3 to 14 mg/m^3, depending on the location in the mine. Therefore, respirable dust exposures may not be the best predictor of bronchitic symptoms and reduced pulmonary function, which are believed to be associated with dust deposition in the thoracic regions of the respiratory tract. The authors recommend that the thoracic/respirable dust ratios determined for this study be supplemented with additional personal sampling to develop estimated thoracic/respirable dust ratios for specific underground occupations. An analysis of existing health data could then be conducted to determine the relationship between estimated thoracic dust exposure and the incidence of bronchitic symptoms and reduced pulmonary function in coal mine worker populations. Collection of health data in the future should include thoracic dust samples.

Data collected for this study indicate that thoracic dust levels on longwall sections are higher than levels on continuous miner sections. Also, unique operating parameters make it more difficult to avoid thoracic dust exposure on longwall sections. Therefore, future thoracic dust control research should concentrate on longwall mining operations. Physical properties of larger dust particles make them easier to separate from the airstream than smaller dust particles; therefore, the authors recommend that simpler and more cost effective techniques be developed for thoracic dust control in the underground mine environment.

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