RI 9425

REPORT OF INVESTIGATIONS/1992

Relationship of Coal Seam Parameters and Airborne Respirable Dust at Longwalls

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UNITED STATES DEPARTMENT OF THE INTERIOR

MARCH 3, 1849

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Library of Congress Cataloging in Publication Data:

Organiscak, John A.
Relationship of coal seam parameters and airborne respirable dust at longwalls / by J.A. Organiscak, S.J. Page, and R.A. Jankowski.

p. cm. — (Report of investigations; 9425)

Includes bibliographical references (p. 14).

1. Coal mines and mining—Dust control. 2. Longwall mining—Environmental aspects—United States. 3. Bituminous coal—United States. I. Page, Steven J. II. Jankowski, Robert A. III. Title. IV. Series: Report of investigations (United States. Bureau of Mines); 9425.

TN23.U43 [TN312] 622 s—dc20 [622'.83] 92-10263 CIP

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Btu	British thermal unit	mg	milligram
Btu/lb	British thermal unit per pound mass	mg/m^3	milligram per cubic meter
cfm	cubic foot per minute	mg/ton	milligram per short ton
fpm	foot per minute	pct	percent
in	inch	wt pct	weight percent
in/rev	inch per revolution		

RELATIONSHIP OF COAL SEAM PARAMETERS AND AIRBORNE RESPIRABLE DUST AT LONGWALLS

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

ABSTRACT

The U.S. Bureau of Mines investigated the relationship of bituminous coal seam parameters and the amount of airborne respirable dust generated at longwalls. Dust and coal samples were obtained from 20 longwalls operating in geographically representative coalfields throughout the United States. Statistical analyses of coal seam parameters and airborne respirable dust measurements indicate a likely causal relationship between seam type and respirable dust.

Low-ash, high-volatile coal seams were associated with higher airborne respirable dust levels. A negative linear correlation (significant at the 95-pct confidence level) was observed between the seam's ash content and airborne respirable dust, explaining up to 18 pct (R^2 = 0.18) of headgate dust level variation and up to 15 pct of tailgate dust level variation. Volatile matter was found to have a positive linear correlation with tailgate dust level, explaining 16 pct of the variation. Further data examination indicates that these relationships with dust are most likely nonlinear, because of improved R^2 values over the linear correlations. However, a notable portion of longwall dust production is influenced by other operational parameters, so additional research under more controlled conditions is needed to determine the seam's causative functions.

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[1] Mining engineer.

[2] Physicist.

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INTRODUCTION

Health researchers have strongly suspected a relationship between dust generation and coal seam type, and numerous studies have been conducted over the past 25 years to identify this relationship. Several researchers have studied the relationship between coal rank and the prevalence of Coal Workers' Pneumoconiosis (CWP) (*1-4*).[4] Some of these studies found a strong positive correlation and others found a range of weak to very little positive correlation. Thus, there is still some uncertainty regarding the relationship between coal rank and CWP.

Other researchers have conducted laboratory studies on the relationships between coal rank, macerals, grindability, and particle size (*5-6*). These studies have shown conclusively that there is a significant relationship between coal rank and grindability, and there is a significant relationship between grindability and amount of respirable-sized particles found in the product. The relationship between grindability and particle size is not surprising since the Hardgrove grindability index (HGI) is based on particle sizing criteria (*7*). However, none of these studies actually related airborne respirable dust to grindability.

After the enactment of the Federal Coal Mine Health and Safety Act of 1969 in the United States, one field study by the U.S. Bureau of Mines established mean dust exposure differences among various occupations in the industry and another field study by the Bureau showed a significant difference in dust exposure for the same occupations in different coal mines and/or seams (*8-9*). The causes of these differences between coal seams could not be quantified, but the differences indicated that coal seam characteristics were one of the likely factors responsible. Under contract to the Bureau, the Southwest Research Institute extensively reviewed the present knowledge of airborne respirable dust generation and provided several insightful hypotheses relating coal chemistry and mineralogy (rank, volatility, and ash) to dust generation (*10*). Furthermore, Bureau observations on prior longwall dust studies indicated notable differences in dust levels in various seams using similar dust control technology. This report describes a recent underground study to determine if type of bituminous coal seam is an influential factor in airborne dust generation. This work is part of the Bureau's program to improve the health of the Nation's miners by reducing their exposure to respirable dust.

SURVEY STRATEGY

This investigation focused on surveying longwall mining operations. Active longwall mining (shearer) sections were chosen because of the presumed similarities and simplicity in the face ventilation arrangements (head-to-tail ventilation) for dust sampling. Also, longwall operators' compliance with the respirable dust standard has recently started to decline (fig. 1) with continued increases in longwall production. Many of the traditional types of dust control technologies are maturing, and further refinement of these traditional technologies may not provide the additional effectiveness needed for more advanced, higher production longwall systems. Therefore, the Bureau is seeking fundamental principles relating seam parameters to airborne dust generation in order to develop and pioneer novel control technology for reducing the amount of respirable dust that becomes airborne. This study was the first phase in identifying any seam parameters associated with airborne respirable dust generation for future causal principle research.

Since a randomized sample was economically impractical because of the large distances between geographical areas of the country, a "nonprobability purposive" sampling strategy was used. This strategy encompasses drawing a nonprobability sample that conforms to a certain criterion.

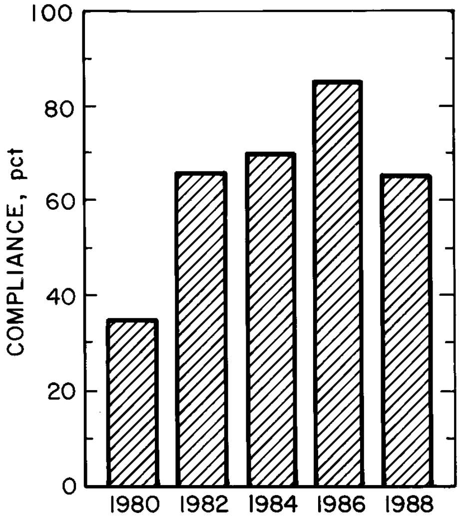

Figure 1.—Percentage of U.S. longwalls in compliance with the Federal dust standard.

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

The criterion used for this study was to obtain a representative sample of longwalls operating in the different bituminous seam types (five bituminous classifications of coal of the American Society for Testing and Materials (ASTM)) and in different geographic areas of the country. The minimum number of longwalls needed in a random survey to obtain a representative dust sample of the longwall industry population was 11, based on a targeted precision of ±0.5 mg/m^3 at the 95-pct confidence level with a longwall industry standard deviation of 0.85 mg/m^3 (from Mine Safety and Health Administration (MSHA) data). However, 16 longwall sections were surveyed in 15 different coal seams to increase industry coverage since a random sample could not be obtained. Two shifts of sampling were planned throughout the study and were achieved at 13 of the 16 sections surveyed, for a total of 29 shifts of sampling. Secondary data available from 4 other past longwall studies were also used to increase the data base to 20 mines, 17 coal seams, and 33 data files.

Data collected for each shift included dust samples, coal samples, ventilation measurements, production during sampling, and other general mine characteristics. Multiple respirable dust samples were collected at support 10, and roughly 10 supports inby the tailgate of each longwall, with personal sampling instruments. Dust sampling was planned to take place for a minimum of four complete mining passes or face advances. This production goal during sampling was achieved in 70 pct of the shifts sampled. Average airborne dust data collected at the sampling locations are shown in table A-1 of the appendix. Production during sampling was determined from face advance, seam height, face width, and density.

Coal samples were collected from the face conveyor at various times during production. These samples were combined, mixed, coned, and quartered to obtain a small representative sample of the run-of-mine product. These samples were packaged into small airtight containers for transport out of the mine to the laboratory for proximate and Hardgrove grindability analysis. Processing of these coal samples was conducted using ASTM proximate analysis and HGI classification procedures. Proximate analysis and HGI data are shown in table A-2 of the appendix.

The sample set collected approximates a normal distribution for bituminous class coals. Figure 2 shows the types of coals in the different coal provinces of the United States; table 1 shows the ASTM coal classifications; and

Table 1.—ASTM standards for coal classification

Class and group	Fixed carbon limits,[1] pct	Volatile matter limits,[1] pct	Calorific value limits,[2] Btu/lb	Agglomerating character
Anthracite:				
Metaanthracite	≥98	<2	≥14,000	Nonagglomerating.[3]
Anthracite	92-98	2- 8	≥14,000	
Semianthracite	86-92	8-14	≥14,000	
Bituminous:				
Low-volatile	78-86	14-22	≥14,000	Commonly agglomerating.[4]
Medium-volatile	69-78	22-31	≥14,000	
High-volatile A	<69	≥31	≥14,000	
High-volatile B	<69	≥31	13,000-14,000	
	<69	≥31	11,500-13,000	
High-volatile C	<69	≥31	10,500-11,500	Agglomerating.[5]
Subbituminous:				
Subbituminous A ...	<69	≥31	10,500-11,500	Nonagglomerating.
Subbituminous B ...	<69	≥31	9,500-10,500	
Subbituminous C ...	<69	≥31	8,300- 9,500	
Lignitic:				
Lignite A	<69	≥31	6,300- 8,300	
Lignite B	<69	≥31	<6,300	

[1] Dry, mineral-matter-free basis.

[2] Moist, mineral-matter-free basis. "Moist" refers to the natural inherent moisture of the coal, does not include visible water on the surface.

[3] If agglomerating, classify in low-volatile group of the bituminous class.

[4] There may be nonagglomerating varieties in these groups.

[5] There are notable exceptions in this group.

NOTE.—Coals having 69 pct or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of calorific value.

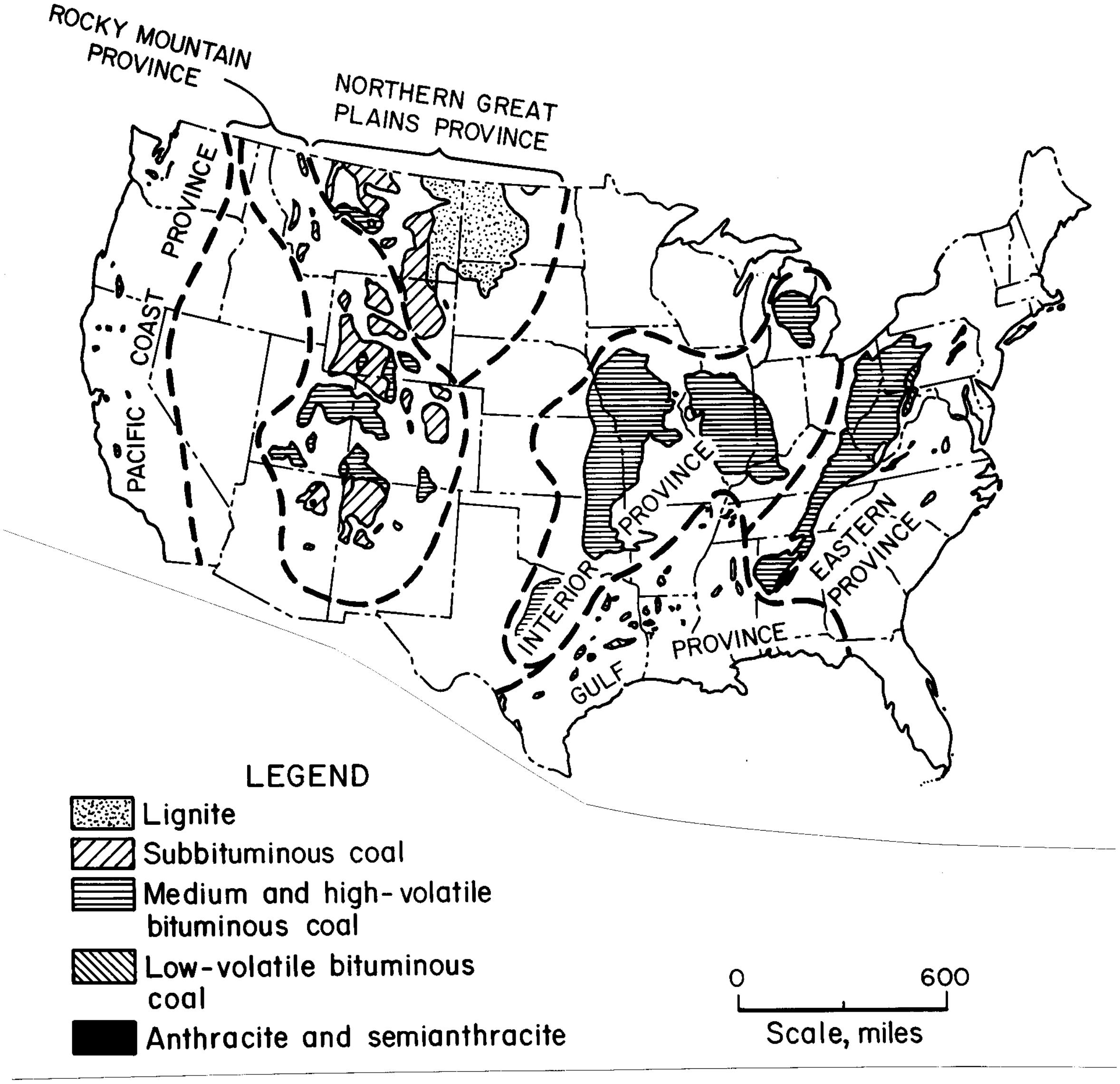

Figure 2.—U.S. coal provinces.

figure 3 shows a frequency histogram of the set of 33 samples divided into the 5 bituminous groups. Medium- and high-volatile A bituminous coal are the most common types of coal in the United States, and the sample data collected correspond to a normal distribution within this bituminous class of coal. Table 2 illustrates the use of the chi-square (χ^2) statistic to test the hypothesis that the sample frequency distribution approximates an assumed normal distribution of bituminous coal in the U.S. coal provinces (*11*). The low-volatile and high-volatile C bituminous coal groups were combined with adjacent groups because their frequency was below the recommended group levels for computation of a chi-square test statistic. The hypothesis could not be rejected at the 95-pct confidence level, so it was believed that a representative sample of bituminous coal seams was obtained.

Ventilation measurements and other general descriptive data were collected from each operation. Velocity measurements were made at the dust sampling locations and at 10 support intervals along the face. Headgate, tailgate, and average face velocity and quantity data are shown in table A-3 of the appendix. General information of the operations sampled, such as mine location, seam, height, face width, and cut sequence used, is shown in table A-4 of the appendix.

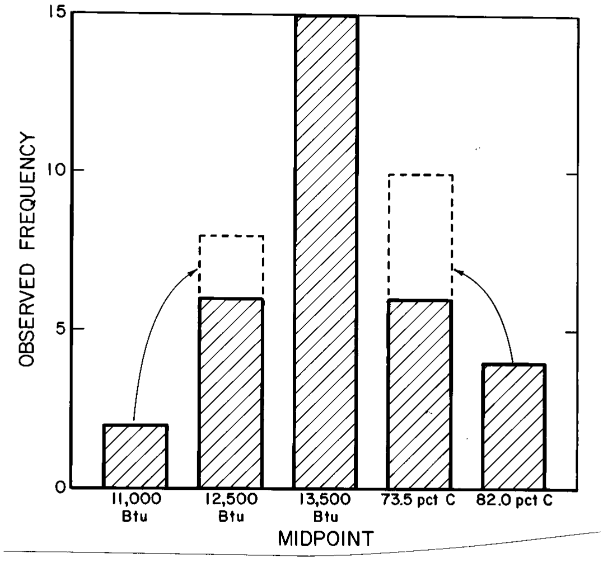

Figure 3.—Frequency histogram of coal seam types sampled.

Table 2.—Chi-square (χ^2) test of sample distribution

Bituminous coal	Midpoint	Adjusted midpoint	Boundary (X_L)	z	Area 0-z	Net area	Expected frequency (Ei)	Observed frequency (Oi)
			10,500 Btu	-3.18	0.4993			
High-volatile C . . .	11,000 Btu							
		12,000 Btu	11,500 Btu	-2.14	.4838	0.2803	9	8 (2 + 6)
High-volatile B . . .	12,250 Btu							
			13,000 Btu	-.58	.2190			
High-volatile A . . .	13,500 Btu	13,500 Btu				.3962	13	15
			14,000 Btu, 69 pct C	.46	.1772			
Medium-volatile . .	73.5 pct C							
		77.5 pct C	78 pct C	1.87	.4693	.3216	11	10 (6 + 4)
Low-volatile	82.0 pct C							
			86 pct C	3.04	.4988			

Heat content: $\bar{x}$ = 13,561 Btu
s = 962 Btu

Carbon content: $\bar{x}$ = 54.6 pct
s = 7.7 pct

$z = (X_L - \bar{x})/s$

$\chi^2 = \sum_{i=1}^{k} (Oi - Ei)^2/Ei$

<u>χ^2 test</u>

H_o: Oi = Ei
H_a: Oi ≠ Ei

Let $\alpha = 0.05$
n = 33

Test over 3 intervals:
df = 2, $\chi^2_{0.05} = 5.99$

$$\chi^2 = \frac{(8-9)^2}{9} + \frac{(15-13)^2}{13} + \frac{(10-11)^2}{11} = 0.510$$

Since $\chi^2_{0.05} > \chi^2_{\text{calculated}}$ ∴ cannot reject H_o

IDENTIFICATION OF SIGNIFICANT COAL SEAM PARAMETERS

A correlation matrix was used to examine the interdependence of coal seam parameters and to identify the most important and independent coal seam characteristics with respect to the airborne dust criteria (fig. 4). The measure of association (correlation) used in this matrix is the Pearson product-moment coefficient (r), including sample size and level of significance (p-value) (*11*). The level of significance is the probability that the variable association is false (Type I error). The dust criterion (dependent variable) is expressed in both concentrations and airborne respirable mass measured per short ton mined during the sampling period (specific dust) at both the headgate and tailgate sampling locations. The actual airborne dust generated per short ton could not be reliably calculated and used as a criterion variable because of notable variations between the headgate and tailgate air quantities at many of these longwalls (see table A-3 of the appendix). The average percent change in air quantity between the headgate and tailgate had a coefficient of variation of 1,160 pct (mean = -3.8 pct, standard deviation = 44.1 pct). The wide variation of the percent change in air quantity along the face for all the longwalls makes this parameter unreliable for specific dust determination.

Examination of the coal seam parameter correlations show strong associations among several parameters. Some of the strongest and most significant correlations are between ash and sulfur, ash and heat content, ash and volatility, volatility and HGI, and volatility and moisture content. This is not surprising since various combinations of these parameters affect the carbon content or rank, which is related to the heat content and hardness (HGI) properties of the coal.

Moisture content	Sulfur content	Ash content	Volatile content	Heat content	HGI	Headgate dust conc	Headgate specific dust	Tailgate dust conc	Tailgate specific dust	
1.000 (33) 0.000	-0.316 (33) 0.074	-0.365 (33) 0.037	0.566 (33) 0.001	-0.175 (33) 0.330	-0.387 (33) 0.026	0.042 (32) 0.818	-0.032 (32) 0.860	0.125 (33) 0.487	0.004 (33) 0.982	Moisture content
	1.000 (33) 0.000	0.796 (33) 0.000	-0.436 (33) 0.011	-0.597 (33) 0.000	0.391 (33) 0.024	-0.226 (32) 0.213	-0.232 (32) 0.202	-0.302 (33) 0.088	-0.234 (33) 0.190	Sulfur content
		1.000 (33) 0.000	-0.531 (33) 0.002	-0.767 (33) 0.000	0.296 (33) 0.944	-0.404 (32) 0.022	-0.427 (32) 0.015	-0.329 (33) 0.061	-0.386 (33) 0.027	Ash content
			1.000 (33) 0.000	0.211 (33) 0.238	-0.857 (33) 0.000	0.199 (32) 0.275	0.051 (32) 0.782	0.405 (33) 0.019	0.201 (33) 0.262	Volatile content
				1.000 (33) 0.000	0.031 (33) 0.865	0.248 (32) 0.171	0.358 (32) 0.044	0.149 (33) 0.408	0.282 (33) 0.113	Heat content
					1.000 (33) 0.000	-0.091 (32) 0.622	0.084 (32) 0.649	-0.383 (33) 0.028	-0.099 (33) 0.583	HGI
						1.000 (32) 0.000	0.909 (32) 0.000	0.483 (32) 0.005	0.631 (32) 0.000	Headgate dust conc
							1.000 (32) 0.000	0.356 (32) 0.046	0.709 (32) 0.000	Headgate specific dust
								1.000 (33) 0.000	0.757 (33) 0.000	Tailgate dust conc
									1.000 (33) 0.000	Tailgate specific dust

KEY

1.000	Correlation coefficient (r)
(33)	Sample size
0.000	Significance level (p)

Figure 4.—Correlation matrix of seam parameters and dust criteria.

Examination of all the seam parameters and the airborne dust criteria show that ash had the highest correlation (significant at the 95-pct confidence level) with dust concentration (r = -0.40, p = 0.02) and specific dust (r = -0.43, p = 0.02) at the headgate sampling location, explaining 16 and 18 pct (R^2 values) of the variation, respectively. At the tailgate, volatility had the highest correlation (r = 0.40, p = 0.02) with the dust concentration, and ash had the highest correlation (r = -0.38, p = 0.03) with specific dust, explaining 16 and 14 pct of the variation, respectively. Ash and volatility are significantly and negatively correlated with one another (r = -0.53, p = 0.00), so the ash was also fairly correlated with dust concentrations at the tailgate (r = -0.33, p = 0.06). Therefore, it was generally concluded that high-volatile, low-ash coal seams tend to experience higher airborne respirable dust levels. Several operational parameters measured (water application, maximum bit depth, etc.) were found to have insignificant correlations with dust concentrations, and their associations will not be included in any further discussions. Figure 5 shows the three-dimensional scatter plot of ash and volatility with respect to the dust concentration at the tailgate.

Scatter plots of individual coal seam parameters and dust (concentration and specific) indicate that indeed ash and volatility were the parameters with the strongest relationships, and these relationships could be accurately characterized as nonlinear in nature. Figures 6 to 9 show

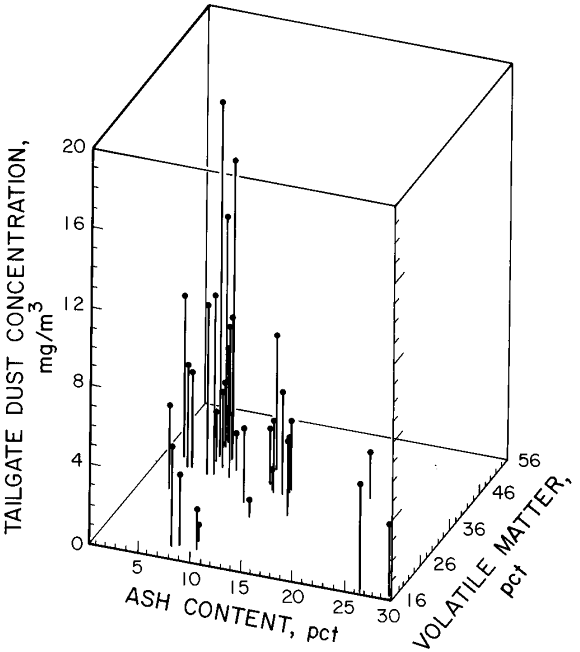

Figure 5.—Scatter plot of ash content, volatile matter, and tailgate dust concentration.

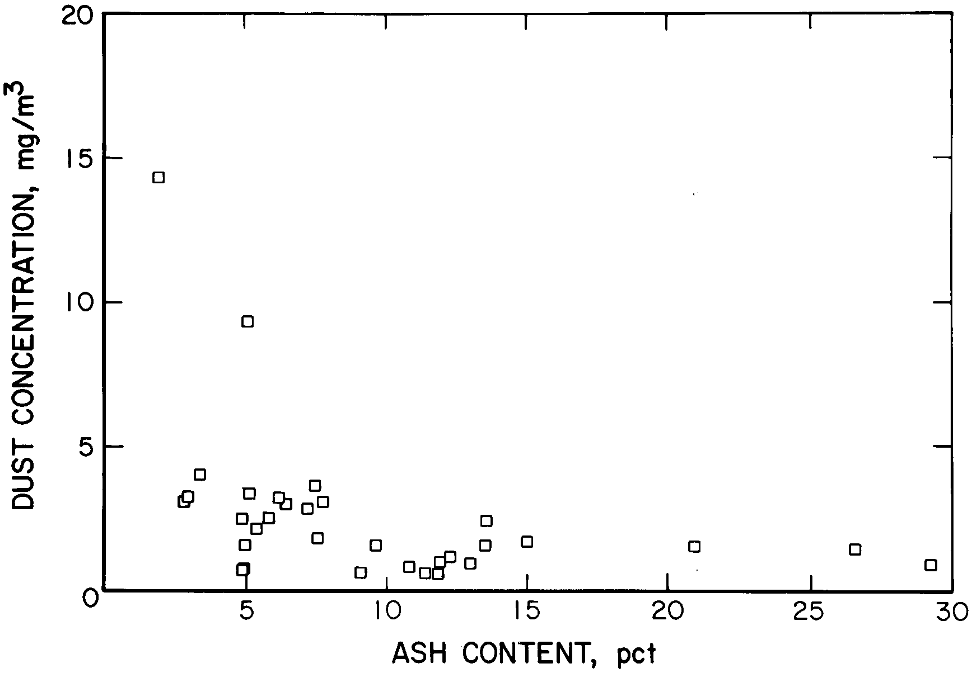

Figure 6.—Scatter plot of ash and headgate dust concentration.

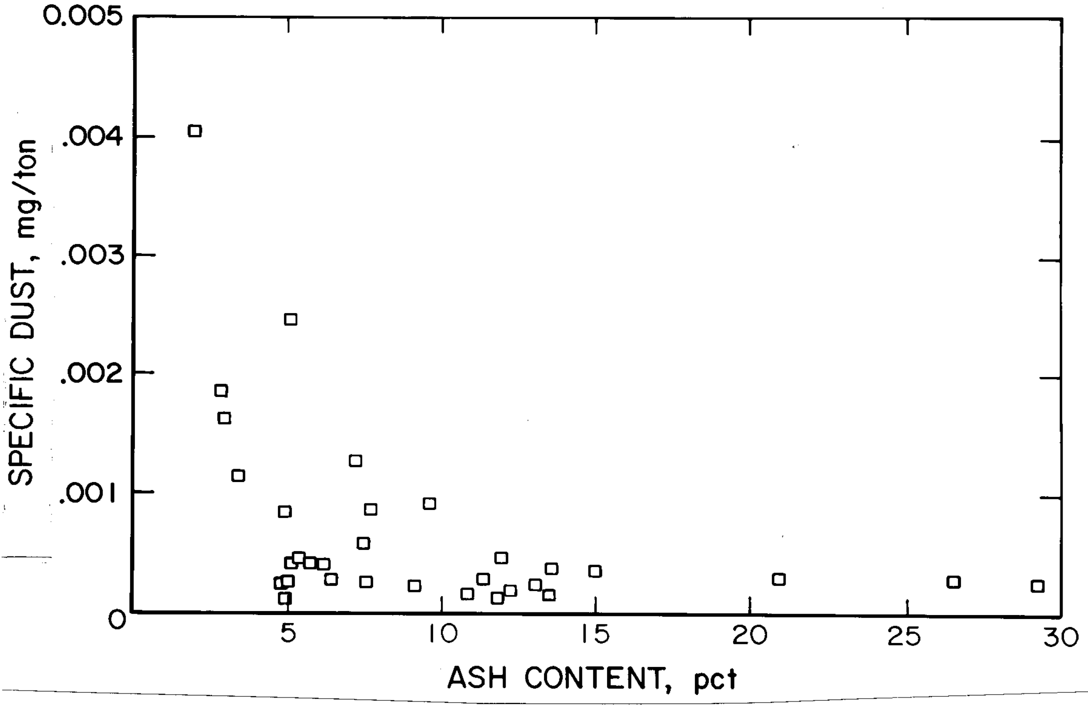

Figure 7.—Scatter plot of ash and headgate specific (normalized) dust.

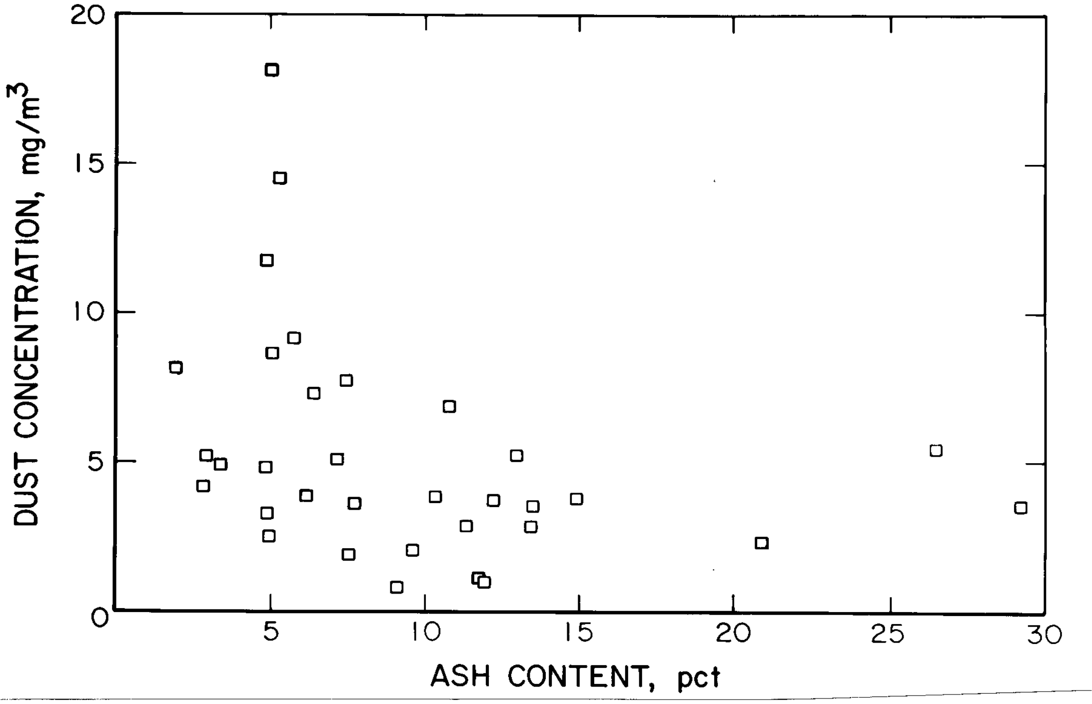

Figure 8.—Scatter plot of ash and tailgate dust concentration.

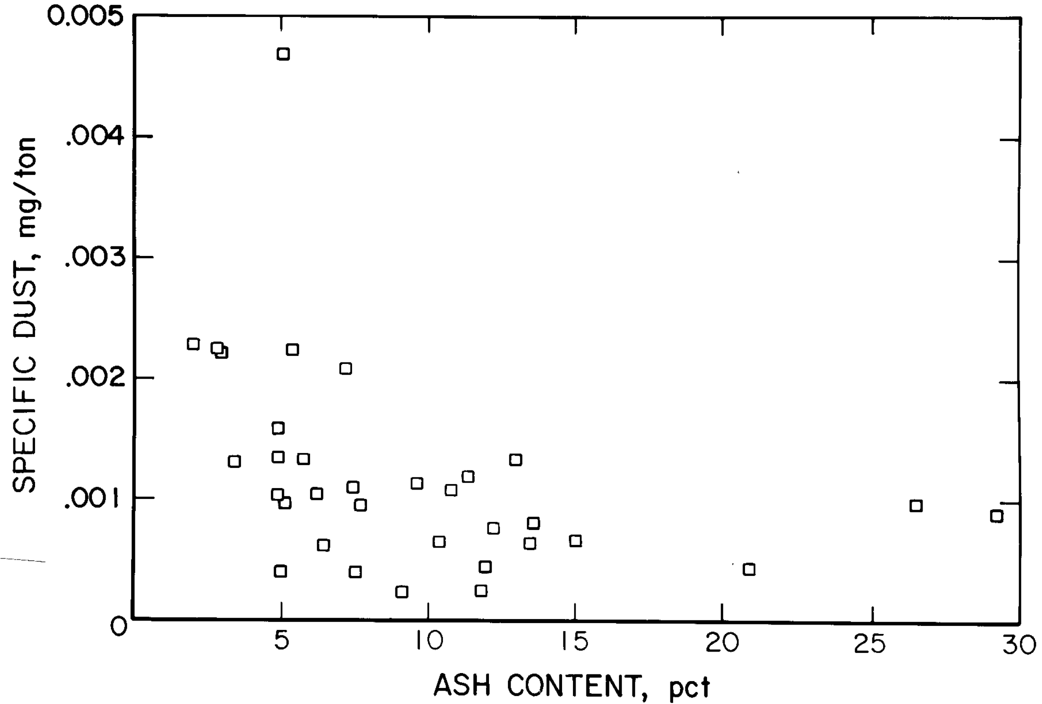

Figure 9.—Scatter plot of ash and tailgate specific (normalized) dust.

the scatter plots for the ash and dust data. It appears that the ash parameter could better fit several decay models ($y = ae^{-bx}$ and $y = ax^{-b}$) for both the dust concentrations and specific (normalized) dust criteria at both the face locations. The parameters and fit statistics of these models are shown in tables A-5 and A-6 of the appendix. Explanation of the dust variation can be increased to 70 pct (R^2 value) at the headgate and 27 pct at the tailgate with the $y = ax^{-b}$ model. Although the $y = ax^{-b}$ model is more efficient than the $y = ae^{-bx}$, it is not a valid model because there is no finite limit to dust generation. Therefore, cautious judgment should be used with parametric modeling analysis of the survey data because of the fair amount of data scatter not accounted for by the ash parameter and because of the limited amount of data at the extreme ranges of seam types, which can enormously affect the determination of model parameters. The tailgate data were found to have much more scatter than the headgate data, which was probably because more source contributions were measured at the tailgate (shearer and supports). Since too many uncontrolled and unmeasured parameters exist in the underground mining environment, controlled laboratory experiments are recommended to determine the most reliable and valid model of the ash parameter.

The volatility and dust concentration relationship at the tailgate was found to be roughly the opposite of the ash relationship (fig. 10). The volatility data may be better described a polynomial model ($y = a - bx + cx^2$). However, caution again is advised with this type of model determination because of the data scatter (more scatter than the ash parameter data) and the low number of points for low-volatile coals.

Since HGI is usually cited as an indicator of coal seam dustiness, it has been examined to observe if this parameter is associated with the airborne respirable dust measured. The only strong association found was a significant negative correlation between HGI and tailgate dust concentrations ($r = -0.38$, $p = 0.03$; see figure 4, the correlation matrix), explaining 14 pct of the dust variation. This HGI and tailgate dust concentration association also coincides with the volatile parameter because HGI and volatile matter are also highly and negatively correlated ($r = -.86$, $p = 0.00$). Figure 11 shows the scatter plot of HGI versus the tailgate dust concentrations. A decay nonlinear model would probably better describe the association, but this analysis is cautioned against because of the scatter in the data.

Although a negative correlation between HGI and dust was observed (significant at the 95-pct confidence level),

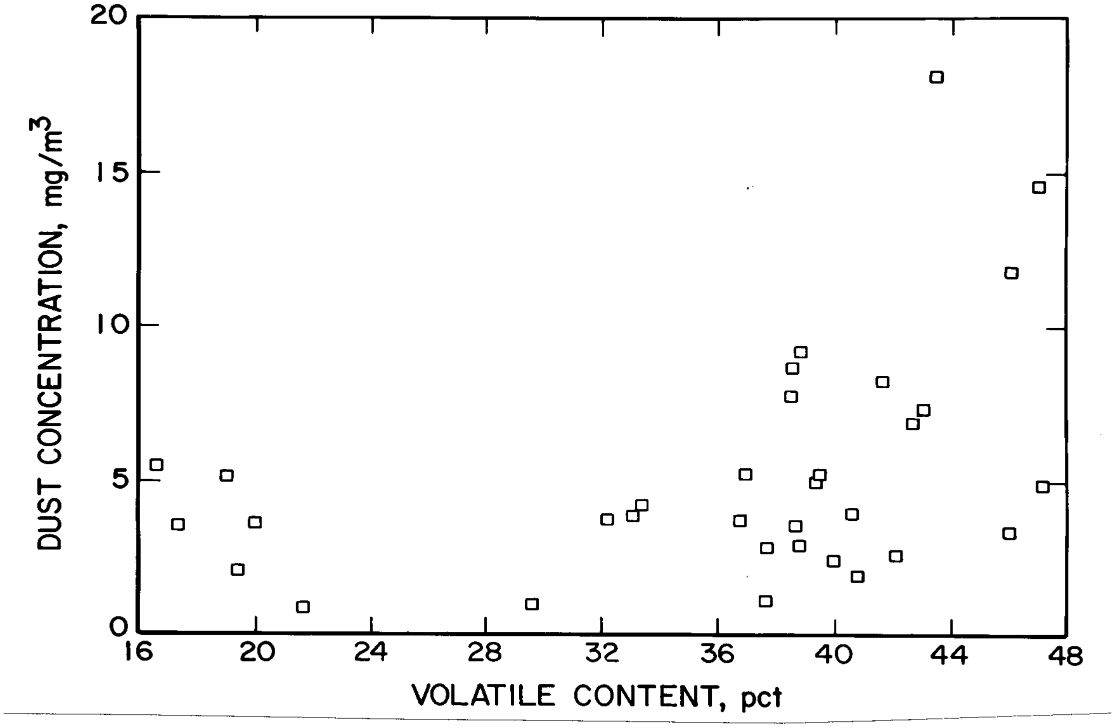

Figure 10.—Scatter plot of volatile matter and tailgate dust concentration.

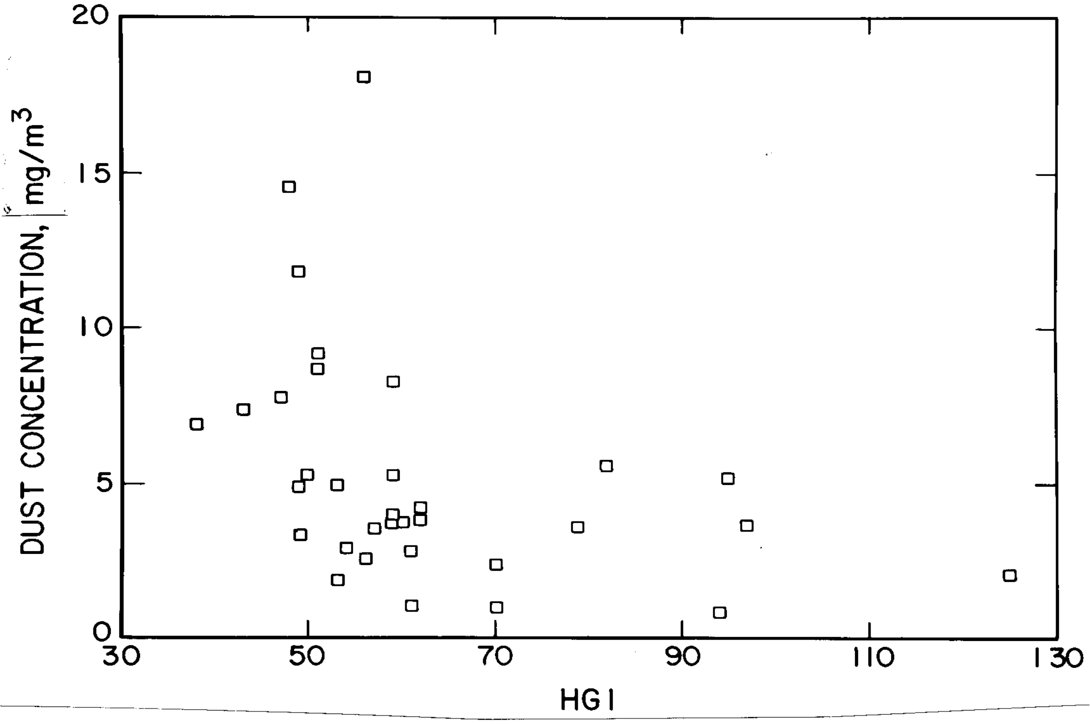

Figure 11.—Scatter plot of HGI and tailgate dust concentration.

this relationship is contrary to the speculated from relationship. The theorized relationship is a positive correlation between HGI and dust generation, derived from laboratory grinding tests. A potential reason for this discrepancy is that the amount of dust entrained into the airstream may not be directly proportional to the amount generated in the product because some other coal seam parameter affects airborne dust generation or entrainment, such as ash and/or volatility.

Some other secondary data that support this hypothesis are the data obtained at two continuous miner sections in two different coal seams (table 3) (*12*). These data were obtained from several individual cuts. The Pittsburgh Coal Seam had a lower HGI index (61) than the No. 2 gas seam (70) and less respirable dust measured in the mined product. However, the Pittsburgh Seam had a significantly higher amount of airborne dust (concentrations and percent airborne per amount in product) measured in the return. Dust concentrations were 300 pct higher and the portion of airborne dust per respirable dust in run-of-mine product was 318 pct higher in the Pittsburgh Seam than in the No. 2 gas seam. Although no proximate analysis was conducted on these coal samples (not part of the original study), the No. 2 gas seam generally has a higher ash and lower volatile content than does the Pittsburgh Seam. Thus, the authors believe that the amount of airborne respirable dust generated from mechanized cutting may not be directly related to HGI as theorized or assumed from laboratory studies. A National Coal Board study has also noted, "... stronger coals produce less dust than the weak, but break more explosively, causing a greater proportion of the fine dust formed to be dispersed into the air" (*13*). Bureau coal-cutting studies in the laboratory have indicated a direct trend between measured peak cutting forces and airborne respirable dust generation (*14*). The strong association of airborne respirable dust to ash and volatility observed from this longwall study indicates that some causal entrainment phenomena linked to these seam parameters may be responsible.

Table 3.—Differences in dust generation by continuous miners in two different coal seams

Coal seam	Pittsburgh	No. 2 gas
Seam height .... in . .	79	61
Number of cuts sampled.	6	4
HGI	61.0±0.5	70.4±2.0
Respirable dust generated in product .... mg/ton . .	5,458±595	5,955±879
Airborne respirable dust generated ...... mg/ton . .	1.32±0.59	0.33±0.10
Portion .... pct . .	0.023±0.012	0.0055±0.0017
Air quantity .... cfm . .	13,467±2,190	4,112±1,278

SEAM TYPES AND DUST COMPLIANCE

From this study it was generally concluded that low-ash, high-volatile coal seams produce more dust. Does this conclusion explain regional differences found in dust compliance rates throughout the MSHA districts in the country? To examine this connection, the seam parameters and dust concentrations (primary data) collected in different geographic provinces were averaged with 95-pct confidence intervals. MSHA compliance samples (secondary data) were also averaged for all longwall operations in these provinces. Figures 12 and 13 show the average seam types and dust concentrations measured for the Eastern, Interior, and Rocky Mountain Coal Provinces in this study, and figure 14 shows their compliance concentration averages for 1986-88 from MSHA data.

These data show that the average seam parameters and dust levels do vary between provinces. The Rocky Mountain Province on average has higher volatility and lower ash coal than the other provinces. This province also had the highest average dust concentration measured in this study and the highest average dust concentration from compliance sampling. The Eastern and Interior Provinces on average have lower volatility and higher ash coal seams. These provinces also had lower dust concentrations measured in this study and lower average dust

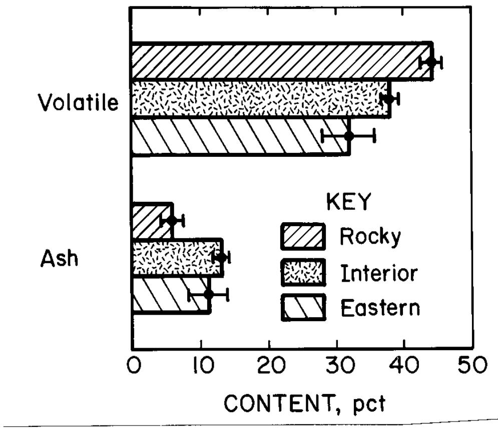

Figure 12.—Average ash and volatile content of provinces sampled.

concentrations from compliance sampling. Thus, the relative differences among the regional MSHA compliance dust data correspond to average regional seam types and dust levels measured in this study.

Similar ash-volatility and dust relationships were also found within the Eastern Province. Figures 15 and 16 show the ash-volatility content and dust concentrations measured within the Eastern Province. Significantly higher dust concentrations were observed at the four longwalls operating in lower ash, higher volatile coal seams. Since the secondary MSHA data concur with the data collected in this study, seam characteristics seem to be an important factor in the amount of dust generated and the ability to maintain compliance.

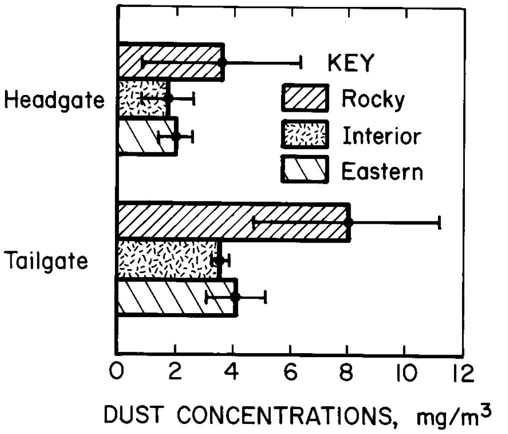

Figure 13.—Average dust concentrations of provinces sampled.

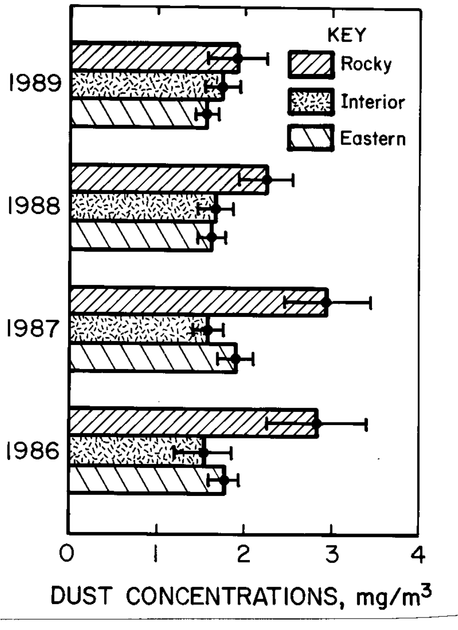

Figure 14.—Average dust compliance concentrations of provinces surveyed.

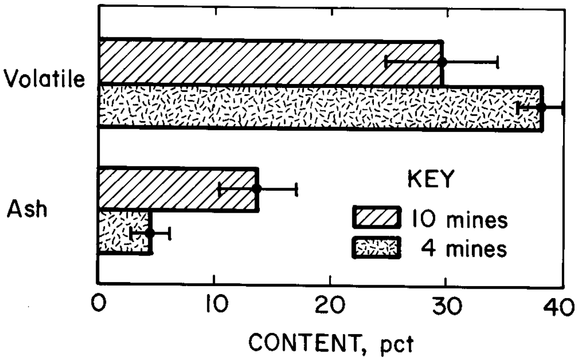

Figure 15.—Average ash and volatile content in two seam types sampled in the Eastern Province.

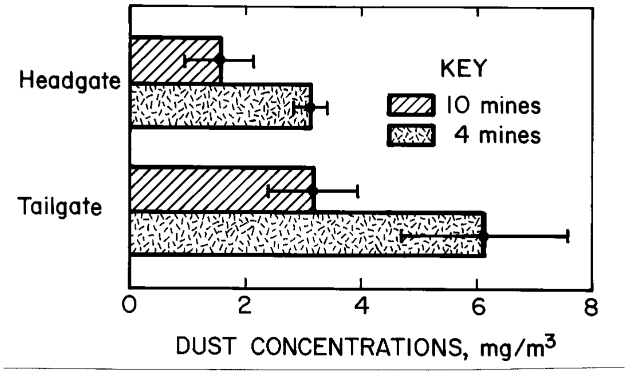

Figure 16.—Average dust concentrations in two seam types sampled in the Eastern Province.

DISCUSSION OF COAL SEAM PARAMETERS

In this longwall study, the Bureau found that low-ash, high-volatile bituminous coals tended to produce more airborne respirable dust. Although these were the chief parameters affiliated with airborne dust generation, their specific causal functions in airborne dust generation are not known. The actual dust generation phenomena may involve several interrelated coal parameters that have chemical and/or mineral causative mechanisms of airborne respirable dust generation. Three possible causative hypotheses are proposed below that could be considered for future research on coal seam airborne dust. The first two hypotheses were proposed by the Southwest Research Institute based on its basic research on coal fragmentation and dust entrainment conducted for the Bureau (*10*), and the third hypothesis was proposed by the authors of this report.

1. Coal fragmentation from cutting usually occurs along planes of imperfections formed by ash material (making the coal a more heterogeneous material), which facilitates breakage into a larger size distribution and reduces the amount of respirable dust generated. Note that ash content and HGI in this study have an insignificant correlation (fig. 4). This statistic indicates that the ash parameter has very little association with grindability and suggests that coal grinding properties may not be the best indicator for airborne respirable dust formed during cutting or haulage fragmentation.
2. Electrostatic charge on respirable coal dust, which is partially responsible for entrainment, may arise as a consequence of surface-air reactions (volatilization and oxidation). Chemical and mineralogical classification research on respirable-sized coal dust found an increase in both carbon and hydrogen content and a decrease in inorganic chemical content with increasing particle size. This may be due to volatilization of light hydrocarbon from the particle surface.
3. Electrostatic charge properties of ash minerals could possibly be responsible for dust coagulation, reducing the amount of respirable dust that becomes airborne. The major components of ash are typically silica, clay (kaolinite), and sulfur. Sulfur or iron pyrite was highly correlated to ash content, but was not as highly associated with airborne dust generation as was ash. Both sulfur and clay particles can have significantly higher electrostatic charges than coal particles (*15-16*).

These three hypotheses center around chemical or mineralogical causes affiliated with ash and volatility parameters identified in this study.

CONCLUSIONS

Coal seam parameters are associated with the amount of dust generated at longwalls. Low-ash, high-volatile bituminous coal seams tend to experience higher respirable dust levels during mining. The ash parameter could be better described by nonlinear decay models for both the dust concentration and specific dust criterion. The volatile matter parameter could better describe the tailgate dust concentrations by a polynomial growth model. HGI was found to be indirectly related to airborne respirable dust generation, contrary to the hypothesized belief of direct association.

The ash-volatility parameters and dust measurements in regional geographic areas (coal provinces) of the United States relatively agreed with MSHA compliance data. The Rocky Mountain Province averaged the highest dust levels for both this survey and MSHA compliance data. This province on average contains low-ash, high-volatile coal seams, coinciding with the ash relationship found in this study. The Eastern and Interior Provinces on average had lower volatile, higher ash coal seams with lower MSHA reported dust levels and higher compliance rates. This ash-volatility and dust relationship was also observed within the Eastern Province, which indicates that low-ash, high-volatile seams are not located only in one province.

Additional research studies should strive to verify the ash and volatility association with airborne respirable dust under strictly controlled conditions by reducing the unexplained data scatter (most likely caused by numerous operational parameters). Reducing the data scatter will also improve nonlinear model development of these coal seam parameters. Further research efforts should target verification of the above suggested hypotheses or any other proposed hypotheses for developing fundamental principles of airborne dust generation.

REFERENCES

1. Morgan, W. K. C. The Prevalence of Coal Workers' Pneumoconiosis. Am. Rev. Respir. Dis., v. 98, 1968, pp. 306-310.

2. Bennett, J. G., J. A. Dick, Y. S. Kaplan, P. A. Shand, D. H. Shennan, D. J. Thomas, and J. S. Washington. The Relationship Between Coal Rank and the Prevalence of Pneumoconiosis. Br. J. Ind. Med., v. 36, 1979, pp. 206-210.

3. Naeye, R. L., J. K. Mahon, and W. S. Dellinger. Rank of Coal and Coal Workers' Pneumoconiosis. Am. Rev. Respir. Dis., v. 103, 1971, pp. 350-355.

4. Hurley, J. F., J. Burns, L. Copland, J. Dodgson, and M. Jacobsen. Coal Workers' Simple Pneumoconiosis and Exposure to Dust at 10 British Coal Mines. Br. J. Ind. Med., v. 39, 1982, pp. 120-127.

5. Baafi, E. Y., and R. V. Ramani. Rank and Maceral Effects on Coal Dust. Int. J. Rock Mech. and Min. Sci. (& Geomech Abstr.), v. 16, 1979, pp. 107-115.

6. Moore, M. P., and C. J. Bise. The Relationship Between the Hardgrove Grindability Index and the Potential for Respirable Dust Generation. Paper in Coal Mine Dust Conference (Morgantown, WV, Oct. 8-10, 1984). Generic Technology Center for Respirable Dust, 1984, pp. 250-255.

7. American Society for Testing and Materials. Standard Test Method for Grindability of Coal by the Hardgrove Machine Method. D409-90 in 1990 Annual Book of ASTM Standards: Volume 05.05. 1990, pp. 197-202.

8. Schlick, D. P., R. G. Peluso, and W. E. Byers. An Evaluation of the Respirable Dust Sampling Program in United States Underground Coal Mines. BuMines TPR 32, 1971, 20 pp.

9. Seibel, R. J., and F. E. McCall. The Dustiness of Different Coal Seams. BuMines TPR 75, 1974, 9 pp.

10. Stecklein, G. L., R. Branstetter, R. Arrowood, D. Davidson, J. Lankford, R. Lyle, and C. Nulton. Basic Research on Coal Fragmentation and Dust Entrainment. Volume I—Technical Information (contract J0215009, Southwest Research Inst.). BuMines OFR 215(1)-83, 1982, 121 pp.

11. Neter, J., W. Wasserman, and G. A. Whitmore. Applied Statistics. Allyn and Bacon, 1988, pp. 329, 526.

12. Ramani, R. V., J. M. Mutmansky, R. Bhaskar, and J. Qin. Fundamental Studies on the Relationship Between Quartz Levels in the Host Material and the Respirable Dust Generated During Mining, Volume I: Experiments, Results and Analysis (contract H0358031, PA State Univ.). BuMines OFR 36-88, 1987, 179 pp.; NTIS PB 88-214325/AS.

13. National Coal Board (United Kingdom). Mining Research and Development Review by Mining Research and Development Establishment. No. 7, Apr. 1973, 12 pp.

14. Strebig, K. C., and H. W. Zeller. Effect of Depth of Cut and Bit Type on the Generation of Respirable Dust. BuMines RI 8042, 1975, 16 pp.

15. Inculet, I. I., R. M. Quigley, and E. M. J. Beisser. Electrostatic Charges on Clays. IEEE Trans. Ind. Appl., v. IA-21, No. 1, Jan./Feb. 1985, pp. 23-25.

16. Mukherjee, A., D. Gidaspow, and D. T. Wasan. Surface Charge of Illinois Coal and Pyrites for Dry Electrostatic Cleaning. Am. Chem. Soc., v. 32, No. 1, 1987, pp. 395-407.

APPENDIX.—SURVEY DATA AND ANALYSIS

Table A-1.—Dust criteria measurements

Mine	Shift	Coal produced, tons	Dust concentration, mg/m^3		Dust mass, mg		Specific dust, mg/ton	
			Headgate	Tailgate	Headgate	Tailgate	Headgate	Tailgate
A	1-4	1,042	1.57	2.05	0.95	1.18	9.079E-04	1.131E-03
B	1-4	1,148	.94	.94	.52	.49	4.512E-04	4.294E-04
C	1-4	2,377	.55	1.04	.28	.53	1.195E-04	2.234E-04
D	1-5	3,067	1.51	2.36	.89	1.34	2.902E-04	4.359E-04
E	1	2,443	2.11	14.54	1.09	5.47	4.458E-04	2.238E-03
	2	2,443	.78	11.83	.25	3.29	1.040E-04	1.346E-03
F	1	1,305	3.22	5.24	2.11	2.89	1.618E-03	2.216E-03
G	1	2,138	1.68	3.77	.73	1.40	3.410E-04	6.525E-04
	2	1,426	(1)	3.83	(1)	.92	(1)	6.445E-04
H	1	751	3.09	4.21	1.40	1.68	1.860E-03	2.242E-03
I	1	3,240	3.62	7.75	1.85	3.52	5.719E-04	1.086E-03
	2	2,835	2.50	9.17	1.17	3.80	4.109E-04	1.339E-03
J	1	3,038	3.34	8.68	1.25	2.92	4.111E-04	9.598E-04
	2	2,126	3.98	4.93	2.40	2.79	1.131E-03	1.312E-03
K	1	950	2.82	5.14	1.21	1.98	1.271E-03	2.088E-03
	2	1,425	3.05	3.62	1.21	1.34	8.477E-04	9.396E-04
L	1	1,316	.59	2.89	.35	1.56	2.675E-04	1.186E-03
	2	1,053	.90	5.24	.24	1.40	2.260E-04	1.333E-03
M	1	826	9.30	18.12	2.03	3.88	2.454E-03	4.695E-03
	2	826	14.30	8.24	3.35	1.88	4.051E-03	2.275E-03
N	1	3,645	1.80	1.90	.90	1.35	2.480E-04	3.701E-04
	2	3,645	1.53	2.53	.92	1.40	2.510E-04	3.846E-04
O	1	1,786	1.54	2.81	.25	1.14	1.417E-04	6.355E-04
	2	1,786	3.81	3.94	.71	1.86	3.987E-04	1.041E-03
P	1	2,430	.89	3.57	.60	2.15	2.449E-04	8.844E-04
	2	2,126	1.44	5.50	.58	2.07	2.747E-04	9.732E-04
Q	1	1,807	.59	.79	.38	.40	2.092E-04	2.230E-04
R	1	1,504	.70	3.31	.36	1.54	2.420E-04	1.021E-03
	2	1,604	2.46	4.87	1.34	2.53	8.373E-04	1.579E-03
S	1	2,495	3.01	7.35	.68	1.53	2.725E-04	6.128E-04
	2	2,495	.75	6.91	.35	2.70	1.395E-04	1.080E-03
T	1	1,382	1.12	3.72	.25	1.04	1.780E-04	7.540E-04
	2	1,382	2.40	3.53	.51	1.09	3.719E-04	7.916E-04

[1] Dumped.

NOTE.—Dust measurements not in MRE equivalents.

Table A-2.—Coal characteristics

Mine	Shift	Heat content, Btu/lb	Moisture content, pct	Sulfur content, pct	Ash content,[1] pct	Volatile content,[1] pct	HGI
A . .	1-4	14,092	3.00	3.84	9.60	19.40	125
B . .	1-4	13,651	1.00	.86	11.90	29.60	70
C . .	1-4	13,875	1.10	2.04	11.80	37.60	61
D . .	1-5	13,820	1.10	3.68	20.90	40.00	70
E . .	1	13,980	3.03	.57	5.36	47.10	48
	2	13,944	3.30	.43	4.90	46.10	49
F . .	1	14,897	.92	1.06	2.97	39.50	59
G . .	1	13,189	.90	1.15	15.00	32.20	59
	2	13,855	.93	.86	10.40	33.10	62
H . .	1	15,074	.89	.65	2.86	33.40	62
I . . .	1	13,899	1.85	.77	7.47	38.54	47
	2	14,195	1.99	.84	5.79	38.87	51
J . .	1	14,390	1.81	1.17	5.14	38.58	51
	2	14,687	1.69	.77	3.38	39.41	53
K . .	1	14,592	.51	.50	7.19	19.05	95
	2	14,434	.48	.51	7.70	19.99	97
L . .	1	13,265	1.60	1.84	11.36	38.82	54
	2	12,993	1.40	2.13	12.99	36.96	50
M . .	1	13,635	3.03	.94	5.07	43.58	56
	2	13,875	3.21	.92	2.00	41.72	59
N . .	1	12,408	6.12	.44	7.53	40.80	53
	2	12,845	6.61	.29	4.97	42.10	56
O . .	1	12,926	.51	3.68	13.47	37.72	61
	2	14,268	.49	1.80	6.18	40.63	59
P . .	1	10,533	.57	5.55	29.23	17.40	79
	2	11,079	.71	3.87	26.53	16.62	82
Q . .	1	14,240	.81	1.11	9.08	21.63	94
R . .	1	13,464	6.19	.49	4.88	46.03	49
	2	13,635	5.95	.51	4.89	47.19	49
S . .	1	13,535	4.31	.52	6.43	43.09	43
	2	13,026	3.54	.47	10.82	42.72	38
T . .	1	12,694	3.72	3.98	12.23	36.76	60
	2	12,530	3.44	3.07	13.52	38.65	57

[1] Dry basis.

Table A-3.—Operation parameters

Mine	Shift	Water applied, wt pct	Max bit depth, in/rev	Air velocity, fpm			Air quantity, cfm			Change in quantity,[1] pct
				Head-gate	Av face	Tail-gate	Head-gate	Av face	Tail-gate	
A . .	1-4	NA	1.42	250	295	261	16,875	18,393	14,929	-12
B . .	1-4	NA	3.23	241	167	98	17,328	12,007	7,046	-59
C . .	1-4	NA	3.11	418	438	450	30,430	25,601	19,845	-35
D . .	1-5	NA	1.97	329	285	267	20,859	20,948	22,321	7
E . .	1	0.94	5.60	230	254	228	30,199	33,350	29,936	-1
	2	.93	5.07	250	261	332	32,825	34,269	43,592	33
F . .	1	.78	1.50	256	357	220	7,424	10,353	6,380	-14
G . .	1	1.94	4.27	242	333	355	13,189	18,149	19,348	47
	2	2.51	3.60	403	376	376	21,964	20,492	20,492	-7
H . .	1	.70	3.14	102	68	98	4,580	3,053	4,400	-4
I . . .	1	1.38	4.80	249	260	248	11,180	11,674	11,135	0
	2	1.68	4.53	222	240	193	9,968	10,776	8,666	-13
J . .	1	.94	4.74	284	238	224	40,016	33,320	31,562	-21
	2	.94	5.05	541	308	322	76,227	43,397	45,370	-40
K . .	1	.81	4.00	816	524	417	62,750	40,296	32,067	-49
	2	.88	5.64	257	474	557	19,763	36,451	42,833	117
L . .	1	1.21	2.63	340	496	490	15,266	22,270	22,001	44
	2	1.18	2.49	373	433	437	16,748	19,442	19,621	17
M . .	1	6.37	2.43	408	239	228	37,903	22,203	21,181	-44
	2	6.45	1.95	278	239	230	25,826	22,203	21,367	-17
N . .	1	8.39	3.10	258	276	308	31,399	33,589	37,484	19
	2	7.70	3.10	258	280	292	31,399	34,076	35,536	13
O . .	1	1.47	3.82	419	313	218	34,903	26,073	18,159	-48
	2	2.11	3.27	416	307	181	34,653	25,573	15,077	-56
P . .	1	1.45	2.27	425	336	308	43,563	34,440	31,570	-28
	2	1.91	3.08	476	329	318	48,790	33,723	32,595	-33
Q . .	1	3.09	3.71	253	217	238	21,075	18,076	19,825	-59
R . .	1	4.98	3.20	327	316	308	39,796	38,457	37,484	-6
	2	3.09	3.20	335	324	320	40,770	39,431	38,944	-4
S . .	1	2.00	4.13	657	502	312	67,342	51,455	31,980	-53
	2	2.73	5.33	294	330	283	30,135	33,825	29,008	-4
T . .	1	5.30	4.13	213	397	414	19,789	36,881	38,461	94
	2	3.72	3.73	210	401	404	19,509	37,253	37,532	92

[1] From headgate to tailgate.

Table A-4.—General mine characteristics

Mine	Seam	Height, in	Panel width, ft	Cut sequence[1]
A . . .	Lower Kittanning	66	440	Bi-Di
B . . .	Eagle	72	680	Uni-Di (H→T cut)
C . . .	Pittsburgh	65	615	Uni-Di (T→H cut)
D . . .	. . do.	90	650	Uni-Di (T→H cut)
E . . .	Blind Canyon	114	760	Uni-Di (H→T cut)
F . . .	Dorchester	50	580	Uni-Di (T→H cut)
G . . .	No. 2 gas	66	580	Bi-Di
H . . .	Campbell Creek	60	550	Uni-Di (T→H cut)
I	Warfield	60	600	Bi-Di
J . . .	Harlan	120	540	Uni-Di (T→H cut)
K . . .	Blue Creek	80	660	Uni-Di (T→H cut)
L . . .	Pratt	60	850	Bi-Di
M . . .	Wattis	90	480	Uni-Di (T→H cut)
N . . .	Eagle No. 5 (F)	108	750	Bi-Di
O . . .	Pittsburgh	84	630	Uni-Di (T→H cut)
P . . .	Upper Freeport	96	750	Bi-Di
Q . . .	. . do.	84	600	Bi-Di
R . . .	O'Connor	108	550	Uni-Di (T→H cut)
S . . .	Hiawatha	96	700	Uni-Di (T→H cut)
T . . .	Herrin No. 6	90	910	Uni-Di (H→T cut)

[1] Bi-Di, bidirectional; Uni-Di, unidirectional; H→T, headgate to tailgate; T→H tailgate to headgate.

Table A-5.—Nonlinear model parameter table

Variable and criterion	Model	Parameter	Parameter value	Standard error	$T_{statistic}$	$T_{critical}^{0.05}$
Ash:						
Headgate dust concentration	ae^{-bx}	a	15.726	4.968	3.166	2.042
		b	0.306	0.079	3.886	2.042
Do.	ax^{-b}	a	29.043	8.150	3.564	2.042
		b	1.407	0.226	6.231	2.042
Headgate specific dust	ae^{-bx}	a	0.010	0.003	3.505	2.042
		b	0.529	0.093	5.709	2.042
Do.	ax^{-b}	a	0.012	0.003	4.267	2.042
		b	1.738	0.212	8.190	2.042
Tailgate dust concentration	ae^{-bx}	a	9.297	2.231	4.167	2.040
		b	0.069	0.033	2.051	2.040
Do.	ax^{-b}	a	11.959	4.273	2.799	2.040
		b	0.410	0.193	2.119	2.040
Tailgate specific dust	ae^{-bx}	a	2.6×10^{-3}	6.1×10^{-4}	4.320	2.040
		b	0.102	0.037	2.796	2.040
Do.	ax^{-b}	a	3.8×10^{-3}	1.2×10^{-4}	3.296	2.040
		b	0.603	0.177	3.412	2.040
Volatility:						
Tailgate dust concentration	$a - bx + cx^2$	a	16.350	7.500	2.180	2.042
		b	1.044	0.505	2.065	2.042
		c	0.019	0.008	2.425	2.042

H_o: Parameter = 0.
H_i: Parameter = 0.
When $T_{statistic} < T_{critical}$, cannot reject H_o; if $T_{statistic} > T_{critical}$, reject H_o.

Table A-6.—Analysis of variance and fit statistics of nonlinear models

Variable and criterion	Model	Source of variation	Sum of squares	Degrees of freedom	Mean square error	R^2	$F_{statistic}$	$F_{critical}$
Ash:								
Headgate dust concentration.	ae^{-bx}	Regression	297.89	2	148.95	0.39	31.82	3.32
		Residual	140.44	30	4.68			
Do.	ax^{-b}	Regression	330.59	2	165.30	0.53	46.02	3.32
		Residual	107.74	30	3.59			
Headgate specific dust.	ae^{-bx}	Regression	2.8×10^{-5}	2	1.4×10^{-5}	0.61	49.48	3.32
		Residual	8×10^{-6}	30	0.00			
Do.	ax^{-b}	Regression	2.9×10^{-5}	2	1.5×10^{-5}	0.70	69.24	3.32
		Residual	1×10^{-6}	30	0.00			
Tailgate dust concentration.	ae^{-bx}	Regression	992.66	2	496.33	0.15	38.50	3.31
		Residual	399.65	31	12.89			
Do.	ax^{-b}	Regression	987.25	2	493.62	0.14	37.78	3.31
		Residual	405.07	31	13.07			
Tailgate specific dust.	ae^{-bx}	Regression	5.2×10^{-5}	2	2.6×10^{-5}	0.24	45.55	3.31
		Residual	1.8×10^{-5}	31	6×10^{-6}			
Do.	ax^{-b}	Regression	5.3×10^{-5}	2	2.6×10^{-5}	0.27	47.18	3.31
		Residual	1.7×10^{-5}	31	1×10^{-6}			
Volatility:								
Tailgate dust concentration.	$a - bx + cx^2$	Regression	1,063.35	3	354.45	0.30	32.32	3.32
		Residual	328.97	30	10.97			

H_o: $\mu_{variable} = \mu_{criterion}$.
H_i: $\mu_{variable} = \mu_{criterion}$.
When $F_{statistic} < F_{critical}$, cannot reject H_o; if $F_{statistic} > F_{critical}$, reject H_o.

NOTE.—R^2 is determined from total corrected source of variation (Σ (y-y)^2).