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Sources and Characteristics of Quartz Dust in Coal Mines

By J. A. Organiscak, S. J. Page,
and R. A. Jankowski

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	mg/m^3	milligram per cubic meter
ft/min	foot per minute	min	minute
ft^3/min	cubic foot per minute	mm	millimeter
gpm	gallon per minute	µg	microgram
h	hour	µm	micrometer
in	inch	pct	percent
L/min	liter per minute	pct/gpm	percent per gallon per minute
mg	milligram	psi	pound per square inch

SOURCES AND CHARACTERISTICS OF QUARTZ DUST IN COAL MINES

By J. A. Organiscak,[1] S. J. Page,[2] and R. A. Jankowski[3]

ABSTRACT

Quartz dust is one of the most significant ongoing health concerns in coal mining today. Since the early 1980's, the U.S. Bureau of Mines has conducted numerous studies in underground and surface coal mines to identify the sources of quartz dust and its fundamental characteristics. This report presents data and conclusions obtained from these studies. The two most significant quartz dust sources were found to be the continuous miner excavating rock and the highwall drill operating in a rock overburden. The percentage of quartz was found to be higher in the smaller size fractions of dust when significant amounts of rock were mined by the continuous miner. Another factor theorized to affect quartz dust generation and size characteristics is the morphology of the quartz-bearing rock.

Several laboratory studies were conducted to investigate capture efficiency of water spray technology and flooded-bed scrubbers with respect to the particle size of the dust. Water sprays and flooded-bed scrubbers were both found to be less efficient on smaller dust particles, and the scrubber was particularly less efficient on quartz dust. These results indicate that quartz control technology should be directed at controlling smaller sized dust particles.

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INTRODUCTION

The Federal Coal Mine Health and Safety Act of 1969 limits the amount of a worker's respirable dust exposure to a 2.0-mg/m^3 average standard for a working shift. If the respirable dust sample contains more than 5 pct quartz, the dust standard is reduced. The more stringent dust standard due to quartz is determined by dividing 10 by the percentage of quartz in the dust.

Enforcement of the 2.0-mg/m^3 standard was swiftly implemented after the legislation was enacted because of the availability of respirable dust measurement technology (Mining Research Establishment (MRE) sampler and personal sampler). Enforcement of more stringent dust standards due to quartz was difficult until the early 1980's because of insufficient analytical methods to determine the quartz percentage in individual respirable dust samples. The technology available was a bulk sample infrared technique that required at least a 5-mg sample of dust (*1*).[4] Since such a large sample was required, individual compliance samples could not be analyzed. Several samples from various workers had to be combined, which was not reflective of the individual exposures to quartz. Also, combining samples and preparing one sample for analysis was a long, labor-intensive effort.

In the late 1970's, the U.S. Bureau of Mines, the Mine Safety and Health Administration (MSHA), and the National Institute for Occupational Safety and Health (NIOSH) jointly developed the low-temperature ash-infrared procedure known as the P7 technique to analyze individual dust samples.[5] The P7 quartz analysis requires a minimum dust sample mass of only 0.5 mg. MSHA adopted this technique in 1981 for determination of more stringent dust standards as stipulated in the regulations (*2*).

In 1981, the number of MSHA quartz analyses increased by more than 140 pct, and the number of more stringent dust standards increased by more than 200 pct (*3*). By 1984, more than 10 pct of the active coal mining operations were on a more stringent dust standard. About one-third of these operations were on a standard below 1 mg/m^3, indicating that they had more than 10 pct quartz in their compliance samples. Nondesignated work positions accounted for about 50 pct of the more stringent dust standards (*4*). These positions were mostly roof bolter operators in underground mines. Surface mine highwall drill operators accounted for about 20 pct of the more stringent dust standards, and this occupation had the lowest average reduced standard at 0.8 mg/m^3. Many of the highwall drill operators were on standards below 0.5 mg/m^3.

In 1983, the Bureau initiated a quartz dust program to identify the extrinsic parameters governing the quartz exposure of coal mine workers. Several in-house and contract studies were conducted to gather a data base to identify the most significant sources, characteristics, and behavior of quartz dust in coal mines. This report summarizes the data and results obtained from the various studies conducted under the Bureau's quartz dust program. The focus of this report is the sources of quartz dust, the characteristics of quartz dust, and the unique aspects of quartz dust affecting the effectiveness of existing control technology.

SOURCES OF QUARTZ DUST

Quartz dust measurements have been made in many locations throughout coal mines to identify the various sources of generation. Major sampling efforts were directed at roof bolter units on continuous miner sections and highwall drilling units at surface mines because they represented the majority of the operations on a more stringent dust standard due to quartz. Other types of production units and areas were also sampled to identify the scope of the problem throughout coal mines. Respirable dust measurements were obtained with personal gravimetric samplers, and quartz analysis was conducted on these samples with the P7 method. Some instantaneous dust sampling with a real-time aerosol monitor (RAM) was also conducted to examine changes in dust levels during particular mining events. Quartz content of bulk materials (rock chip samples) was measured by X-ray analysis. Results from both underground and surface mine operations are discussed.

UNDERGROUND COAL MINES

Roughly 70 pct of the operations on more stringent dust standards due to quartz are in underground coal mines (*4*). More stringent dust standards are most frequently found at continuous miner sections. Other areas in underground coal mines make up a smaller fraction of the operations on more stringent standards.

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[4]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

[5]Standard Method P-7. Infrared Determination of Quartz in Respirable Coal Mine Dust.

Continuous Mining Sections

Roof bolter operator was the most frequent worker occupation on more stringent dust standards due to quartz. Studies were conducted at eight continuous miner sections[6] to identify the major source(s) of quartz (*5-7*). These sections were selected because they were in mines on more stringent dust standards. Dust samples were taken in the areas of production activities. Gravimetric sampling was conducted in the roof bolter return air when the roof bolter was operated upstream of the continuous miner, at the continuous miner operator's cab, in the return air of the continuous miner, and in the roof bolter return air when the roof bolter was operated downstream of the continuous miner. Figure 1 illustrates these locations on a typical single-split return face ventilation system. Tables A-1 and A-2 of the appendix summarize the dust concentrations and quartz content measured at the various sampling locations in these mines.

Bulk samples of the various materials mined were also collected and analyzed for quartz content to identify the geologic source materials of quartz. Chip samples of roof rock, coal, rock partings (if any), and floor rock were collected and analyzed. Rock materials contained the highest amounts of quartz, which are shown in table A-3 of the appendix.

Data analysis from these continuous mining sections indicates that the roof bolting machine was not the major source of the quartz dust exposure of the roof bolter operators. Figure 2 shows the average dust and quartz concentrations at each sampling location for the eight mines. The roof bolter return on the intake side of the continuous miner shows a significantly lower average of respirable dust and quartz dust than do the other sampling locations.

Cuttings from the roof bolter dust collector had the highest quartz content of any of the bulk materials analyzed at these sections (fig. 3), demonstrating that the dry vacuum collection systems (used at all eight mines) on roof bolters are very efficient. However, the roof bolter collection system must be properly maintained and cleaned because notably higher levels of dust were measured in the bolter return when the filters were not properly seated in the collector. Dust concentrations from the bolter in mine C averaged 0.74 mg/m^3 with 8.3 pct quartz for four shifts with the collector working properly. During one shift, the cartridge-type filter was not properly seated and leaked, yielding 3.68 mg/m^3 of dust containing 13.3 pct quartz.

[6]Mines are designated by capital letters as used in the appendix tables.

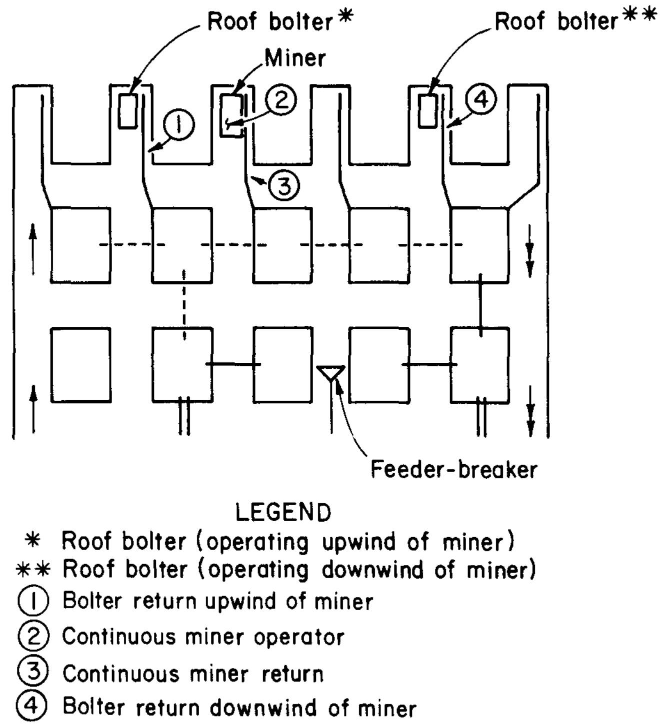

Figure 1.—Underground dust sampling plan at continuous miner sections.

The continuous miner cutting rock was the major source of quartz dust at these sections. Figure 2 reveals that both respirable dust and quartz dust concentrations are fairly high at the continuous miner operator's position and are the highest on the return side of the continuous miner. Instantaneous dust measurements with a RAM made at the continuous miner operator's cab during production indicate that the dustiest process was cutting rock. Figure 4 illustrates that dust levels notably increased at mines A and C when cutting rock.

Roof bolter operators were exposed to high levels of quartz dust when operating on the return side of the continuous miner. Average dust levels in the bolter return when operating on the return side of the miner were significantly higher than when operating on the intake side of the miner (fig. 2). Roof bolter operators at these mines were exposed to the dust generated by the continuous miner during a portion of the shift. Their major source of quartz dust exposure was from the continuous miner cutting rock.

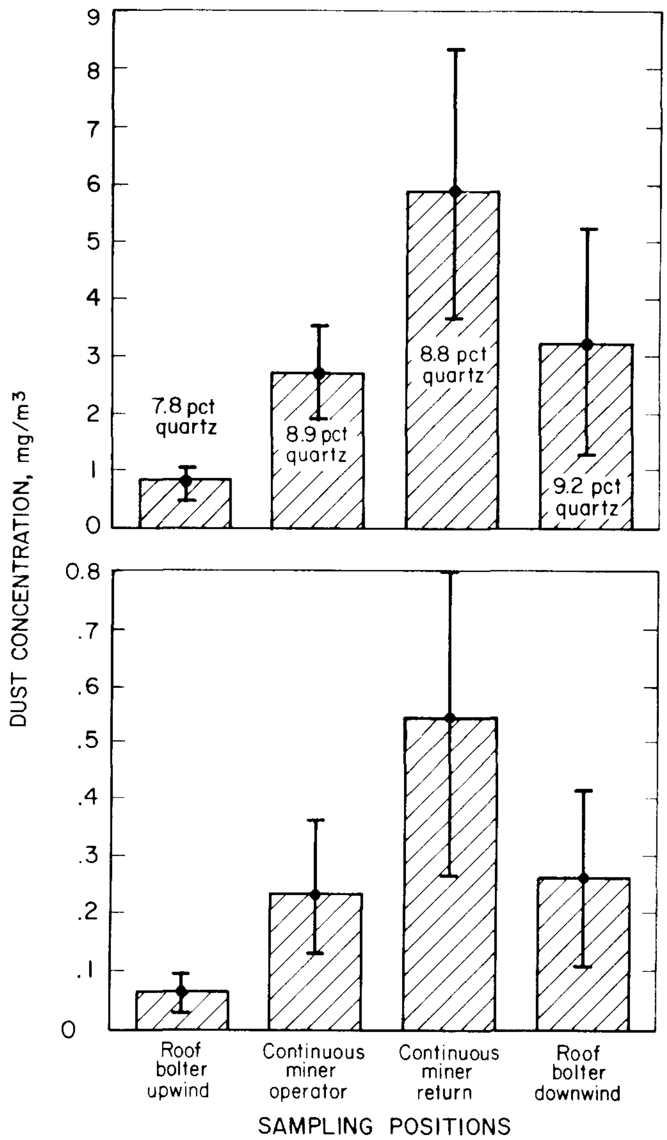

Figure 2.—Average dust concentrations and quartz content (top) and average quartz dust concentrations (bottom) at continuous miner sections. Error bars are at the 95-pct confidence level.

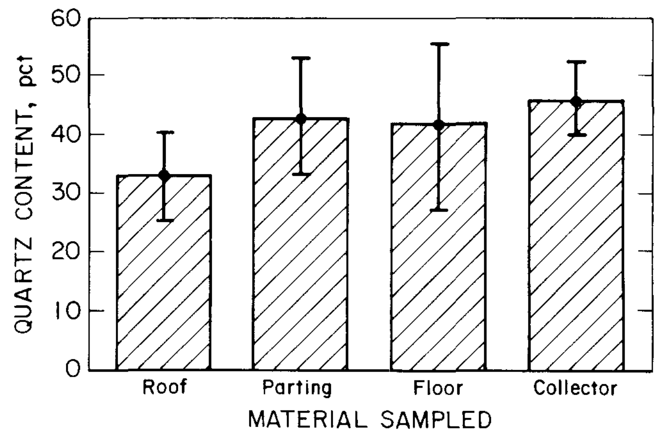

Figure 3.—Average quartz content of rock samples and roof bolt cuttings. Error bars are at the 95-pct confidence level.

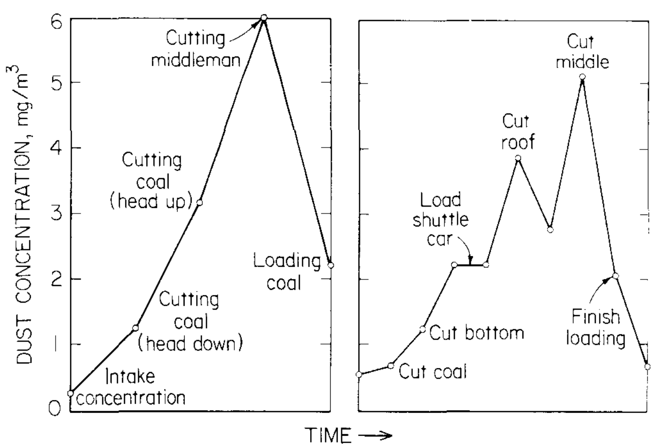

Figure 4.—Instantaneous dust levels at continuous miner operator's position in mine A (left) and mine C (right).

Longwall Mining Sections

Approximately 5 pct of designated areas on longwall mining sections have been placed on more stringent dust standards due to quartz. As previously noted, coal seams contain only a small percentage of quartz and it is the mining of top and bottom rock that contributes the greatest amount of quartz to the respirable dust. Although roof and floor rock are often mined during development of the longwall panel, the longwall machine itself seldom needs to extract top or bottom rock. This can be well illustrated by a situation at one particular longwall mine. During development of the longwall panel in a particular area, the continuous mining section was operating on a more stringent dust standard of 1.3 mg/m^3; MSHA sampling had determined that the average quartz content of the respirable dust was 7.5 pct. During retreat panel extraction by the longwall system, the section operated at the normal standard of 2.0 mg/m^3; MSHA sampling had determined that the average quartz content of the respirable dust was 3.5 pct. During panel development, the continuous mining machine was required to remove roof rock to provide adequate clearance for subsequently moving in the longwall face equipment. Removal of roof rock was not necessary or desired during longwall extraction.

Potential sources of airborne respirable quartz can be illustrated by the following three longwalls sampled for quartz (data can be found in table A-4 of the appendix). Mine A extracted a mining height of 13 ft from the middle of a 23-ft coal seam, leaving 5 ft of top and bottom coal. Quartz dust levels along the face are shown in figure 5 (top panel). These results show only trace amounts (<2 pct) of quartz in the airborne respirable dust and illustrate that cutting in clean coal does not contribute to the airborne respirable quartz dust levels.

Many coal seams contain rock intrusions or mineral partings within the seam, which represent the potential sources of airborne respirable quartz found at longwall mining operations. When rock intrusions are encountered, they must usually be mined during the longwall extraction. Rock partings must also be removed with the seam and can contribute airborne respirable quartz during extraction by the shearer or subsequent breakage in the sections crusher (located at the headgate). This feature is illustrated in figure 5 (middle panel). Mine B had a minor rock intrusion from the roof into the coal face between shields 25 and 35 and a major intrusion from shields 85 to 90. Average quartz dust levels along the face were approximately 3.0 pct, increasing to 4.0 at shield 30 and 7.2 at shield 90. However, the average quartz dust exposure of face workers was still under 3.0 pct, and the section was operating on a standard of 2.0 mg/m³.

Mine C was a bidirectional operation with a sandstone top and numerous rock intrusions along the face. The bottom panel of figure 5 shows a consistent buildup of quartz dust levels along the entire face. This was due to a combination of airborne respirable quartz dust contributed from the shearer extracting the top rock and the release of quartz dust during movement of roof supports. Although quartz dust levels at the tailgate exceeded 12 pct, face workers spent little time in this area and had quartz exposure levels below 5 pct. All three longwall cases illustrate that quartz was not a significant problem, but the potential for problems exists under certain mining conditions.

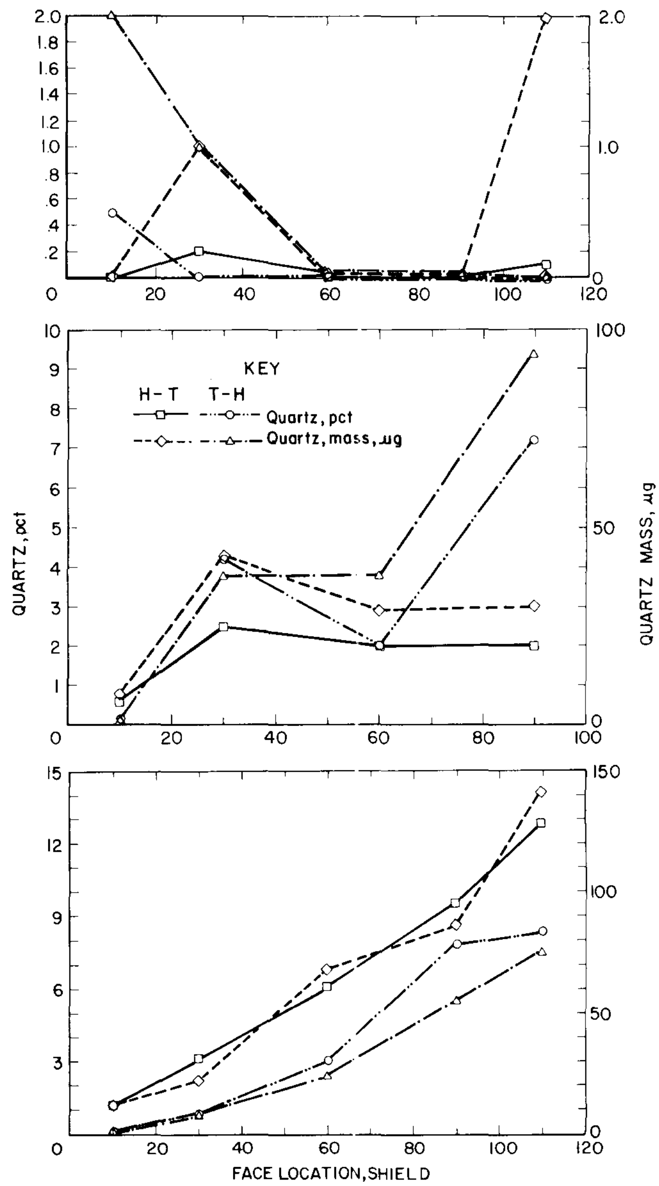

Figure 5.—Quartz content and mass measured at longwall A (top), longwall B (middle), and longwall C (bottom). (H = headgate; T = tailgate.)

Conventional Mining Sections

Quartz dust generation was investigated at two mines utilizing both conventional and continuous mining methods (*8*). Since the most significant source of quartz dust in underground mines was the continuous miner when cutting rock, dust sampling was conducted in the immediate return of the conventional and continuous mining operations to make comparisons between the two mining methods. Both conventional and continuous sections at each mine operated in identical mining conditions, so a good comparative study of the mining methods was achieved. The amount of reject in the product at both mines was greater than 40 pct, and the quartz content in this reject was greater than 30 pct. Dust sampling at the conventional sections was conducted in the outermost intake entry to eliminate any upstream contamination from other, concurrent conventional mining operations in the section. Measurements were made at stationary positions in the intake and immediate return of the production face over several complete cut cycles. Dust sampling at the continuous sections was mobilized with the continuous miner. Again, measurements were made in the intake and return of the production face. Table A-5 of the appendix shows the data from these studies. Figure 6 illustrates the

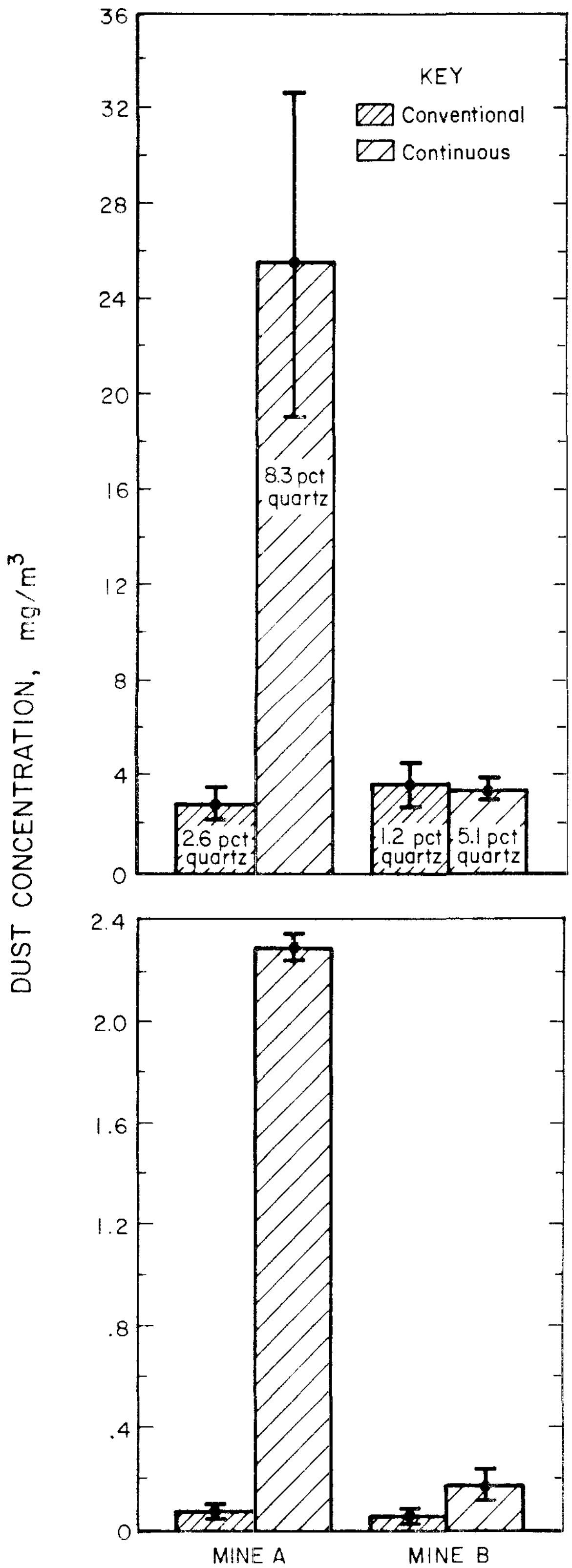

Figure 6.—Average dust concentrations and quartz content (top) and average quartz concentrations (bottom) at conventional versus continuous miner sections. Error bars are at the 95-pct confidence level.

average return respirable and quartz dust concentrations from both mines.

Results from the two-mine study show that conventional mining produced significantly less quartz dust than continuous mining and significantly less respirable dust in mine A (fig. 6). At mine A, single-split exhaust ventilation (curtain) was used on both sections. The average respirable dust concentration in the continuous miner return was nearly eightfold higher than in the return air of the conventional operation. The average continuous miner quartz dust concentration was nearly 31-fold higher than the conventional quartz dust concentrations. At mine B, the conventional and continuous sections both employed blowing face ventilation (curtain). A fibrous flooded-bed scrubber was used on the continuous mining machine for dust control. Respirable dust concentrations were nearly identical in both the continuous and conventional returns. However, the average quartz dust concentration for the continuous miner was 2.7-fold higher than for the conventional section.

These results indicate that conventional mining produces notably less quartz dust than continuous mining and should not pose serious quartz dust problems in coal mines. The blasting of rock in conventional mining increases its product size, producing fewer fines and less dust. The rotary cutting action of a continuous miner mills the rock into a finer product with more dust.

Outby Areas in Underground Coal Mines

Several designated outby areas on more stringent dust standards due to quartz prompted some dust sampling to evaluate the potential of quartz generation in these areas. Areas sampled included shuttle car travel entries, the area around the feeder-breaker, belt entries, a belt-to-rail transfer dump, a main rail haulage (trolley) entry, and several locomotives. Table A-6 in the appendix summarizes the dust concentrations measured at outby areas in 11 underground coal mines and the quartz percentage in the product reject. Figure 7 shows the average respirable dust and quartz dust concentrations measured in four basic outby areas.

Belt entries had the highest dust concentrations in outby areas, with the lowest quartz content. These concentrations were measured between transfer points and around transfer points in main belt and section belt entries. Good perceptible air movement outby was measured in all the belt entries sampled (average for the mines surveyed ranged between 80 and 100 ft/min). Two of the mines (K and L in table A-6 of the appendix) had low percentages of quartz in the product reject, so low quartz dust levels would be expected. However, mine J had a high percentage of quartz dust in the product reject yet had low levels of quartz dust in its main belt entries. This

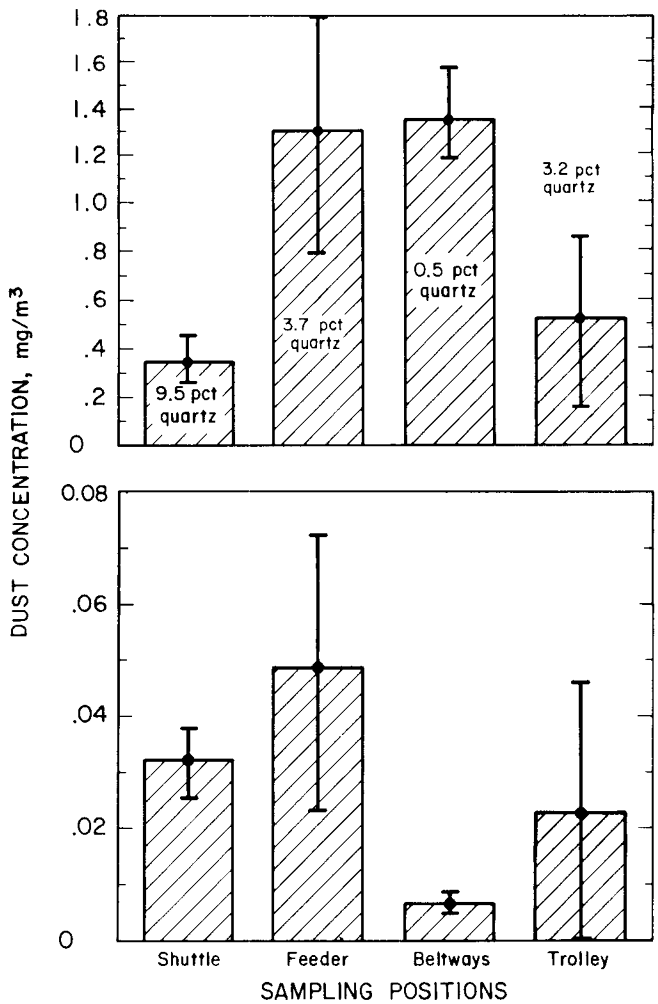

Figure 7.—Average dust concentrations and quartz content (top) and average quartz concentrations (bottom) in outby areas of underground coal mines.

indicates that conveyor belts can be a significant source of respirable dust but may not be a significant source of quartz dust. Conveyor belts are probably not prone to generating respirable quartz dust because of the elastic properties of the belt and because the durable nature of quartz materials (rock) can better weather mechanical comminution by drives, takeups, and idlers. Coal, which is more easily ground, may be readily processed into finer particles through belt abrasion and pulverization.

The second highest dust concentrations and the highest quartz dust concentrations measured outby were around the feeder-breaker. Although the feeder-breaker generated the largest amount of quartz dust in any of the outby areas (fig. 7), the amount generated did not pose a problem at the sections surveyed. However, there exists a potential problem with quartz dust if a large quantity of large-sized rocks had to be crushed over an extended period of time. This dust could contaminate inby ventilation to the face, so this source should not be completely disregarded as a problem.

Measurements in shuttle car entries outby the face and inby the feeder-breaker showed low dust concentrations with high quartz content. The dust found in the shuttle car haulage entries is a result of several sources in the section. Contaminated (dusty) air from the production face and feeder-breaker can migrate into these entries. Also, shuttle car movement through the entries can entrain the fine roof bolter cuttings dumped into these haulage entries. The amount of quartz dust found in these entries was still insignificant because dust concentrations were low.

Rail haulage had generally low concentrations of respirable dust and quartz dust associated with its operation (fig. 7). Dust concentrations were measured at the belt-to-rail dump chute, at stationary positions in the haulage entry, and on the haulage motors (see table A-6 of the appendix). The highest dust concentration and quartz content (0.88 mg/m³ and 6.9 pct quartz) were measured at the belt-to-rail dump chute. Airflow in the entry at this location averaged 90 ft/min. Respirable dust and quartz concentrations were very low in the main haulage entry. Dust concentrations on the haulage motors were similar to those in the haulage entry, but the quartz content was notably higher. The higher quartz content at the locomotives was probably from rail sanding to improve traction on an outby grade leading up to the mine portal. The sand contained 98 pct quartz, and instantaneous dust concentrations (from RAM sampling) nearly reached 3.0 mg/m³ on the trailing motor when sanding took place. Also, a noticeable amount of sand was deposited along the rail, and instantaneous dust levels in the entry increased as the locomotives passed. However, the amount of quartz measured at the motors was still inconsequential to the exposure of motor operators. To avoid any potential silica problems on rail haulage systems, an amorphous silica sand or crushed slag could be used for traction media.

SURFACE MINES

Roughly 20 pct of the more stringent dust standards due to quartz in coal mining apply to surface mine highwall drillers (*4*). This occupation has the lowest average standard at 0.8 mg/m³, and many highwall drill operators are on standards below 0.5 mg/m³. According to MSHA data, the jobs of highwall driller and helper are two of the occupations with the greatest potential for exposure to quartz. The Bureau conducted studies around highwall drills to pinpoint the sources of quartz dust exposure of operators (*9*).

The basic sampling configuration is shown in figure 8. Samplers were placed immediately downwind of the drill platform, drill skirt, collector air discharge, and collector

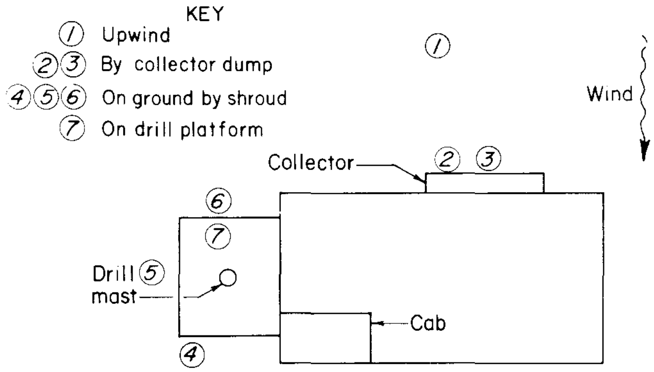

Figure 8.—Dust sampling strategy at highwall surface mine drills.

material discharge. Bulk samples of the drill cuttings and the dry collector dust discharge were also collected and analyzed for quartz content.

Tables A-7 and A-8 of the appendix summarize the dust concentrations and quartz content measured at the sampling locations for nine mines. The dust samples presented are short term and are area samples instead of personal samples. Therefore, they represent potential exposure hazards for the drill operator and helper. The testing protocol involved measuring dust concentrations attributable to the drill at immediate downwind locations. Sampling of the drills at each mine occurred over several days. In general, at least one test without the dust control system in operation was performed each day. Test duration was dictated by the need to collect 0.5 mg of combined sample at each location for method P7 analysis. Consequently, the duration of test periods ranged from 15 min to 2 h. The tests without dust control required the least sampling time.

Figure 9 presents overall average dust and quartz concentration results at the various area sampling locations. These mines used either a dry dust collector or water injection for dust control. The test results show that these dust control systems are capable of achieving between 66 and 93 pct respirable dust reductions and 77 to 90 pct quartz dust reductions. The most significant reductions were observed around the shroud. Without the aid of dust controls, dust leakage from the shroud area is the largest dust source. With a functional dry dust collector, dust levels tend to be the highest and most inconstant at the point of collector material discharge. This is usually the case because the collector merely dumps the collected fine material onto the ground. This procedure creates significant dust problems because of the material's impact with the ground and dispersion by ambient wind conditions.

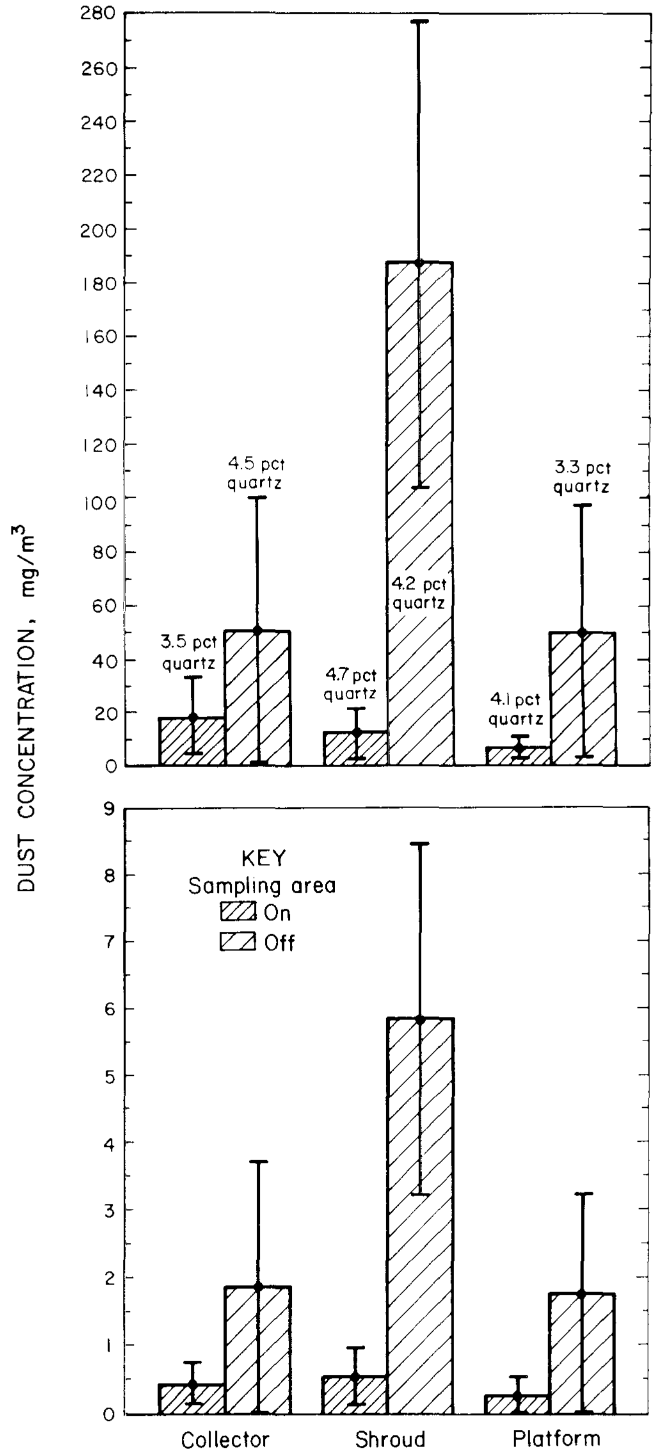

Figure 9.—Average dust concentrations and quartz content (top) and average quartz dust concentrations (bottom) around highwall drills with and without dust controls. Error bars are at the 95-pct confidence level.

The most significant variable affecting the degree of dust control appeared to be operation of the systems. Individual tests show a high degree of variability in control efficiencies at some mines. This variability is most often due to operation practices and the conditions of the material being drilled (e.g., moisture content). Rarely did a control system fail outright. For dry collection systems, well-operated devices can achieve greater than 95-pct control. The principal reason for not achieving this level of control is the operational practice of not lowering the shroud to seal with the ground. Wet systems are also capable of greater than 95-pct control. The principal problem in achieving high control levels is determining and maintaining the correct waterflow to optimize control.

Figure 9 indicates that there was no significant impact of the dust control on the percentage of respirable quartz. In any case, the respirable quartz content ranged from below detectable limits to slightly more than 11 pct. The overall minewide average for all sampling positions ranged between 3 and 5 pct. Bulk sample X-ray diffraction analysis showed that the quartz content of the drill cuttings ranged from 20 to 69 pct (see table A-9 in the appendix). The bulk sample analysis of the dry collector discharge ranged from 37 to 53 pct.

Although surface blasthole drills can generate significant quantities of respirable dust and there is a significant health hazard potential in the immediate vicinity, there is evidence that the exposure of downwind personnel to drill-generated dust may not be a significant problem. Simultaneous dust and tracer gas sampling was performed at the downwind locations of drilling operations to evaluate the transport of drill-generated dust. Conclusions from this sampling are that:

- The highest percentage of dust due to the drilling operation that was transported to downwind locations was 42 pct, measured within a 100-ft radius of the drill.
- The transport of respirable dust from drilling operations decreased rapidly with distance. The dust percentage decreased to 27.6 pct at 70 ft and 0.6 pct at 140 ft downwind.

CHARACTERISTICS OF QUARTZ FOUND IN COAL MINES

Studies were conducted at four underground coal mines to investigate fundamental physical characteristics of quartz produced from continuous mining machines (*10*). Data were collected for 15 individual cuts at continuous miner sections in these 4 mines. Face channel sampling, airborne dust sampling, and run-of-mine product sampling were conducted for each individual cut. Airborne dust and quartz samples were collected with personal gravimetric samplers (respirable and total dust) and Sierra model 298 Marple[7] cascade impactors (personal sampler for aerodynamic size classifications operating at 2 L/min). The grease used on the impactor substrates was a mixture of toluene and 20-pct petroleum jelly instead of the silicon-based grease, so the quartz analysis would not be affected by the grease. Bulk material and dust samples were analyzed with the P7 method for their quartz content to maintain a consistency between quartz analyses of dust and bulk samples. Bulk samples were processed to obtain a minus 400 mesh, which was then dispersed in a fluid and deposited on a filter before P7 analysis. The P7 infrared analysis was also used to determine the amount of kaolinite mineral (clay) in the dust of the impactor samples.

Channel samples were collected and analyzed for each selected cut to identify the amount of quartz in the premined material. These channel samples were collected directly from the face before a cut was mined. Data from all cuts sampled are shown in table A-10 of the appendix, and the quartz averages for each mine are summarized in figure 10. Results indicate that the main quartz sources are the roof rock (at all mines) and floor rock (at two of the mines). The rock thickness mined at all four mines averaged 25 pct of the total height extracted (mine A, 32 pct; mine B, 16 pct; mine C, 27 pct; and mine D, 23 pct).

During mining of each selected cut, respirable dust, total dust, and run-of-mine product were sampled for quartz analysis. Multiple airborne respirable and total samples were collected in the immediate return of the continuous miner for each cut. The run-of-mine product

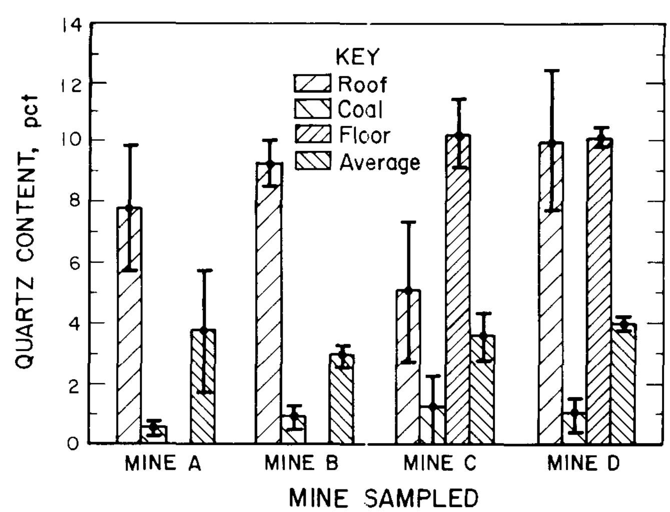

Figure 10.—Average quartz content in seam components of mines studied for fundamental quartz characteristics.

[7]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

sample was obtained by collecting individual samples from all the cars at the feeder-breaker. Processing of these samples for each cut involved preliminary screening, weighing, and cone and quartering into smaller samples for transportation out of the mine. Dust and mine product quartz data are shown in table A-11 of the appendix, and the averages for each mine are presented in figure 11. At three of the mines (A, C, and D), quartz content was observed to be higher in smaller particle size ranges. Respirable dust had the highest quartz content, and the mine product had the lowest quartz content. Mine B did not exhibit quartz content differences among the different particle size ranges as did the other three mines. A suspected reason for this anomaly is that the roof rock (the only rock mined) was mainly made up of draw slate that broke away easily during mining. The miner did not have to expend considerable energy to mill away the rock (from underground observation). Finally, mine B did extract the least amount of rock of the four mines.

Run-of-mine product samples for mines B and C were also size-classified for their coal and rock constituents. Run-of-mine samples of minus 1 in were subjected to float-sink tests at two specific gravities of 1.45 and 1.6. The float matter at the 1.45 separation is considered to be mostly coal, while the sink of 1.6 gravity is considered

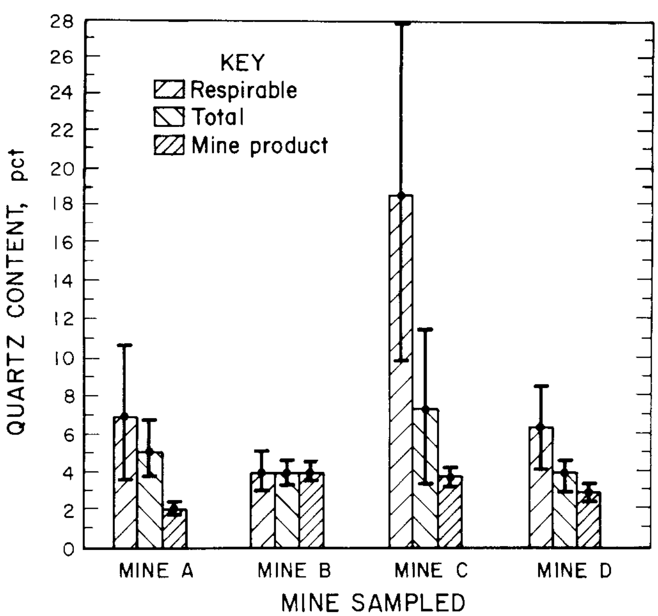

Figure 11.—Average quartz content of dust and mine product in fundamental studies. Error bars are at the 95-pct confidence level.

rock. Figure 12 shows the Schuhamanm size distribution plots of the coal and rock constituents of the mine product for mines B and C. From these graphs, it can be seen that the slope for the rock size distribution is less (mine B, 0.57; mine C, 0.65) than the slope for the coal distribution (mine B, 0.76; mine C, 0.87), meaning that the rock is made up of smaller particles. As an example, 10 pct of the rock and coal particles are below 0.24 and 0.57 mm, respectively, for mine B and 0.32 and 0.52 mm, respectively, for mine C.

Impactor sampling was also conducted in the immediate return, two crosscuts, and four crosscuts outby the face in the return air to provide additional data on how quartz content varies with the size of dust particles. Impactor dust samples were collected over nine cuts and analyzed

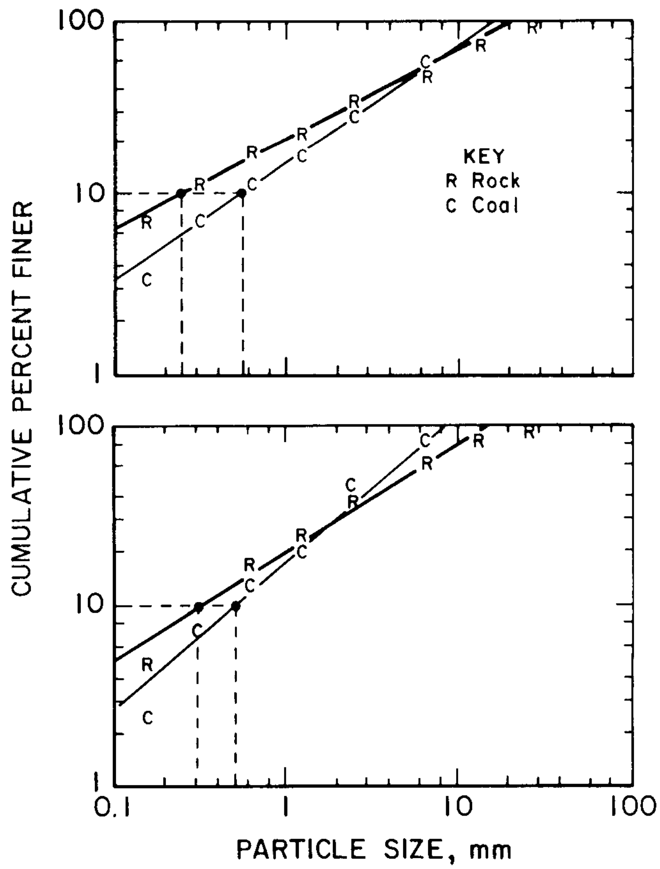

Figure 12.—Schuhamanm size distributions of rock and coal product from mine B (top) and mine C (bottom). Material sized is minus 1 in to plus 400 mesh. Dashed lines indicate 10-pct levels for rock and coal, respectively.

for their quartz and kaolinite mineral content. Quartz and kaolinite results from the sampling are shown in tables A-12 and A-13 of the appendix. The average quartz content in the return for three dust size ranges is shown in figure 13, and individual mine results are shown in figures 14 and 15.

Several stages of the impactor samples had to be combined for a significant amount of mass for quartz analysis. The size distribution ranges combined and analyzed for quartz included 0.6 to 3.5, 3.5 to 10, and 10 to 21 µm. The procedure of combining the various dust masses from the stages was designed to maximize the number of samples that possessed the minimum desired 25 µg of quartz mass for analysis. This procedure was successful in creating the proper quartz mass in 64 pct of the impactor samples analyzed. The P7 method has a 13- to 22-pct measurement error for 25 to 250 µg of quartz. Some of the impactor samples (mostly the 0.6- to 3.5-µm range) possess a lower precision than this as a result of less weight.

Results for aerodynamically sized quartz indicate that the quartz content tends to increase for smaller sized particles when significant amounts of rock are cut. This smaller size segregation of quartz can be observed from the average of all mines shown in figure 21. Quartz content in the 10- to 21-µm dust was significantly lower than in the other two smaller size ranges. The 0.6- to 3.5-µm dust on average had a higher quartz content than the 3.5- to 10-µm dust, but had more variance in measurements than the two larger size ranges. This variability was most likely caused by the diminished precision of quartz analysis for the lower masses collected in this size range and the diversity in rock cut. The degree of quartz size segregation varied widely among the individual mines, indicating a high dependency on the coal seam lithology and/or rock morphology (figs. 14-15). Also, quartz content was observed to be fairly consistent at the various return locations during each cut, especially at mines B, C, and D (see table A-12 of the appendix and variances in figure 15).

Further data examination indicates that the degree of size segregation of quartz in airborne dust may be directly related to the amount of rock mined (percentage of height mined) and the morphology of quartz-bearing rock. Mine C extracted large amounts of rock (27 pct by height) and was observed to have the greatest segregation of quartz by particle size (fig. 15). Mine B and cut 1 of mine A extracted notably smaller amounts of rock (16 and 12 pct, respectively) and had the least size segregation (figs. 14-15). Cut 2 at mine A extracted significantly more rock, and the size segregation of quartz increased.

Figure 16 shows the scatter plot of the quartz content in respirable dust samples versus the portion of rock mined (percentage of seam height) for all the cuts. This plot shows that there is a moderate correlation between

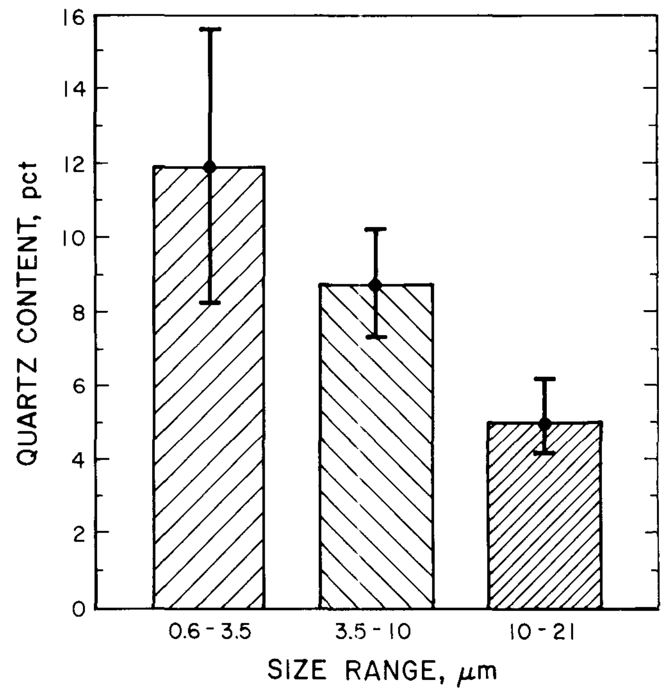

Figure 13.—Average quartz content of impactor samples from all mines. Error bars are at the 95-pct confidence level.

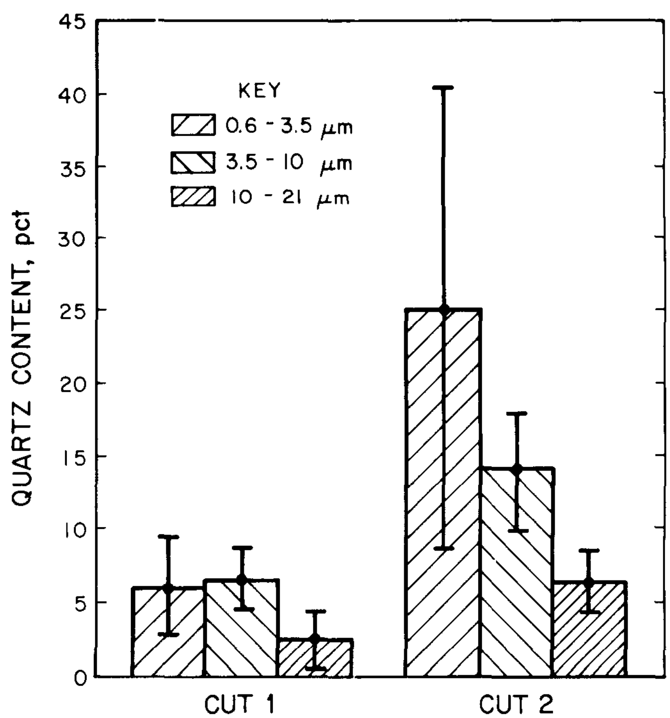

Figure 14.—Quartz content of impactor samples from mine A. Error bars are at the 95-pct confidence level.

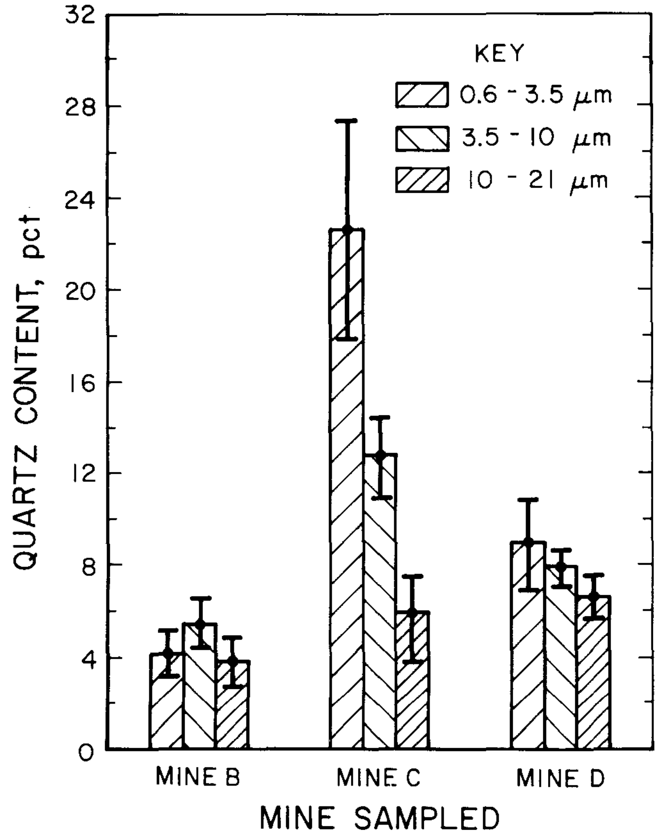

Figure 15.—Quartz content of impactor samples from mines B, C, and D. Error bars are at the 95-pct confidence level.

the amount of rock mined and quartz content in the respirable dust. However, the profound spread of some of the data points (especially the contrasting differences between mines A and C) indicates that some other unexplained factors exist.

Further examination into the percentages of quartz and kaolinite minerals detected in the impactor dust samples indicates that the structural bonding of the quartz in the rock may be another factor responsible for the amount and size segregation of the quartz dust generated. The impactor samples collected were analyzed for both quartz and kaolinite content. Figure 17 shows the average results of the mineral content in the impactor dust samples (0.6 to 21 μm) versus the weighted average of the quartz in the rock material mined. Both the quartz and kaolinite content in the dust for mine A notably increased from cut 1 to 2 with a significant increase in the amount of rock (sandstone) mined (12 pct to 39 pct). However, mine C mined 30 pct less rock (shale) than cut 2 of mine A and still had a notably higher quartz content in the dust than cut 2 of mine A, but discrepancies were observed between the kaolinite and quartz portions of the dust. At mine C, kaolinite content in the dust was significantly lower than the quartz content, and at mine A the kaolinite content was slightly higher than the quartz content. Also, although both mines C and D mined roughly similar amounts of shale and the quartz levels in the shale at D were higher, the quartz dust in mine D was notably lower. Kaolinite content at both of these mines was significantly lower than

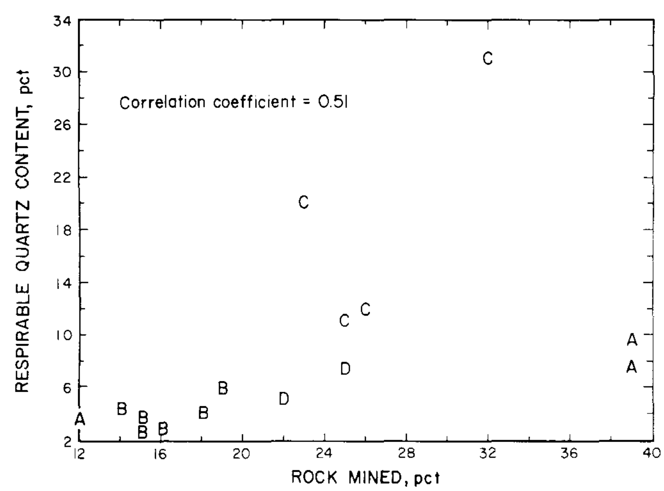

Figure 16.—Scatter plot of quartz content in respirable dust samples and amount of rock mined. Capital letters indicate mines.

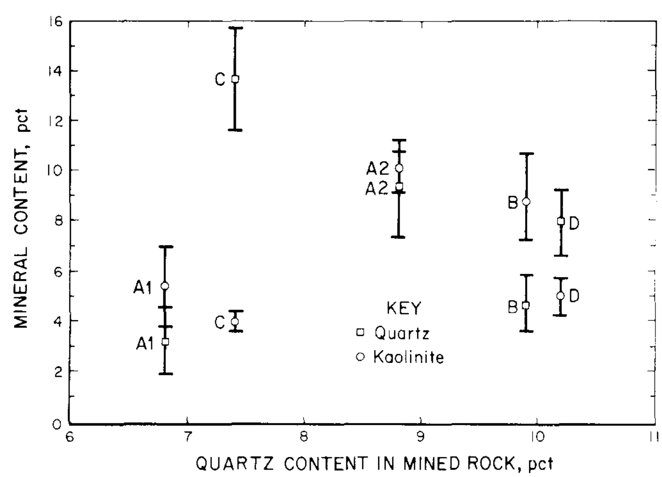

Figure 17.—Mineral content in impactor dust samples and quartz content in rock mined. Capital letters indicate mine data; numbers after letters indicate specific cuts. Error bars are at the 95-pct confidence level.

quartz content, but the kaolinite content was higher at mine D. These results indicate that although the amount of rock mined affects the amount and size characteristics of quartz dust generated, individual differences in the rock morphology are most likely another influential factor between mines.

IMPACT OF QUARTZ ON DUST CONTROL

The attributes of quartz dust discussed above present unique problems for existing dust control technology in coal mines. These problems stem from the fact that existing dust control technology is less efficient for smaller particles. The two most commonly used control technologies in underground coal mining are water sprays for dust suppression and flooded-bed scrubbers for dust collection. The Bureau has measured the inefficiency of these current technologies to adequately control quartz dust in coal mines.

Water sprays are the most common dust control technology utilized in underground coal mines, but their efficiency notably diminishes as particle size decreases (*11*). Figure 18 shows the relationships between water spray efficiency and dust particle size for two water spray pressures. These data were obtained with Anderson Cascade impactors (operating at 1 ft^3/min) from laboratory experiments in a dust box with a single hollow-cone nozzle to determine spray suppression capabilities (fig. 19). The low-water-pressure tests were conducted at 100 psi and 1.5 gpm, and the high-pressure tests were conducted at 2,500 psi and 1.35 gpm with a high-pressure nozzle. Both efficiencies are normalized and expressed in percent reduction per gallon of water. The 100-psi test condition is representative of an underground situation. This test showed that the spray efficiency rapidly decreased when dust particle size was below 2.52 μm. The 2,500-psi high-pressure tests showed a dramatic improvement for suppression efficiency. However, high-pressure water systems are far from implementation in underground coal mines.

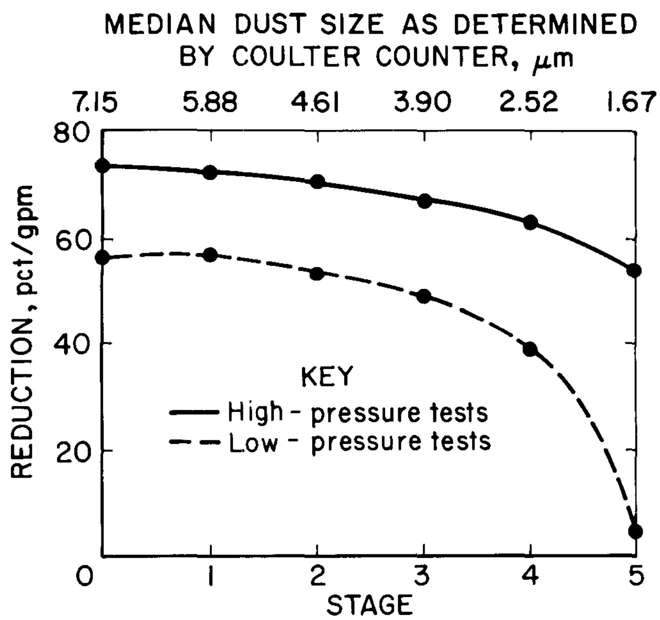

Figure 18.—Water spray dust collection efficiency on various particle sizes.

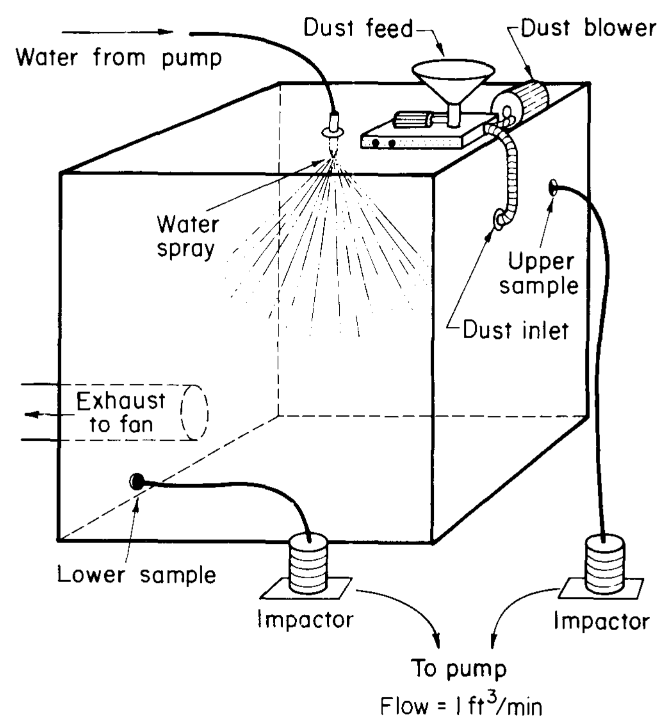

Figure 19.—Water spray laboratory test setup.

The second most common dust control system used on continuous miner sections is the fibrous flooded-bed scrubber. Figure 20 shows a boom-mounted system with the inlets located close to the cutter head. These scrubbers have been proven to be one of the most efficient technologies for controlling respirable dust generated by the continuous mining machine. However, the Bureau has discovered that their efficiency in collecting quartz dust is diminished.

A continuous miner section having difficulty with quartz dust while using blowing face ventilation with a flooded-bed scrubber prompted an underground study by the Bureau to identify any technological deficiencies with the scrubber (*12*). Results from this study indicated that the scrubber was not as efficient on quartz dust as on coal dust. The mine studied had return dust reductions over 40 pct, but the quartz fraction was reduced by only 15 pct, increasing the quartz percentage of dust from 11.3 pct at the face area to 15.7 pct in the return. This study indicated that a potential problem existed with the ability of the flooded-bed scrubber to control quartz dust.

Followup experiments on the flooded-bed scrubber were conducted by the Bureau to verify the presumably inferior scrubber efficiency in quartz dust collection under strictly controlled laboratory conditions (*13*). Tests were performed on a standard 40-layer stainless steel scrubber panel. Results from these tests, shown in figure 21, indicate that the scrubber is less efficient on quartz dust than on coal dust as measured on the basis of equivalent aerodynamic size. The reason for this difference is believed to be the smaller absolute size distribution of the quartz dust compared with coal dust. Anderson Cascade impactors were used to collect the data in the laboratory setup shown in figure 22. These experiments verified that the standard flooded-bed scrubber technology (40-layer stainless steel scrubber panel) has an inferior collection efficiency for the control of quartz dust in underground coal mines.

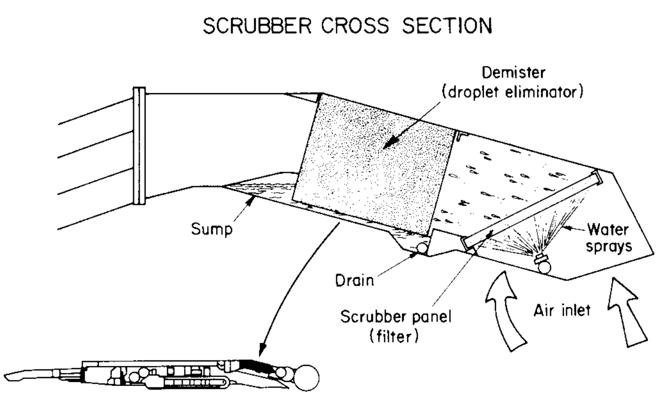

Figure 20.—A fibrous flooded-bed scrubber.

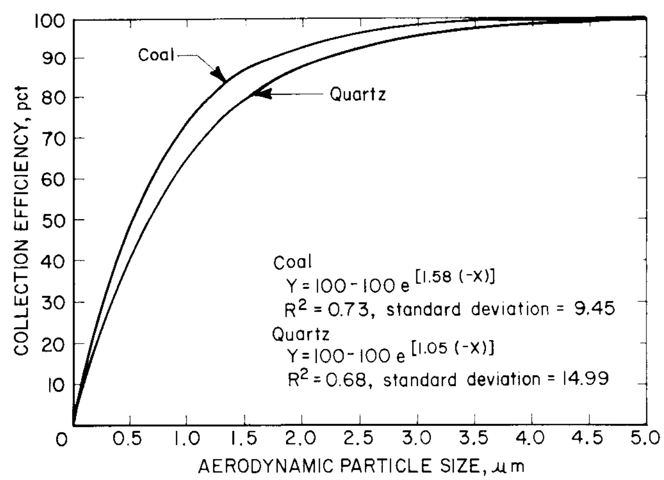

Figure 21.—Scrubber efficiency curves for coal and quartz dust.

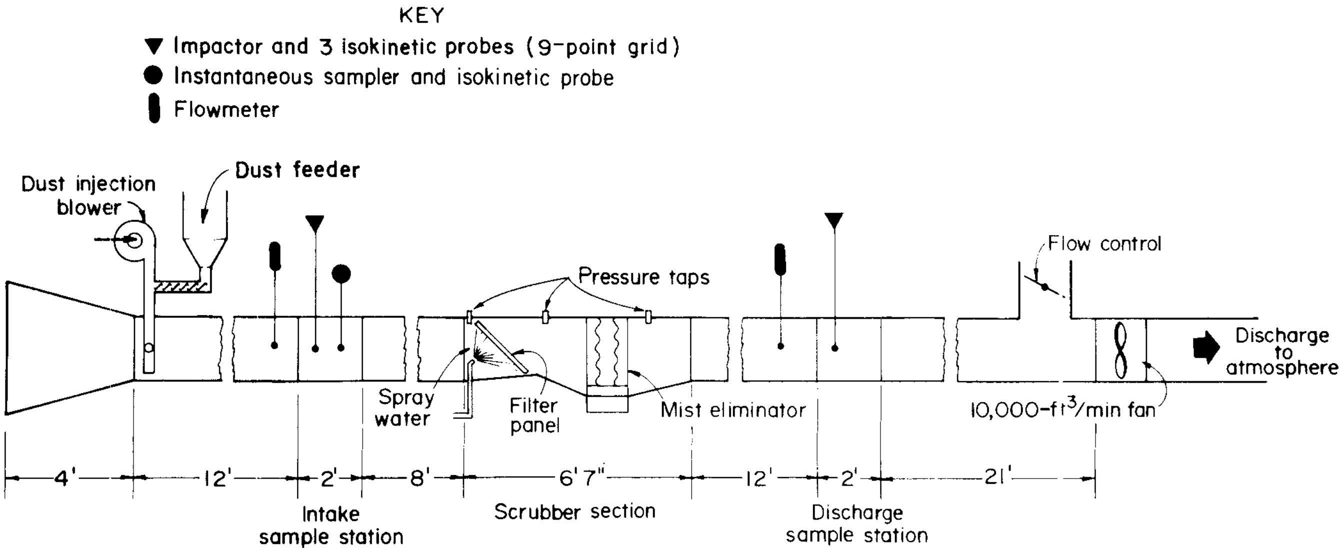

Figure 22.—Scrubber efficiency laboratory test setup.

CONCLUSIONS

Quartz dust has been identified as the most important health concern in coal mines since the early 1980's, and it is frequently generated from mechanical cutting of rock by a continuous mining machine in underground mines or by drilling of rock overburden at surface mines. In underground mines, numerous people are exposed to quartz dust because secondary support operations (roof bolting) take place on the return side of the mining machine. At surface mining operations, usually only the drill operator and helper are exposed to quartz dust because the dust dissipates a short distance away from the drill rig.

Quartz within the dust was found to be segregated into smaller size ranges when considerable amounts of rock were mined. This size segregation appears to be interrelated to rock morphology. Also, quartz content in the dust remained fairly uniform up to several hundred feet in the return of the dust source, demonstrating the mobility of quartz dust from the generation source in underground ventilation systems. These unique attributes impede existing dust control technology from adequately controlling quartz dust in the coal mining industry.

Laboratory testing of both water sprays and scrubbers established the deficiencies of existing technology in combating quartz dust in coal mines. Both water spray and scrubber control technology have been shown to exhibit lower collection efficiencies for smaller sized dusts. Other evidence of inadequate technology to control quartz dust is the considerable percentage of compliance samples that contain more than 5 pct quartz. One-third of the dust samples collected in coal mines contain more than 5 pct quartz (*3*).

To combat this ongoing quartz dust problem, research should focus first on technology to increase suppression, capture, and agglomeration of smaller sized dust particles. Second, advanced cutting technologies should be addressed, to enhance the efficiency and reliability of cutting systems in rock in order to reduce the amount of quartz fines from mechanical comminution. Finally, the morphology of minerals in rock types and the liberation mechanisms involved should be investigated to provide long-term direction for pioneering novel quartz dust prevention and control technology.

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APPENDIX.—SAMPLING RESULTS AND ANALYSIS[1]

Table A-1.—Respirable dust concentrations from area sampling at continuous sections (in milligrams per cubic meter)

Mine	Roof bolter upwind	Continuous miner operator cab	Continuous miner return	Roof bolter downwind
A	1.17∓0.80	2.33∓0.58	5.24∓1.71	1.66
B	.33∓ .14	4.99∓1.91	6.43∓1.80	4.64∓3.11
C	1.32∓1.18	3.65∓1.15	11.64∓2.23	NM
D	.42∓ .42	2.05∓ .97	7.05∓1.96	1.48∓1.07
E	.55∓ .23	2.86∓2.76	9.54∓4.81	8.06∓3.35
F[1]	.47∓ .18	1.60∓ .35	1.51∓ .30	1.30∓ .31
G	1.23∓ .98	2.40∓1.00	2.00∓ .84	.65∓ .15
H	.62∓ .15	1.48∓ .48	3.79∓ .87	4.90∓1.70

NM Not measured.
[1]Blowing ventilation with flooded-bed scrubber on continuous mining machine.

Table A-2.—Quartz fraction of respirable dust from area sampling at continuous sections (in percent)

Mine	Roof bolter upwind	Continuous miner operator cab	Continuous miner return	Roof bolter downwind
A	12.1∓2.6	13.8∓2.0	13.0∓0.9	9.5
B	4.4	11.8∓ .9	12.3∓ .4	12.6∓1.6
C	9.3∓3.9	7.7∓2.3	7.6∓ .4	NM
D	6.2	15.5∓5.7	15.6∓2.4	17.6∓6.5
E	5.6∓2.5	5.4∓1.7	5.0∓ .5	6.0∓1.1
F[1]	15.1∓5.3	10.6∓3.0	10.8∓2.8	13.8∓5.8
G	3.3	2.2∓ .7	2.2∓1.0	2.9
H	6.1∓3.4	4.5∓2.7	3.8∓ .2	2.6∓ .8

NM Not measured.
[1]Blowing ventilation with flooded-bed scrubber on continuous mining machine.

Table A-3.—Quartz content of materials mined at continuous sections (in percent)

Mine	Roof rock	Rock parting	Floor rock	Collector cuttings	Mine	Roof rock	Rock parting	Floor rock	Collector cuttings
A	26	38	82	52	E	28	NAp	34	39
B	28	NAp	42	44	F	22	NAp	32	38
C	56	48	18	54	G	32	NAp	26	37
D	40	NAp	60	66	H	32	NAp	40	40

NAp Not applicable.

[1]All confidence intervals are at the 95-pct confidence level.

Table A-4.—Quartz percentage and mass (in micrograms) measured along longwall face

Mine	Process	Quartz measure	Shield 10	30	60	90	110
A	H-T clean	Pct	0.0	0.2	0.0	0.0	0.1
	..do.	Mass	0	1	0	0	2
	T-H cut	Pct	0.5	0.0	0.0	0.0	0.0
	..do.	Mass	2	1	0	0	0
B	H-T clean	Pct	0.6	2.5	2.0	2.0	NAp
	..do.	Mass	8	43	29	30	NAp
	T-H cut	Pct	0.2	4.2	2.0	7.2	NAp
	..do.	Mass	1	38	38	94	NAp
C	H-T cut	Pct	1.2	3.1	6.1	9.5	12.8
	..do.	Mass	12	22	68	86	141
	T-H cut	Pct	0.1	0.8	3.0	7.8	8.3
	..do.	Mass	1	8	24	55	75

H Headgate.
NAp Not applicable.
T Tailgate.

Table A-5.—Dust concentrations and quartz content at conventional and continuous operations

Mine	Sampling location	Dust concentration, mg/m³	Quartz dust, pct	Quartz in rock, pct
A	Conventional return	2.91∓0.62	2.6∓0.7	34
	Continuous return	25.89∓6.59	8.3∓3.5	32
B[1]	Conventional return	3.70∓ .90	1.2∓1.0	32
	Continuous return	3.51∓ .14	5.1∓1.5	32

[1]Blowing face ventilation was used at this mine with a fibrous flooded-bed scrubber on the continuous mining machine.

Table A-6.—Dust concentrations and quartz content in underground outby areas

Mine	Sampling location	Dust concentration, mg/m³	Quartz dust, pct	Quartz in rock, pct
A[1]	Shuttle car entry	0.25∓0.11	12.6∓5.2	38
B[1]	..do.	.37∓ .10	6.6∓2.0	35
C[1]	..do.	.48∓ .08	5.7∓1.5	46
D[1]	..do.	.30∓ .11	13.1∓4.6	55
E	Feeder breaker	.69∓ .53	3.4∓3.9	22
F	..do.	1.03∓1.05	6.6∓3.9	34
	..do.	1.01	4.9	32
H	..do.	2.06∓ .62	2.6∓ .8	32
	..do.	2.07	4.2	32
I	Belt dump to rail	.88∓ .30	6.9∓2.8	21
	Main trolley entry	.34∓ .21	.7∓ .3	21
	Haulage motors[2]	.34∓ .08	2.1∓ .7	21
J	Main belt	1.43∓ .52	.6∓ .1	31
K	..do.	1.49∓ .08	.4∓ .1	8
L	Section belt	1.17∓ .57	.5∓ .2	7
	Feeder breaker	.83∓ .67	.3∓ .1	7

[1]Same A, B, C, and D mines as in tables A-1 through A-3.
[2]Used sand containing 98 pct quartz for sanding rails.

Table A-7.—Average respirable dust concentrations from area sampling around surface coal drills[1] (in milligrams per cubic meter)

Mine	Dust control[2]	Upwind (1)	Collector (2)	Collector (3)	Shroud (4)	Shroud (5)	Shroud (6)	Drill platform (7)
A	On, dry ..	0.07∓0.09	36.90∓ 61.18	45.10∓22.19	NM	NM	7.50∓ 11.19	9.58∓11.76
	Off	.08	6.70	12.00	NM	NM	272.00	42.80
B	On, dry ..	.59∓ .66	1.34∓ 1.63	2.54∓ 2.80	NM	NM	6.57∓ 1.69	2.73∓ .53
	Off	.48∓ .39	28.10∓ 10.70	22.90∓ 6.24	NM	NM	311.00∓ 84.28	47.40∓ 3.17
C	On, dry ..	.10∓ .06	8.52∓ 4.72	NM	NM	4.77∓ 3.76	2.72∓ 2.49	.83∓ .56
	Off	.10∓ .06	179.00∓143.75	NM	NM	144.00∓121.93	57.70∓ 53.70	2.12∓ 2.17
D	On, wet ..	.26∓ .20	NM	NM	3.36∓ 3.16	6.62∓ 10.64	5.95∓ 8.30	10.90∓13.28
	Off	.31∓ .30	NM	NM	16.00∓ 11.37	11.70∓ 8.19	11.40∓ 10.58	23.50∓26.36
E	On, wet ..	.15∓ .06	NM	NM	3.34∓ 2.68	4.12∓ 2.78	1.95∓ 1.28	NM
	Off	.20∓ .10	NM	NM	55.00∓ 18.56	80.10∓ 20.80	50.90	NM
F	On, wet ..	.15∓ .05	NM	NM	7.59∓ 3.48	11.46∓ 5.60	12.08∓ 15.77	NM
	Off	.17∓ .04	NM	NM	21.40∓ 3.64	24.30∓ 12.44	15.80∓ 10.99	NM
G	On, dry ..	.07∓ .04	NM	NM	4.61∓ 4.70	11.50∓ 18.84	4.66∓ 3.95	3.97∓ 1.13
	Off	.06∓ .07	NM	NM	346.00∓493.39	200.00∓134.85	553.00∓839.18	19.40∓21.08
H	On, dry ..	.01∓ .00	NM	NM	4.58∓ 5.34	1.40∓ 1.11	4.25∓ 7.84	.79∓ .95
	Off	.01	NM	NM	126.00	583.00	116.00	16.60
I	On, dry ..	.08∓ .02	11.30∓ 9.32	NM	NM	46.60∓ 35.36	99.00∓ 63.71	18.90∓ 4.38
	Off	.09∓ .03	NM	NM	NM	575.00	358.00	194.00

NM Not measured.
[1]Sampling locations are shown in figure 8.
[2]Dry = dry dust collector; wet = water injection.

Table A-8.—Average quartz content in respirable dust samples around surface coal drills[1] (in percent)

Mine	Dust control[2]	Upwind (1)	Collector (2)	Collector (3)	Shroud (4)	Shroud (5)	Shroud (6)	Drill platform (7)
A	On, dry	0.0	2.3∓1.3	1.3∓0.7	NM	NM	2.0∓2.4	1.7∓1.9
	Off	.0	6.0	4.0	NM	NM	.8	3.6
B	On, dry	2.2∓ 4.2	3.2∓2.9	4.2∓1.8	NM	NM	3.7∓4.6	.7∓ .5
	Off	6.1∓ 6.0	2.7∓2.0	4.5∓1.7	NM	NM	4.7∓3.4	3.4∓2.1
C	On, dry	3.0∓ 2.0	3.7∓1.5	NM	NM	3.4∓1.2	4.8∓3.9	3.9∓2.8
	Off	2.9∓ 2.4	3.7∓ .7	NM	NM	4.6∓2.9	3.1∓2.4	2.7∓3.3
D	On, wet ...	.9∓ .7	NM	NM	3.0∓2.6	2.5∓2.3	1.6∓1.4	4.2∓1.9
	Off	1.0∓ 1.0	NM	NM	4.1∓3.0	4.1∓3.7	1.9∓1.7	4.1∓1.4
E	On, wet ...	.6∓ 1.1	NM	NM	7.3∓2.5	7.4∓2.4	6.2∓ .4	NM
	Off	.0∓ .0	NM	NM	11.6∓3.2	8.7∓ .5	6.9	NM
F	On, wet ...	.0∓ .0	NM	NM	6.0∓1.5	6.4∓ .8	5.4∓1.5	NM
	Off	.0∓ .0	NM	NM	4.4∓1.0	8.0∓4.1	3.7∓2.7	NM
G	On, dry	10.0∓11.3	NM	NM	7.3∓2.7	6.7∓2.2	8.5∓2.7	7.6∓2.5
	Off	10.0∓19.5	NM	NM	1.6∓2.2	3.4∓ .2	4.6∓3.3	4.4∓ .2
H	On, dry	.0∓ .0	NM	NM	3.7∓2.8	3.0∓1.7	1.4∓1.7	5.8∓2.5
	Off	.0	NM	NM	2.8	1.9	3.9	3.4
I	On, dry	.0∓ .0	6.2∓1.3	NM	NM	4.5∓ .7	4.5∓ .7	4.8∓ .3
	Off	.0	NM	NM	NM	2.4	1.5	1.5

NM Not measured.
[1]Sampling locations are shown in figure 8.
[2]Dry = dry dust collector; wet = water injection.

Table A-9.—Quartz content in drill cuttings around surface coal drills (in percent)

Mine	Drill cuttings: Dust control on	Drill cuttings: Dust control off	Dust collector discharge	Mine	Drill cuttings: Dust control on	Drill cuttings: Dust control off	Dust collector discharge
A	31.00	22.00	NM	F	64.00	61.00	NM
B	49.00	51.00	NM	G	35.00	20.00	43.00
C	56.00	69.00	53.00	H	24.00	24.00	37.00
D	34.00	44.00	NM	I	31.00	37.00	40.00
E	58.00	56.00	NM				

NM Not measured.

Table A-10.—Type, thickness, and quartz content of materials mined for fundamental quartz characteristics study

Mine	Cut	Roof mined: Type	Roof mined: Thickness, in	Roof mined: Qtz, pct	Coal mined: Type	Coal mined: Thickness, in	Coal mined: Qtz, pct	Floor mined: Type	Floor mined: Thickness, in	Floor mined: Qtz, pct	Average channel: Thickness, in	Average channel: Qtz, pct
A . . .	1	Sandstone . .	6	6.8	Upper Freeport.	46	0.6	NM	NM	4.8	52	1.8
	2	. . do.	30	8.8	. . do.	46	.5	NM	NM	3.5	76	4.8
	3	. . do.	30	NA	. . do.	46	.8	NM	NM	7.6	76	4.9
B . . .	1	Draw slate . .	15	9.2	Pittsburgh . .	69	.5	NM	NM	NA	84	2.8
	2	. . do.	15	10.1	. . do.	66	1.0	NM	NM	NA	81	3.6
	3	. . do.	11	10.5	. . do.	70	.8	NM	NM	NA	81	2.8
	4	. . do.	11	8.3	. . do.	62	1.8	NM	NM	NA	73	3.3
	5	. . do.	12	8.4	. . do.	64	.8	NM	NM	NA	76	2.9
	6	. . do.	12	8.8	. . do.	67	1.0	NM	NM	NA	79	2.8
C . . .	1	Shale	6	4.9	No. 2 Gas . .	48	3.6	Shale . . .	8	9.4	62	4.8
	2	. . do.	7	4.3	. . do.	42	.7	. . do. . . .	8	9.8	57	3.1
	3	. . do.	10	2.8	. . do.	42	.3	. . do. . . .	10	9.8	62	2.9
	4	. . do.	10	8.4	. . do.	48	.5	. . do. . . .	6	11.8	64	3.5
D . . .	1	. . do.	7	8.8	Eagle	68	1.3	. . do. . . .	12	10.0	87	4.0
	2	. . do.	14	11.2	. . do.	61	.9	. . do. . . .	6	10.2	81	4.1

NA Not analyzed.
NM Not measured.

Table A-11.—Quartz content in dust and mine product for fundamental quartz characteristics study (in percent)

Mine	Cut	Respirable quartz dust	Total quartz dust	Run-of-mine quartz	Mine	Cut	Respirable quartz dust	Total quartz dust	Run-of-mine quartz
A	1	3.6	3.6	1.9	C	1	20.0	9.8	3.8
	2	9.7	6.3	2.1		2	12.0	4.0	4.2
	3	7.6	5.5	NA		3	31.0	12.0	3.2
B	1	4.2	5.2	4.6		4	11.2	3.6	4.1
	2	6.1	4.1	2.9	D	1	5.2	3.6	3.3
	3	4.4	3.7	3.5		2	7.5	4.5	2.8
	4	2.5	2.9	4.0					
	5	2.9	4.4	4.0					
	6	3.8	3.8	3.9					

NA Not analyzed.

Table A-12.—Quartz results from impactor sampling of fundamental quartz characteristics study (in percent)

Mine	Cut	Sampler location	Particle size ranges			
			0.6-3.5 µm	3.5-10 µm	10-21 µm	0.6-21 µm
A	1	Face return	8.3	7.9	0.6	1.8
	1	2 crosscuts	2.3	4.3	4.4	4.1
	1	4 crosscuts	7.3	7.3	2.2	3.8
	2	Face return	11.5	10.6	7.0	8.4
	2	2 crosscuts	41.1	15.0	7.8	11.3
	2	4 crosscuts	22.8	17.0	4.5	8.5
B	1	Face return	5.7	7.4	4.8	6.2
	1	2 crosscuts	4.3	8.2	5.3	6.2
	1	4 crosscuts	4.4	7.0	4.8	5.6
	2	Face return	2.6	4.4	4.0	3.7
	2	2 crosscuts	2.8	2.4	1.5	2.2
	2	4 crosscuts	3.1	4.0	2.2	3.2
	3	Face return	6.0	5.1	2.0	4.7
	3	2 crosscuts	4.2	6.0	5.4	5.4
	3	4 crosscuts	4.8	5.3	4.7	5.0
C	1	Face return	25.9	16.0	9.5	16.4
	1	2 crosscuts	23.0	12.8	6.3	13.6
	1	4 crosscuts	22.0	12.8	2.0	14.2
	2	Face return	11.5	9.7	4.9	8.6
	2	2 crosscuts	29.2	13.1	6.2	14.8
	2	4 crosscuts	23.8	12.5	6.6	14.0
D	1	Face return	6.1	6.3	4.7	5.9
	1	2 crosscuts	7.2	8.1	6.2	7.4
	1	4 crosscuts	6.1	7.6	5.2	6.5
	2	Face return	14.0	9.5	6.9	9.8
	2	2 crosscuts	9.1	8.1	7.4	8.3
	2	4 crosscuts	11.6	8.5	9.1	9.8

Table A-13.—Kaolinite results from impactor sampling of fundamental quartz characteristics study (in percent)

Mine	Cut	Sampler location	Particle size ranges			
			0.6-3.5 µm	3.5-10 µm	10-21 µm	0.6-21 µm
A	1	Face return	13.2	14.4	1.8	3.8
	1	2 crosscuts	.8	10.9	4.9	6.3
	1	4 crosscuts	2.7	12.2	4.2	6.3
	2	Face return	22.2	15.8	6.0	10.2
	2	2 crosscuts	15.2	13.1	9.2	10.8
	2	4 crosscuts	8.4	20.0	4.8	9.2
B	1	Face return	16.4	10.9	7.4	11.6
	1	2 crosscuts	14.9	11.5	8.1	11.1
	1	4 crosscuts	13.6	11.2	4.7	9.0
	2	Face return	13.0	8.4	5.4	8.5
	2	2 crosscuts	7.4	3.7	2.4	4.2
	2	4 crosscuts	10.8	6.1	3.9	6.5
	3	Face return	11.1	5.4	.7	6.5
	3	2 crosscuts	17.4	11.0	5.6	12.0
	3	4 crosscuts	12.9	9.5	6.1	9.8
C	1	Face return	5.3	2.8	3.0	3.4
	1	2 crosscuts	4.9	3.4	5.0	4.2
	1	4 crosscuts	4.7	3.8	.7	3.6
	2	Face return	6.4	3.8	2.6	4.0
	2	2 crosscuts	6.3	4.6	3.0	4.6
	2	4 crosscuts	5.5	4.0	2.7	4.0
D	1	Face return	11.3	5.2	3.5	6.8
	1	2 crosscuts	10.5	4.5	.3	5.2
	1	4 crosscuts	9.6	3.3	2.8	4.6
	2	Face return	10.7	3.9	.5	4.5
	2	2 crosscuts	7.7	5.2	2.3	5.4
	2	4 crosscuts	7.4	2.5	.8	4.2

*U.S. Government Printing Office: 1990 — 511-010/40010