Taylor & Francis
Taylor & Francis Group

Aerosol Science and Technology

ISSN: 0278-6826 (Print) 1521-7388 (Online) Journal homepage: http://www.tandfonline.com/loi/uast20

Using Proximate Analysis to Characterize Airborne Dust Generation from Bituminous Coals

Steven J. Page & John A. Organiscak

To cite this article: Steven J. Page & John A. Organiscak (2002) Using Proximate Analysis to Characterize Airborne Dust Generation from Bituminous Coals, Aerosol Science and Technology, 36:6, 721-733, DOI: 10.1080/02786820290038393

To link to this article: http://dx.doi.org/10.1080/02786820290038393

Published online: 30 Nov 2010.

Submit your article to this journal

Article views: 109

View related articles

Citing articles: 2 View citing articles

Full Terms & Conditions of access and use can be found at
http://www.tandfonline.com/action/journalInformation?journalCode=uast20

Download by: [Stephen B. Thacker CDC Library] **Date:** 06 April 2017, At: 09:16

Aerosol Science and Technology 36: 721–733 (2002)
© 2002 American Association for Aerosol Research
Published by Taylor and Francis
0278-6826/02/$12.00 + .00
DOI: 10.1080/0278682029003839 3

Using Proximate Analysis to Characterize Airborne Dust Generation from Bituminous Coals

Steven J. Page and John A. Organiscak
National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory, Pittsburgh, Pennsylvania

The amount of airborne respirable dust generated from breakage of different coals varies widely. This research was conducted to identify the facets of airborne respirable dust liberation from the coal product. Laboratory crushing experiments were conducted on a range of low to high volatile bituminous coals to investigate the various factors influencing airborne respirable dust generation. Bituminous coal samples from 8 mines (5 U.S. and 3 Polish) were uniformly prepared and processed through a double roll crusher located in a low air velocity wind tunnel. Experimental factors studied included inherent coal seam constituents, specific energy of crushing, product size characteristics, dust cloud electrostatic field, and specific quantity of airborne respirable dust generated.

The results of this investigation build upon previously published results, which indicated that a combination of several factors are associated with the generation of airborne respirable dust. One factor involved is the effect of coal rank, described by the inherent moist fuel ratio, on the product size characteristics, defined by Schuhmann size function parameters. However, since coals of high moist fuel ratio (high rank) are generally more extensively cleated, it is suggested in the present work that the degree of cleating is directly responsible for the quantity of respirable-sized particles produced in the crushed product material for eastern U.S. coals. This is implied by the relationship of ash content and at least one mineral constituent (pyrite, determined from pyritic sulfur analysis) to the percentage of airborne respirable dust. To validate this hypothesis, a description is offered that is based on known coal petrography.

Another key factor is the effect of air dry loss moisture in the coal seam on the breakage-induced electrostatic field of airborne dust. The air dry loss moisture factor appears to control the amount of airborne respirable dust that is liberated from the product. The resultant effect of these factors is that different percentages of coal particles smaller than 10 μm are dispersed as airborne respirable dust, with a well-defined peak in the normalized airborne respirable dust for a narrow range of air dry loss moisture ÷ ash ratios. A clear delineation of coals, based on well-known proximate analysis characteristics, that generate the most respirable dust appears to be possible. It was also shown that the dust-generating characteristics of coals could be reasonably described by both the moist fuel ratio and the Hardgrove Grindability Index (HGI). These results show a clear distinction between eastern and western U.S. coals. However, no consistent distinction for Polish coal was observed.

INTRODUCTION

Prolonged exposure to airborne respirable coal dust is responsible for the prevalence of Coal Worker's Pneumoconiosis (CWP). Health research studies have identified that the severity of CWP is directly related to the amount of dust exposure and the coal rank (Attfield and Seixas 1995; Attfield and Morring 1992; Hurley and Maclaren 1987). Coal rank is defined as the degree of coalification, or coal formation. Since the passage of the 2.0 mg/m^3 dust standard (average shift concentration exposure limit) in the Federal Coal Mine Health and Safety Act of 1969 (U.S. Congress 1969), average dust levels were reduced from over 6.0 mg/m^3 to current levels just under the 2.0 mg/m^3 standard (Attfield and Wagner 1992). Through its Coal Worker's X-ray Surveillance Program, the National Institute for Occupational Safety and Health (NIOSH) has recently determined that coal miners continue to have an elevated risk for CWP under the current 2.0 mg/m^3 dust standard and has recommended a 1.0 mg/m^3 dust standard to further reduce the prevalence of CWP (NIOSH 1995). To achieve this goal, coal mine worker dust exposure needs to be notably reduced.

Laboratory coal comminution studies have shown a significantly consistent positive correlation between coal rank and the amount of respirable-sized particles found in the product (Srikanth et al. 1995; Moore and Bise 1984; Baafi and Ramani 1979). These studies show conclusively that either a grinding or crushing process yields total and respirable dust generation rates that increase with coal rank. It is important to note that these results were measurements of dust *in the product* and not measurements of airborne dust. In the mining and roll crushing of coal there is much less regrinding (Organiscak and Page 1998; Ramani et al. 1987). Pulverization is a repeated, multiple breakage process and is known not to predominate either in the underground mining process or the crushing tests described in

---

Received 18 January 2001; accepted 3 December 2001.
Address correspondence to Steven J. Page, National Institute of Occupational Safety and Health, Pittsburgh Research Laboratory, P.O. Box 18070, Pittsburgh, PA 15236. E-mail: sep8@cdc.gov

this paper. Therefore it would not be expected that the standard Hardgrove Grindability Index (HGI; ASTM 1997) would be a good measure of airborne dust concentrations (Organiscak et al. 1992; Organiscak and Page 1993). Mark and Barton (1997) concluded that the HGI is a poor predictor of coal strength. Based on the above results, it seems quite reasonable to deduce that HGI may not be a good measure of airborne dust generation and that some other characteristic of coal must be sought.

In 1957 the National Coal Board's Mining Research Establishment observed discrepancies in airborne dust and the product sizes produced as compared to the breakage processes of the coal (Knight 1958; Hamilton and Knight 1957). Laboratory shatter tests and tumbler breakage tests were conducted on various coal seams mined in Great Britain, yielding negative correlations between coal compressive strength and the product sizes. Although the higher rank weaker coals (lower compressive strength coals) consistently produced a smaller product size distribution, airborne dust generation differences were observed between these 2 breakage processes.

Work by Organiscak et al. (1992) indicated that high volatile, low ash coal seams (lower rank coals) tended to produce more airborne respirable dust. Organiscak and Colinet (1999) studied 12 longwalls in 12 seams and showed again that ash content was significantly correlated to airborne dust. Additional work indicated that lower ranked coals, as described by their moist fuel ratio (defined as [fixed carbon ÷ volatile matter] ÷ inherent moisture content), also produced more total airborne dust but that there was no relationship with the ash content of the coals (Page et al. 1993). Differences in the correlation of particular coal parameters, such as ash, were believed to be associated with the inherent weakness of the coal's cleat (or joint) structure. Others have postulated that coal fragmentation from cutting usually occurs along planes of imperfections (cleats or joints) or weaknesses formed by mineral matter (Stecklein et al. 1982). However, the existence of correlations of coal parameters such as volatile matter, ash, fixed carbon, or moisture content to airborne respirable dust does little to explain the underlying mechanisms responsible for the correlations.

Organiscak and Page (1998) showed that the coal moist fuel ratio and crusher specific energy were different for eastern and western U.S. coals. An apparent physical difference proposed that may explain the inconsistent energy relationship between these 2 coal groups was that the eastern U.S. coals tested tended to have a more distinguishable cleat system than the western U.S. coals. However, the authors noted that no one factor is decisively associated with airborne respirable dust generation, but airborne respirable dust generation is a likely result of several interrelated factors.

It has long been known that airborne dust particles can have a significant amount of electrostatic charge (Hopper and Laby 1941; Kunkel 1948, 1950; Dodd 1952) and that this charge can place dusts in varying degrees of agglomeration (Kunkel 1948; Kaya and Hogg 1992). Coal mine worker health and dust control methods are probably influenced by these charging and agglomeration characteristics. Also, lung deposition has been found to increase directly with the charging properties of airborne dust (Melandri et al. 1983). The increased prevalence of CWP observed with coal rank may be partly related to the increased dust cloud charging in higher ranked coals as measured by Organiscak and Page (1998). This increased deposition may also be attributed to the higher lung deposition efficiency of agglomerated ultrafine submicron particles as well as to image charging effects within the lung (Yu and Chandra 1978; Becker et al. 1980).

Kaya and Hogg (1992) state that one would not intuitively expect significant agglomeration of airborne dust in the mine atmosphere at the levels of dust concentrations found even in the most dusty mines. They also postulate that observed agglomeration (Polat et al. 1991) occurs immediately at the point of dust generation.

This work offers a representation that suggests a cause and effect relationship between coal characteristics, described by certain proximate analysis constituents of coal, and airborne respirable dust generation, as well as providing a potential mechanism for increased prevalence of CWP in higher rank coals. The objectives of this research were to (1) develop a repeatable laboratory testing protocol for generating coal airborne respirable dust and (2) identify key factors influencing airborne respirable dust generation, where one of the factors is different bituminous coals.

EXPERIMENTAL DESIGN

The intent of this research was not to conduct experiments with a specialized coal cutting or breakage apparatus, but to use commercially available equipment to accomplish the research objectives. Commercially available equipment is preferable to use because it is more widely understood and familiar. A double-roll crusher was selected to study the primary breakage properties of medium-sized coal lumps (approximately 50 mm) because this equipment yields a small size reduction ratio of 1.5:1 to 5:1 (ratio of average feed size to product size) without a significant amount of regrinding (Cummins and Given 1973). Eight low to high volatile bituminous coal samples from 8 mines were studied using the coal-crushing procedure developed. The 8 different bituminous coals were roll crushed under uniform procedures to investigate the effects of coal moist fuel ratio, physical coal strength properties (specific energy of crushing), coal breakage characteristics (product size distribution), and dust cloud electrostatic field on specific airborne respirable dust generation. Detailed information on the product size distributions, airborne dust size distributions, and test procedures have been previously published (Organiscak and Page 1998).

Test Facility

The experimental test facility was comprised of a roll crusher located in the intake end of a 1.2 m high by 0.6 m wide by 6.1 m long wood-framed, plastic-sheath-enclosed wind tunnel. A dust collector and exhaust fan were located at the discharge end of the tunnel. The crusher was a 1.1 kW compact double-roll crusher (79.4 mm diameter rolls) operating at approximately 70 rpm, with twenty-four 12.7 mm high staggered teeth on each roll. An inductive current transformer (±0.1 A) was installed to monitor the crusher's current usage. The crusher's operating capacity was 227–1361 kg/h of up to 101.6 mm feed-size lumps of coal or rock material.

Dust sampling was conducted 3 m downstream of the crusher and approximately 2.4 m upstream of the tunnel transition to the dust collector and exhaust fan. Dust sampling was conducted with 2 Sierra 298 personal sampling impactors, each equipped with the standard inlet cowl and positioned at one-half the tunnel height from the floor and one-third the tunnel width from the wall. Impactor stages 1–6 (20 μm through 1.55 μm cut point sizes) were used with the smaller than 1.55 μm particle sizes collected on the final filter. An MIE RAM-1 sampler continuously monitored the respirable fraction of dust from a 10 mm Dorr Oliver cyclone location in the middle of the sampling location (Williams and Timko 1984). All the sampler inlets were faced into the airflow.

Dust cloud electrostatic field measurements were made immediately downstream of the crusher (within 0.3 m) at a fixed location with a Monroe 245 electrostatic field meter and were stored on an analog data logger. This location was chosen due to the rapid dissipation of the dust cloud charge. Preliminary measurements showed that the electrostatic field at the dust sampling location (3 m downstream of the crusher, 30 s transit time) was below the level of detection. The field meter was chosen to measure the net charge of the generated dust cloud because, for a fixed generation mechanism and measurement location, the field produced is proportional to the vectorial sum of all charges in the distribution. This procedure is adequate since absolute charge measurements are not necessary for relative comparisons between coal types. Air velocities were determined by using the time it took the dust to travel 3 m to the RAM-1 sampling location after crusher start up. Preliminary crushing tests indicated that the lowest possible wind tunnel air velocity to maximize dust concentrations and mass collection was 0.10 m/s (45 m^3/s air quantity). Lower velocities permitted dust to escape from the tunnel inlet, so wind tunnel airflow was targeted for 0.10 m/s for all of the experiments.

Experimental Procedure

The key elements for reducing experimental error during crushing are feed size and feed methods. In developing a reproducible crushing procedure, both size and feed methods were studied in a series of crushing experiments conducted on 470 kg of Pittsburgh coal obtained from NIOSH's Safety Research Coal Mine at the Pittsburgh Research Laboratory. A large batch of coal lumps were jaw crushed, screened, and riffled (a sample splitting process) (Taggart 1945) into 32 representative test samples (14.7 kg by weight) of various feed sizes that would be tested under different feed methods. The size ranges that would be tested measured 50.0 by 25.0 mm, 25.0 by 19.0 mm, 19.0 by 12.5 mm, and a mixture consisting of equal weights of these 3 size ranges. The 2 feed methods studied were batch feed (the crusher self-feeds the batch of coal from its hopper, approximately 30 s per sample) and trickle feed (a separate vibrating feeder slowly trickles coal into the crusher, approximately 2 min per sample). The various test samples were randomly processed through the crusher for the 2 feed methods, yielding 4 runs for each test condition. After each test, the crushed material was removed for size distribution and proximate analysis.

The crushing variables studied during these experimental procedure validation tests included energy consumption, airborne respirable dust concentration, dust cloud electrostatic field, and product size parameters. Their averages and variations (standard error (SE) and coefficient of variation (CV)) are shown in Table 1. Energy consumption was determined from crusher current, voltage, and time. Airborne respirable dust was determined by applying the American Conference of Governmental Industrial Hygenists (ACGIH) definition of respirable dust to the mass sizes collected on the Sierra 298 impactors, sampling rate, and time (Potts et al. 1990). The electrostatic field was determined by averaging the field over a time period equal to the crusher operating time plus 10 s. This allowed sufficient time for the generated dust cloud to travel beyond the field meter position. The crusher product was screened for size classification. Schuhmann size function parameters defined in Table 1 (Schuhmann 1940) were determined by nonlinear least-squares regression of the cumulative size distribution data.

The experimental procedure validation results shown in Table 1 indicate that the batch feed method for both the size mix and 50.0 by 25.0 mm feed samples had the lowest amount of measurement error for all the crusher variables investigated. Airborne respirable dust had the highest variability out of all the measured variables, but had CVs below 20% for the batch feed method of the size mix and the 50.0 by 25.0 mm samples. Energy consumption measurements were the least variable for the batch feed method. The larger variations in energy consumption measurements for the trickle feed method were likely due to poor resolution of the very low crushing currents measured. Both the electrostatic field measurements and Schuhmann size parameters had low measurement errors for all the feed method and size tests. In addition, half of the test samples were analyzed for coal constituents (ASTM 1996), and the results were that the CVs for the inherent moisture, ash, volatile matter, and fixed carbon were all below 10%. These results indicate that representative feed samples were obtained with the feed preparation procedures.

The batch feed crushing method of a coal size mix was the chosen procedure for minimizing the variable measurement error of the remaining coal airborne respirable dust generation experiments. The lower Schuhmann exponent parameters for the batch feed method indicate that some regrinding occurs as compared to the trickle feed, which parallels the lower Schuhmann exponent parameters observed with run-of-mine coals (Ramani et al. 1987). The size mix feed was preferred to the 50.0 by 25.0 mm feed because as bulk coal samples are processed (crushed and screened) to make the feed samples, more feed material can be obtained from a given amount of bulk coal.

Table 1

Precision of experimental procedures with PRL coal

	Energy consumption, W*min			Airborne respirable dust concentration, mg/m^3			Electric field, V/cm			Schuhmann size function[b] (All R^2s > 0.99)			
Feed method and size	Mean[a] $\sum X/n$	Standard error[a] $s/\sqrt{n}$	CV[a] s/mean	Mean $\sum X/n$	Standard error $s/\sqrt{n}$	CV s/mean	Mean $\sum X/n$	Standard error $s/\sqrt{n}$	CV s/mean	Top size "a," mm	s_a, mm	Exponent "b"	s_b
Batch													
Mix	77.09	1.91	0.05	6.17	0.57	0.18	119.4	8.45	0.07	15.1	0.11	0.88	0.01
50.0 × 25.0 mm	88.00	5.82	0.13	7.38	0.63	0.17	134.6	6.25	0.05	13.8	0.12	0.89	0.01
25.0 × 19.0 mm	94.06	0.80	0.02	5.67	1.23	0.43	112.9	7.87	0.07	14.5	0.15	0.86	0.01
19.0 × 12.5 mm	66.59	4.11	0.12	5.71	1.29	0.45	115.5	16.50	0.14	17.7	0.15	0.89	0.01
Trickle													
Mix	35.15	2.38	0.14	4.55	0.79	0.35	118.9	5.69	0.05	15.2	0.17	1.28	0.03
50.0 × 25.0 mm	70.73	7.47	0.21	4.53	0.87	0.38	115.2	10.04	0.09	14.3	0.13	1.12	0.02
25.0 × 19.0 mm	23.90	7.48	0.63	4.65	0.93	0.40	114.0	9.17	0.08	14.8	0.15	1.31	0.03
19.0 × 12.5 mm	22.36	6.12	0.55	3.60	0.77	0.43	77.8	6.38	0.08	16.3	0.18	1.60	0.04

[a] $X =$ variable, $n =$ number of measurements, $s =$ standard deviation, CV = coefficient of variation.

[b] Schuhmann size function: $Y = (X/a)^b$, where $Y =$ cumulative % of weight $< X =$ size of particles, mm, $a =$ Schuhmann top size regression parameter, $b =$ Schuhmann exponent regression parameter, $s_a =$ standard error of regression parameter "a", $s_b =$ standard error of regression parameter "b".

Based on this procedure validation, the coal samples were randomly run in the roll crusher test facility by batch feeding a mixture of the 3 size ranges described earlier. Experimental factors studied include inherent coal constituents, specific energy of crushing, product size attributes, dust cloud electrostatic field, and specific airborne respirable dust generated. A small coal test sample was riffled from the crushed product after screening for determination of the coal constituents by proximate analysis (ASTM 1996). The coal constituent data are included in Table 2.

Sample Collection

Three bituminous coals were initially targeted for sample collection. These ranged from a low-volatile, high-ash coal (higher rank) to a high-volatile, low-ash coal (lower rank) with 1 coal type in the middle of this range. The bulk coal samples were collected at 3 continuous miner sections located in the Eagle and Upper Freeport seams in West Virginia and the Blind Canyon seam in Utah. Three days of coal collection were conducted at each mining section. The coal was channeled from the mine wall near the working area. This coal was hand screened and packaged into 3 size ranges of >50.0 mm lumps, 50.0 by 25.0 mm lumps, and 25.0 by 19.0 mm lumps. Approximately 50 kg of bulk coal were collected each day. Run-of-mine product samples were also collected from shuttle cars during the cut at the feeder breaker dump point for size analysis.

The underground bulk coal samples were processed in the laboratory to obtain 2 mixed-size test samples for each mining

Table 2
Properties of eastern (E), western (W) U.S. and Polish coal samples tested

	As determined								
Coal seam	Sample no.	Air dry loss, %	Inherent moisture, %	Ash, %	Volatile matter, %	Fixed carbon, %	HGI	Pyritic sulfur, %	ADL/ ash
Eagle (E)	1	1.2	0.6	5.6	32.5	61.4	62	0.42	0.21
Eagle (E)	2	0.9	0.6	5.4	32.4	61.6	60	0.14	0.17
Eagle (E)	3	1.0	0.6	8.2	32.4	58.8	55	0.14	0.12
Eagle (E)	4	0.9	0.6	9.2	31.4	58.8	55	0.10	0.10
Eagle (E)	5	1.1	0.5	7.3	32.0	60.3	59	0.39	0.15
Eagle (E)	6	1.0	0.4	7.5	32.5	59.6	58	0.21	0.14
Upper freeport (E)	1	1.2	0.3	17.6	16.4	65.7	91	0.94	0.07
Upper freeport (E)	2	1.1	0.3	17.3	16.2	66.2	91	0.88	0.06
Upper freeport (E)	3	1.1	0.3	16.3	16.9	66.4	89	1.26	0.07
Upper freeport (E)	4	1.1	0.4	17.9	16.5	65.2	87	0.83	0.06
Upper freeport (E)	5	1.2	0.3	21.3	16.3	62.1	89	1.66	0.05
Upper freeport (E)	6	1.1	0.3	20.4	17.0	62.4	89	0.88	0.05
Blind canyon (W)	1	3.8	1.4	5.5	43.5	49.6	49	0.02	0.70
Blind canyon (W)	2	3.4	1.8	5.3	43.6	49.2	49	0.02	0.64
Blind canyon (W)	3	3.1	1.2	10.3	42.5	45.9	48	0.03	0.30
Blind canyon (W)	4	2.8	0.8	8.1	44.3	46.8	46	0.02	0.34
Blind canyon (W)	5	3.4	1.3	6.0	43.7	48.9	48	0.04	0.56
Blind canyon (W)	6	2.9	1.8	5.1	44.0	49.0	47	0.03	0.56
Wadge (W)	1	4.6	3.8	11.5	38.4	46.4	42	0.03	0.40
Wadge (W)	2	5.6	2.4	12.2	39.5	45.9	42	0.02	0.45
Wadge (W)	3	5.0	3.1	13.5	37.5	46.0	43	0.04	0.37
Wadge (W)	4	5.6	2.5	14.5	37.7	45.3	43	0.03	0.38
Pittsburgh (E)	1	0.8	1.0	5.4	37.9	55.7	51	0.34	0.14
Pittsburgh (E)	2	0.7	1.0	5.9	37.5	55.7	51	0.41	0.13
Pittsburgh (E)	3	1.1	0.7	6.7	36.8	55.8	51	0.43	0.17
Pittsburgh (E)	4	1.1	0.8	6.2	37.2	55.8	51	0.39	0.18
Polish seam A	1	5.1	2.8	13.6	33.8	49.8	39	0.49	0.38
Polish seam A	2	5.9	2.8	11.8	35.4	50.0	37	0.35	0.49
Polish seam B	1	5.9	3.1	5.0	36.4	55.6	47	0.13	1.20
Polish seam B	2	6.0	3.0	5.1	36.5	55.5	44	0.16	1.19
Polish seam C	1	1.4	1.2	16.2	33.8	48.8	49	0.94	0.08
Polish seam C	2	1.5	1.2	16.4	33.7	48.7	49	0.85	0.09

cut, for a total of 6 test samples for each mine. Jaw crushing was conducted on the larger lumps to obtain the equal portions of feed sizes needed for testing. Riffling was done to split the coal samples from each cut into equal portions. All of the coal test samples were weighed and stored in sealed cans. A high-volatile, high-ash bulk coal, from the Wadge seam in Colorado (collected for another underground project), was also processed in the same manner to obtain 4 additional test samples for the crushing experiments. In addition, coal samples were obtained from 3 Polish coal seams in such quantities to provide, after processing, 2 additional test samples for each seam. The Polish samples were shipped in unsealed containers. Thus the as-received condition does not reflect the in situ nature of the coal. After sample preparation, the samples were stored in sealed cans until tested.

The run-of-mine samples collected from the 3 mining operations surveyed were also screened for size analysis. The underground run-of-mine product size distributions confirmed that some coal product regrinding occurs during coal cutting because the run-of-mine coal product size distributions are described by lower Schuhmann exponent parameters <1, which is similar to the Pittsburgh coal product size distribution for the batch feed crushing procedure. Further information on the test facility, experimental procedure, and sample collection has been previously published (Organiscak and Page 1998).

EXPERIMENTAL RESULTS

Table 3 summarizes the pertinent measured and calculated parameters for the tests. From the data in Table 3, the specific energy can be calculated and is the energy consumed per unit weight of the coal sample crushed. The specific airborne respirable dust is the total amount of airborne respirable dust generated in the airstream per unit of material crushed. The 4 batch-fed, mixed-size tests run on Pittsburgh coal were also included in this data analysis. Thus 32 tests were completed by the same crushing procedure on 8 low to high volatile bituminous coals.

Good experimental precision was obtained for each seam tested. Low sample variability for each coal seam tested was achieved with the coal collection and sample preparation procedures. The coal size distributions illustrate that the various bituminous coals have distinct breakage attributes when crushed under a uniform process. The airborne dust size distributions generated for the various coal seams were more consistent than the coal product size distributions (Organiscak and Page 1998).

As shown in Table 3, the measure of normalized airborne dust is designated as PAR10 and defined as the percentage of respirable-sized particles in the crushed product that become airborne, normalized per kilogram of product crushed. Mathematically, PAR10 is expressed as

$$\text{PAR10} = \frac{\text{specific airborne respirable dust, mg/kg}}{\text{product fines } \leq 10\,\mu\text{m, mg/kg}} \times 100\%. \qquad [1]$$

Figures 1a and b show the relationship between air dry loss moisture, PAR10, and the electrostatic charge field associated with breakage of these coals, categorized by geographic location. In a general sense, Figure 1a could be interpreted as possessing a peak at approximately 5% air dry loss. It should be pointed out at this time that there is one source of systematic variation associated with the air dry loss moisture measurements that will introduce some error in the x-axis of Figure 1. The source of this variation is in the varying time lag between an individual test and the analysis. Although the samples were stored in sealed bags, the samples were not analyzed until as many as 14 tests were performed. This corresponds to a time period of 7 weeks. As a result, there is a distinct possibility that the air dry loss moisture (which easily escapes the coal) was escaping the coal samples proportionally to the time between test and analysis as well as the degree to which a particular coal will lose moisture. Although the amount of moisture lost prior to analysis is not known for each sample, an estimated correction of the air dry loss moisture values was performed. A simplified model based on moisture loss as an asymptotically increasing function of time maintained the overall characteristic peak of Figure 1a. Page (2000) observed these same trends in specific airborne respirable dust (mg/kg) using the inherently different breakage mechanism of pulverization. Page (2000) attributed the increase in specific airborne respirable dust to decreasing agglomeration of the dust in the pulverized product as a result of less electrostatic binding. The subsequent decrease in specific airborne respirable dust beyond a certain moisture content (in the present study, above 5% air dry loss) was attributed to dust reduction by physical wetting, at which point the electrostatic charge was effectively neutralized. In view of the above, it appears unlikely (1) that the data above 4% air dry loss moisture is a result of error in the determination of PAR10 and 2) that the relationship between PAR10 and air dry loss moisture is a monotonically increasing function over the range of 1% to 6% air dry loss moisture. Figure 1b shows that there is a concurrent decrease in the electrostatic charge field with increasing air dry loss moisture. The charge field dispersion of the eastern U.S. coals will be addressed later in relationship to the moist fuel ratio.

A key point regarding the use of the PAR10 variable is that there are 2 significant factors that affect airborne respirable dust generation. Having established that air dry loss moisture has a pronounced effect on the electrostatic charge carried by the crushed product, which in turn plays a large role in the agglomerating or binding forces that keep the within-product dust from becoming airborne, it remains to identify some significant factor that is responsible for the amount of respirable dust generated in the crushed product. Obviously, the amount of airborne respirable dust is dependent upon how much within-product dust is present. This is the source of the airborne respirable dust. For the data set as a whole, crushing energy showed a low negative correlation with the amount of product $<10\ \mu\text{m}$ ($r^2 = 0.31$), measured in mg/kg, as well as PAR10. There were insignificant correlations between airborne respirable dust, measured in

Table 3

Measured and calculated parameters resulting from coal crushing tests

Coal seam	Sample no.	Energy, kW min	Feed weight, kg	Specific airborne respirable dust (ARD), mg/kg	Electrostatic field, V/cm	Product fines <10 μm, mg/kg	Product D_{50}, mm	PAR10[a], %
Eagle	1	0.0403	12.652	13.074	112.8	3169	6.26	0.413
Eagle	2	0.0538	12.624	15.814	112.4	3291	6.16	0.480
Eagle	3	0.0648	13.894	12.612	72.0	2689	6.44	0.469
Eagle	4	0.0595	13.811	11.701	116.0	2346	6.60	0.499
Eagle	5	0.0410	13.608	12.882	76.4	2617	6.50	0.492
Eagle	6	0.0600	13.608	12.473	77.6	2756	6.45	0.453
Upper freeport	1	0.0229	11.725	13.211	146.0	10717	4.59	0.123
Upper freeport	2	0.0118	11.762	10.445	180.0	11423	4.53	0.091
Upper freeport	3	0.0282	11.618	14.353	131.2	9837	4.81	0.146
Upper freeport	4	0.0208	11.644	10.369	158.8	10296	4.75	0.101
Upper freeport	5	0.0334	11.766	13.103	128.8	9134	4.91	0.143
Upper freeport	6	0.0229	11.737	7.620	162.0	10540	4.71	0.072
Blind canyon	1	0.0461	12.176	14.198	55.2	2240	6.86	0.634
Blind canyon	2	0.0487	12.179	12.715	64.0	2015	6.98	0.631
Blind canyon	3	0.0410	12.576	21.334	108.8	1815	7.20	1.176
Blind canyon	4	0.0660	12.573	15.616	53.6	1761	7.29	0.887
Blind canyon	5	0.0422	11.239	18.655	100.4	1720	7.26	1.084
Blind canyon	6	0.0521	11.236	15.753	90.8	1858	7.17	0.848
Wadge	1	0.0307	12.651	11.953	24.0	272	8.83	4.393
Wadge	2	0.0347	12.665	9.881	−28.8	299	8.51	3.300
Wadge	3	0.0422	12.031	7.787	−25.2	339	8.42	2.295
Wadge	4	0.0403	12.012	8.895	−9.2	339	8.42	2.621
Pittsburgh	1	0.0734	14.634	7.120	114.2	1579	6.79	0.451
Pittsburgh	2	0.0734	14.674	4.539	139.2	1624	6.83	0.279
Pittsburgh	3	0.0792	14.658	7.780	99.2	1673	6.90	0.465
Pittsburgh	4	0.0819	14.675	6.966	124.8	1703	6.81	0.409
Polish seam A	1	0.1116	12.301	26.492	−12.80	563	8.03	4.703
Polish seam A	2	0.0868	12.271	16.702	−34.0	704	7.80	2.373
Polish seam B	1	0.0319	8.642	7.163	17.2	930	7.44	0.770
Polish seam B	2	0.0299	8.663	1.795	9.2	1172	7.33	0.153
Polish seam C	1	0.0286	7.803	10.866	0.4	3634	5.84	0.299
Polish seam C	2	0.0333	7.784	19.460	−1.6	3524	5.88	0.552

[a] PAR10 is defined as the percentage of specific airborne respirable dust (mg/kg) per amount of specific crusher product (mg/kg) <10 μm.

mg/kg, and all coal constituents, moist fuel ratio, Schuhmann size function parameters, and crusher-specific energy consumption. The specific energy of coal breakage is dependent upon 2 strength factors: the degree of cleating and the inherent strength of the coal matrix. Because of the known differences of cleating characteristics between eastern and western U.S. coals, it is insightful to examine the amount of product <10 μm after geographic classification of the data.

Figures 2a and b show the amount of product <10 μm and PAR10 dust as a function of the specific energy of breakage for the coals tested. These figures suggest that there are distinct breakage relationships for the eastern U.S., western U.S., and Polish coals. Figure 2a also shows that, although there is significant overlap in the specific energy range 3–5 W min/kg, some of the Polish coals could be considered similar to either the eastern or western U.S. coals. For example, C1 and C2 could be considered similar to the eastern U.S. coals, and B1 and B2 could be considered similar to the western U.S. coals. Some of these similarities also seem to be found in Figure 2b. However, it is important to bear in mind that crushing energy is responsible for the amount of product <10 μm and not the amount that becomes airborne, represented by PAR10 in Figure 2b.

Figures 2a and b also show that an increase in the amount of dust in the product of a crushed coal does not necessarily result in an increase in airborne dust. For example, some of the eastern U.S. coals generating the largest amount of product <10 μm

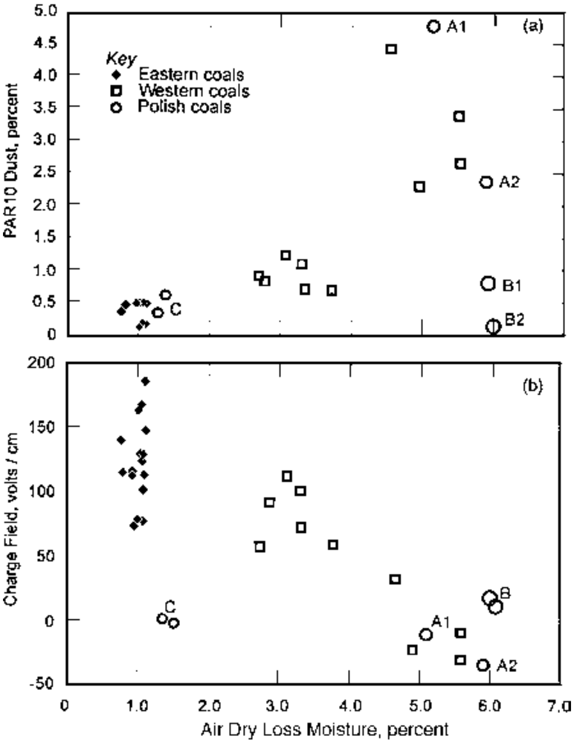

Figure 1. (a) Relationship between PAR10 dust, defined as the percentage of specific airborne respirable dust (mg/kg) per amount of specific crusher product (mg/kg) <10 μm, and air dry loss moisture; (b) Relationship between the breakage-induced electrostatic charge field and air dry loss moisture.

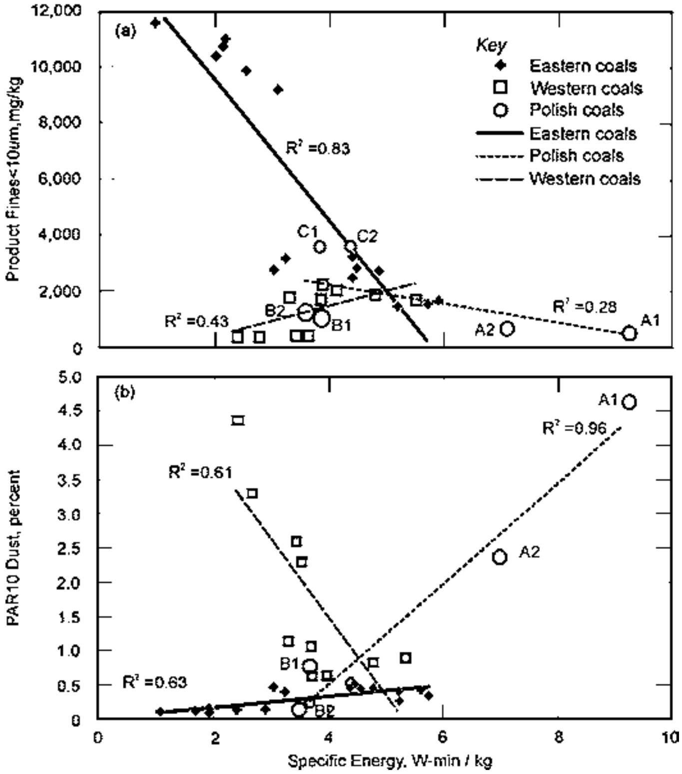

Figure 2. (a) Relationship between product fines, defined as the amount of specific crusher product (mg/kg) <10 μm, and specific energy; (b) Relationship between PAR10 and specific energy.

produce the lowest values of PAR10. Likewise, some of the western U.S. and Polish coals that generate the lowest amount of product <10 μm produce the highest values of PAR10. Polish coals B1 and B2 appear to present an exception to this pattern, showing low values for both the amount of product <10 μm and PAR10 dust as a function of the specific energy of breakage. This result would appear consistent with Figure 1a, which shows B1 and B2 to have the highest air dry loss moisture content. Thus it is possible that the low values of PAR10 for B1 and B2 are due to "wet" rather than electrostatic agglomeration of the dust in the product. These results suggest that the specific energy of coal breakage is not, in general, a good measure of dust production, either airborne or within the product.

A plot of PAR10 dust versus ash reveals a peak similar in appearance to Figure 1a, although somewhat more centered in the data range at approximately 14% ash content. Therefore neither ash nor air dry loss moisture alone would be an adequate variable in terms of the definition of PAR10 dust. In view of the results of Organiscak et al. (1992), which established a relationship between airborne respirable dust and ash content, it can be suggested that an independent variable for PAR10 can be expressed as % air dry loss moisture ÷ % ash for the range of air dry loss moisture from <1% up to 6%. Figure 3 shows the resultant plot of PAR10 dust versus% air dry loss moisture ÷ % ash. It is noted that the occurrence of the peak in Figure 3 indicates that another, unaccounted for, product or airborne dust generation mechanism may be operating. One might suspect that the specific energy is a reasonable choice for this unaccounted for mechanism. However, normalizing PAR10 for the specific energy shows no change in the appearance of Figure 3, indicating that specific energy is not an important factor in PAR10 production. This is consistent with the results of Figure 2b. Because of the ratio of moisture and ash contents, it is possible that the peak in Figure 3 is due simply to the interaction of 2 competing factors—one factor that generates the dust within the product and another factor (moisture) that determines how much of the within-product becomes airborne. Nevertheless, Figure 3 indicates that a clear delineation of coals that generate the most airborne respirable dust appears possible based on well-known proximate analysis characteristics.

For the coals tested, some additional correlations were also observed. The highest rank coals, determined by the moist fuel ratio, had the least amount of inherent moisture and demonstrated what might appear to be an inverse power relationship ($\sim 1/x^2$) between PAR10 and the moist fuel ratio when all data are viewed without regard to geographical distinction. However, differentiating the coals for geographical type clearly reveals linear relationships. As shown in Figure 4a, the eastern

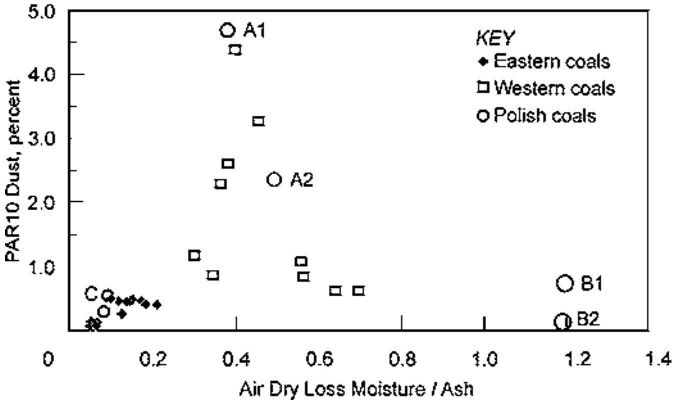

Figure 3. Relationship between PAR10 dust and the ratio of air dry loss moisture ÷ ash content.

U.S. coals show a slight negative linear relationship ($r^2 = 0.83$) for PAR10 over a broad range of moist fuel ratios from approximately 2 to 14. Over this same range of moist fuel ratio, Figure 4b shows that the eastern U.S. coals exhibit a positive linear increase ($r^2 = 0.48$) in the charge field. The western U.S. coals show a steep negative linear relationship of PAR10 with moist fuel ratios ($r^2 = 0.48$) over a narrow range of moist fuel ratios <1.27, while simultaneously exhibiting a steep positive linear increase ($r^2 = 0.34$) in the charge field. The Polish coals appear to be split in terms of PAR10 in Figure 4a (4 of 6 samples could belong to either group, as noted earlier), even though all of the Polish coals exhibit the charge field characteristics of western U.S. coals.

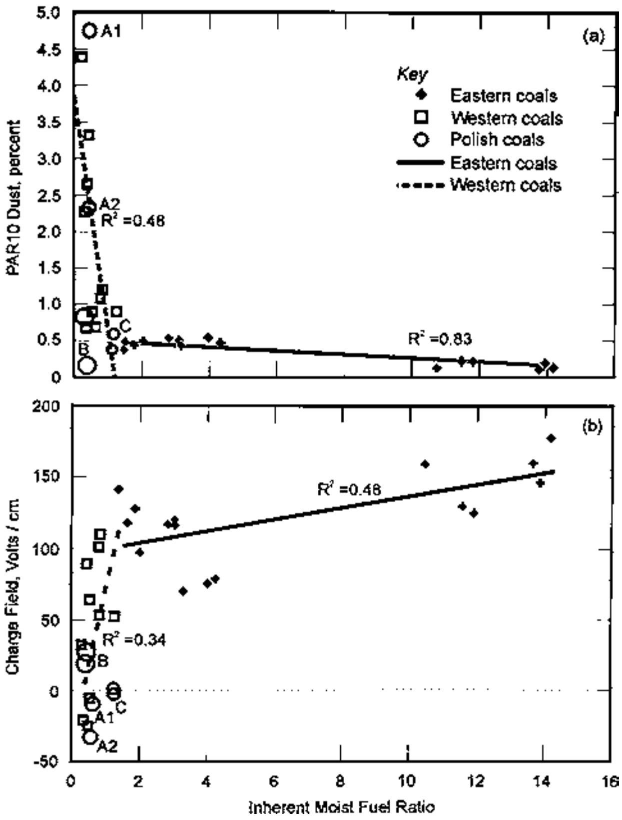

Figure 4. (a) Relationship between PAR10 dust and the moist fuel ratio based on the inherent moisture content; (b) Relationship between the breakage-induced electrostatic charge field and the moist fuel ratio based on the inherent moisture content.

In addition it is found that relationships similar to Figure 4a exist for PAR10 versus HGI. Namely, for eastern U.S. coals $r^2 = 0.83$ and for western U.S. coals $r^2 = 0.94$. Although the r^2 values are higher when HGI is used, better r^2 values are not necessarily a criteria for choosing one independent variable over another. For the western U.S. coals, the steep slope makes the r^2 value extremely sensitive to slight changes in positioning of the x-values, whether they be HGI or moist fuel ratios.

These results perhaps suggest an explanation for the appearance of Figure 1b as well as the wide charge field range of the eastern U.S. coals (air dry loss moisture approximately 1%). It might be suggested that the moist fuel ratio and HGI, which can be considered measures of coal matrix strength (Page et al. 1993), play a significant role in determining the initial charge magnitude produced upon coal breakage, while the air dry loss moisture determines the net resultant charge on a dust particle. The highest rank coals also produced more product fines <10 μm (see Figure 2), and these product fines are equally correlated with moist fuel ratio and HGI ($r^2 = 0.98$ in both cases) when no distinction is made between coals. This is not necessarily surprising since both HGI and moist fuel ratio are measures of coal rank and the HGI and moist fuel ratio are linearly related in this data with $r^2 = 0.96$. It is interesting to note that Page et al. (1993) observed what appeared to be a negative exponential dust concentration (measured in mg/m^3) versus moist fuel ratio relationship (the western U.S. coals yielding the highest concentrations) in their tests, which was not seen in this work. However, there are 2 important differences between the studies that explain the apparent inconsistency. The experiments by Page et al. (1993) were performed on coal product that had both been reduced during sample preparation to a size significantly smaller than the cleat structure and had also been oven-dried at 100°C to remove the air dry loss moisture. Both of these method differences have the direct impact of eliminating the representation of air dry loss moisture ÷ ash. In view of the present work, it would appear that the previous work by Page et al. (1993) may be better described by 2 linear relationships.

It is clear that representations of PAR10 using either air dry loss moisture ÷ ash or moist fuel ratios identify the same 6 samples that generate the largest amount of PAR10. It is also clear that, since the air dry loss moisture content of any coal is independent of the proximate analysis characteristics fixed carbon, volatile matter, ash, and inherent moisture, a more complete PAR10 model would likely include both air dry loss moisture ÷ ash and moist fuel ratio. This combined variable would be a logical result of the fact that in crushing, regardless of coal type, there is no one breakage mechanism at work. As suggested by this work, crushing the more friable, cleated eastern U.S. coals possibly results in dust production primarily from breakage along the cleat/fracture structure with less dust generation occurring from breakage of the coal matrix itself. Crushing the blockier western U.S. coals possibly results in dust production primarily from breakage of the coal matrix and less dust generation occurring from breakage along the cleat/fracture structure. However, there is not sufficient data in this work to warrant an independent variable of this type. Nevertheless, it is important that for the first time a clear delineation of coals that generate the most airborne respirable dust appears possible. This appears to be very useful for dust control to protect the health of coal miners as well as fugitive dust emissions from coal preparation plants for environmental air quality improvement.

The following discussion will attempt to provide a physically meaningful rationale for the role that the ash content plays in relationship to PAR10 generated from more extensively cleated coals. Evidence will be presented from the literature relating to the relationship between the cleat structure of the coal and the mineral matter from which the ash content is derived.

DISCUSSION

In the Introduction of this paper several independent laboratory and underground studies were discussed that are very suggestive of a cleat\ash relationship with dust generation since the ash content relationship with airborne dust only occurred in the tests where the coal sizes being broken are larger than the cleat/fracture structure of the coal. The data presented in this paper used feed material with a top size of 50 mm and Tables 2 and 3 show an obvious relationship between the normalized airborne dust PAR10 and ash content of the coal channel samples. Among these studies, if a cleat\ash relationship with dust generation did not exist, one would expect the ash relationship with dust generation to persist even at sizes below the cleat structure—this has not been seen to occur.

Having presented test results from multiple, independent studies that yield an airborne dust versus ash content correlation, the next question that must be answered (or at least some reasonable explanation presented) is simply "why should the airborne dust be correlated with ash content and only in those tests where cleating is present in the material being broken?" This is an important question to resolve because this ash content, as such, is not a constituent of the coal as it is being broken and therefore cannot be directly responsible for dust generation. This ash content is derived from the mineral matter content of the coal that resides throughout the coal and in the fractures and cleats. Since it has been established that the dust versus ash content relationship does not appear to exist when breaking material whose size is below the cleat size, this result suggests that the ash (mineral matter) responsible for the dust generation is associated somehow with the cleat, fracture, or bedding plane structure of the coals.

If it is assumed for the moment that the mineral matter associated with the cleat/fracture structure is a factor involved in the generation of dust, it would certainly be useful if there were other evidence to help validate this assumption. Ideally it would be useful if there was some characteristic associated only with the cleat that could be identified. Although other epigenetically-formed minerals can occur in the cleat structure and pyrite can occur within the coal matrix, it would be very informative and suggestive if at least one mineral closely associated with the cleat structure showed a relationship with ash content.

Pyrite can occur in a variety of locations and forms throughout a coal seam. In relation to the present study, the pertinent form is as filling material (along with other minerals such as kaolinite and calcite) in the cleating structure and dessication fractures of the coal (Ball 1935). There are various theories to logically explain the formation of pyrite in coal seams. In part, this is attributable to the fact that pyrite may have been formed at different times and in different ways throughout the coal seam (Bischoff 1854; Wheeler 1921; Cook 1975; Cady 1935). Since pyrite can form epigenetically in the cleating structure of the coal (Casagrande 1987), this particular mineral could possibly serve as a tracer material. The coal samples used in this study represent channel coal only (obvious rock material excluded) and macroscopic forms of pyrite do not create an interfering factor. To possibly demonstrate a relationship between the PAR10 ash dependency and the degree of cleating in the coals, the crushed channel coal samples were analyzed for pyritic sulfur content. Figure 5 shows the relationship between pyritic sulfur and ash content. The western U.S. coals, being much younger than eastern U.S. coals, are generally much less cleated and each one tested had pyritic sulfur content <0.05% regardless of ash content. This is significantly less than the other coals tested. Even though the western U.S. coals possess cleat structure and the ash content ranged from 5 to 15%, there is obviously no relationship between pyritic sulfur and ash content as seen in the eastern U.S. and Polish coals. The eastern U.S. coals showed a positive linear relationship ($r^2 = 0.74$) of pyritic sulfur with ash content and the Polish coals showed a parallel positive linear relationship ($r^2 = 0.87$). It could be further inferred from

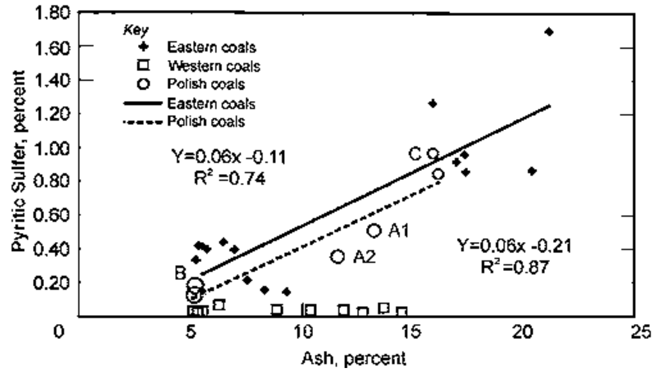

Figure 5. Relationship between pyritic sulfur and ash content.

this graph that if this pyritic sulfur content in the western U.S. coals represents some baseline that obviously has no relation to ash content, in the geologic time formation of coal this baseline would be present within the older eastern U.S. and Polish coals. If this is so, subtraction of this baseline still results in a pyritic sulfur versus ash relationship that appears to be explained only by the cleating of the coal.

Having shown a possible link between the ash content, pyritic sulfur content, and PAR10, it remains to provide further supporting evidence for the relationship of these factors and the cleat structure. As stated earlier, the pyrite may be considered as equivalent to a tracer, suggesting that most of the respirable dust is generated by breakage along the cleat and fracture structure in the eastern U.S. coals. It appears, perhaps not coincidentally, that these more cleated coals contain less moisture and therefore more electrostatic charge is associated with them upon breakage. Hence there is significant agglomeration of dust in the product, reducing the percentage amount (PAR10) that becomes airborne. Thus a physically meaningful model of the defined ratio air dry loss moisture ÷ ash and its relationship with PAR10 dust can be suggested based on current knowledge of coal seam formation and dust generation.

The breakage of coal and the resultant airborne respirable dust production present in the mining of coal bears some similarity to the process of coal cleaning. In this regard, Chapman and Mott (1928) report that on crushing of coal, breakage occurs to the greatest extent along the bedding planes (where cohesion is lowest) and some of the dirtier bands are freed. This preferential breakage will also occur along the cleat structure of the coal seam. Support for preferential breakaging along the cleat structure that contains pyrite is provided by Yancey and Fraser (1929) and Neavel (1981). Further support for the choice of pyrite as a suitable tracer material for the degree of coal cleating is provided by the relationship of the product mass median size (D_{50} in Table 3) and the pyritic sulfur content of the coals measured in this work, which were inversely related with a linear regression $r^2 = 0.62$. This relationship suggests that the more extensively cleated coals, which produced a smaller product mass median size than the less cleated coals, may contain a significant amount of pyritic sulfur associated with the cleat structure.

In support of the suggested relationship between cleat and ash content of coal, Raistrict and Marshall (1939) note that cleating is absent in true anthracites and that this may have a close bearing on their low ash content. Additionally, Law (1993) states that many of the cleats in high rank coals are commonly mineral filled and that high rank coals have closely spaced cleats.

Pyrite, as well as other minerals, residing in the cleat structure of the coal seam can be rather easily liberated upon breakage since the breakage preferentially occurs along these fractures. Organiscak and Page (1998) observed that comparisons between 2 different material feed mechanisms in the same crusher produced very little difference in airborne respirable dust but a significant difference in airborne total dust, indicating that most of the airborne respirable dust appears to come from the breakage along the cleat fractures. The crusher feed mechanisms tested were a trickle feed, where very little secondary breakage occurred, and a batch loading of the crusher, which allowed for some secondary breakage to occur due to regrinding before the coal passed through the crusher.

As stated earlier, this work offers a representation that suggests a cause and effect relationship between coal characteristics, described by certain proximate analysis constituents of coal, and airborne respirable dust generation, as well as providing a potential mechanism for increased prevalence of CWP in higher rank coals. If it is true, as suggested, that the mineral matter associated with the cleat/fracture structure is a factor involved in the generation of airborne dust, there may be other ramifications associated with the health effects of breathing this dust. Although beyond the scope of this work, it is well known that there are numerous other toxic substances present in the mineral matter content of coal and that in many cases there is an enrichment of these substances when compared to their natural occurrence in the earth crust. For example, Bethell (1962) cites numerous references who have proven that arsenic occurs in coal mainly (if not entirely) extrinsically as arsenopyrite ($FeS_2 \cdot FeAs_2$). Additionally, Bethell cites a reference that recorded an outbreak of chronic arsenical poisoning among workers in the Belgian briquetting industry, attributed to the presence of arsenical pyrites in the coal.

CONCLUSIONS

The results of this work indicate that the relative dust-generating characteristics of coals from eastern and western U.S. coal seams and Polish coal seams can be sharply defined by several parameters measured by proximate analysis. The air dry loss moisture content of coal appears to control, through the breakage-induced electrostatic field associated with dust, the amount of respirable dust that is liberated from the product and becomes airborne. The percentage, expressed as PAR10, of coal dust particles smaller than 10 μm in the product that are dispersed as airborne respirable dust increases with air dry loss moisture increasing over the range from 1 to 5%. This trend appears to be followed by a possible rapid decrease in PAR10 dust in the range of air dry loss moisture from 5 to 6%, which is in agreement with previously published data. The data shows that there is a concurrent decrease in the electrostatic charge field with air dry loss moisture increasing over the range from 1 to 6%.

Another representation shows that the PAR10 dust exhibits a well-defined peak when characterized by the ratio of air dry loss moisture ÷ ash content. Based on this work and previous independent studies, a hypothesis is offered to provide a physically meaningful explanation for the relationship between airborne dust generation and the air dry loss moisture ÷ ash content ratio of coal. This hypothesis suggests that in crushing (as opposed to pulverization) and mining of eastern U.S. coals, the amount of dust particles smaller than 10 μm in the crushed product material is largely determined by primary breakage along the cleat/fracture structure of coal.

It was also shown that the PAR10 dust-generating characteristics of coals could be reasonably described by both the moist fuel ratio and the HGI. These results show a clear distinction between the eastern U.S. coals and the western U.S. coals. This is to be expected since both HGI and moist fuel ratio are measures of coal rank and the HGI and moist fuel ratio show a very high linear correlation. Crushing the blockier western U.S. coals possibly results in dust production primarily from breakage of the coal matrix, represented by the moist fuel ratio or HGI, and less dust generation occurring from breakage along the cleat/fracture structure. However, no consistent distinction for the Polish coals was observed.

For the first time, a clear delineation of coals that generate the most airborne respirable dust appears possible based on well-known proximate analysis characteristics. Practical applications of this research illustrate the predictive ability to identify coal mines that are susceptible to respirable dust problems. Also, unique dust-charging polarity and magnitude signatures associated with various coals may now allow for the proper matching of water spray surfactants used for dust control to particular coal types. This could possibly reduce the generation of airborne respirable dust, enhancing the respiratory protection of coal miners. In addition, realization of the inherent dust generation characteristics of different coals would be useful for determining and controlling fugitive dust emissions from coal preparation plants for environmental air quality improvement.

REFERENCES

American Society for Testing and Materials. (1996). *ASTM D3172—Standard Practice for Proximate Analysis of Coal and Coke*, Annual Book of ASTM Standards, vol. 5.05, pp. 288–297.

American Society for Testing and Materials. (1997). *ASTM D409—Standard Test Method for Grindability of Coal by the Hardgrove-Machine Method*, Annual Book of ASTM Standards, West Conshohocken, PA, vol. 5.06, pp. 39–47.

Attfield, M. D., and Morring, K. (1992). An Investigation into the Relationship Between Coal Worker's Pneumoconiosis and Dust Exposure in U.S. Coal Miners, *Am. Ind. Hyg. Assoc. J.* 53(8):486–492.

Attfield, M. D., and Seixas, N. S. (1995). Prevalence of Pneumoconiosis and its Relationship to Dust Exposure in a Cohort of U.S. Bituminous Coal Miners and Ex-Miners, *Am. Ind. Med.* 27:137–151.

Attfield, M. D., and Wagner, G. (1992). Respiratory Disease in Coal Miners. In *Environmental and Occupational Medicine*, 2nd ed., edited by W. N. Rom. Little, Brown and Company, Boston, MA, pp. 325–344.

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

Ball, C. G. (1935). *Contributions to the Study of Coal: Mineral Matter of No. 6 Bed Coal at West Frankfort, Franklin County, Illinois*, Illinois State Geol. Survey, RI 33, Champaign, IL.

Becker, R. S., Anderson, V. E., Allen, J. D., Birkhoff, R. D., and Ferrell, T. L. (1980). Electrical Image Deposition of Charges from Laminar Flow in Cylinders, *J. Aerosol Sci.* 1:461–466.

Bethell, F. V. (1962). The Distribution and Origin of Minor Elements in Coal, *The British Coal Utilization Res. Ass. Monthly Bulletin* 26(12):401–430.

Bischoff, G. (1854). Elements of Chemical and Physical Geology, *Proc. of The Cavendish Society*, London, 1:163.

Cady, G. H. (1935). *Distribution of Sulfur in Illinois Coals and its Geological Implications*, Illinois State Geol. Survey, RI 35, Champaign, IL.

Casagrande, D. J. (1987). Sulphur in Peat and Coal. In *Coal and Coal-Bearing Strata: Recent Advances*, edited by A. C. Scott. Geologic Society, Special Publication No. 32, Blackwell Scientific Publications, Oxford, pp. 87–105.

Chapman, W. R., and Mott, R. A. (1928). *The Cleaning of Coal*, Chapman & Hall Ltd., London, pp. 3–6.

Cook, A. C. (1975). The Spatial and Temporal Variation of the Type and Rank of Australian Coals. In *Proc. of Symp. on Australian Black Coal—Its Occurrence, Mining, Preparation and Use*, Feb. 18–20, edited by A. C. Cook. Australasian Institute of Mining and Metallurgy, Illawara Branch, pp. 63–84.

Cummins, A. B., and Given, I. A. (1973). *SME Mining Engineering Handbook*, sect. 28.3.1-Crushing. Society of Mining Engineers, New York, pp. 13–14.

Dodd, E. E. (1952). The Statistics of Liquid Spray and Dust Electrification by the Hopper and Laby Method, *J. Appl. Physics* 24:73–80.

Hamilton, R. J., and Knight, G. (1957). *Laboratory Experiments on Dust Suppression with Broken Coal*, National Coal Board, Mining Research Establishment, Report 2083, Research Programme Reference 9.2, London, UK.

Hopper, V. D., and Laby, T. H. (1941). The Electronic Charge, *Proc. of Royal Society* 16:243–273.

Hurley, J. F., and Maclaren, W. M. (1987). *Dust-Related Risks of Radiological Changes in Coal Miners over a 40-year Working Life: Report on Work Commissioned by NIOSH*, Edinburgh, Scotland: Institute of Occupational Medicine, Report TM/87/09.

Kaya, E., and Hogg, R. (1992). In-Situ Measurements of Agglomeration of Airborne Dust in Mines, *Proc. Emerging Process Technology for a Cleaner Environment*, Feb. 24–27, Phoenix, AZ, SME, Littleton, CO, pp. 259–267.

Knight, G. (1958). *The Formation of Dust and Debris and the Dispersion of Dust at the Breakage of Lump Coal in Relation to the Strength, the Water Content and Superficial Wetting*, National Coal Board, London, U.K., Mining Research Establishment Report 2088, Research Programme Reference 9.2.

Kunkel, W. B. (1948). Growth of Charged Particles in Clouds, *J. Appl. Phys.* 19:1053–1055.

Kunkel, W. B. (1950). Charge Distribution in Coarse Aerosols as a Function of Time, *J. Appl. Phys.* 21:833–837.

Law, B. E. (1993). The Relationship Between Coal Rank and Cleat Spacing: Implications for the Prediction of Permeability in Coal. In *Proc. of the International Coalbed Methane Symp*, vol. 2, May 17–21.

Mark, C., and Barton, T. M. (1997). Pillar Design and Coal Strength. In *Proc. New Technology for Ground Control in Retreat Mining*, US Department of Health and Human Services, NIOSH IC 9446, pp. 49–59.

Melandri, C., Tarroni, G., Podi, V., De Zaiacomo, T., Formignani, M., and Lombardi, C. C. (1983). Deposition of Charged Particles in the Human Airways, *J. Aerosol Sci.* 15:657–669.

Moore, M. P., and Bise, C. J. (1984). The Relationship Between the Hardgrove Gindability Index and the Potential for Respirable Dust Generation. In *Proc. of the Coal Mine Dust Conference*, Generic Technology Center for Respirable Dust, October 8–10, Morgantown, WV, pp. 250–255.

National Institute for Occupational Safety and Health. (1995). *Criteria for a Recommended Standard: Occupational Exposure to Respirable Coal Mine Dust*, US Department of Health and Human Services (NIOSH) 95–106, September.

Neavel, R. C. (1981). Origin, Petrography, and Classification of Coal. In *Chemistry of Coal Utilization*, 2nd Supp. Vol, edited by M. A. Elliott. John Wiley & Sons, pp. 91–58.

Organiscak, J. A., and Colinet, J. F. (1999). Influence of Coal Properties and Dust Control Parameters on Longwall Respirable Dust Levels, *Mining Engineering, Technical Papers* 51:41–48.

Organiscak, J. A., and Page, S. J. (1993). Laboratory Investigation of Coal Grindability and Airborne Respirable Dust, *J. Mine Vent. Soc. of S. Africa* 46:98–105.

Organiscak, J. A., and Page, S. J. (1998). *Investigation of Coal Properties and Airborne Respirable Dust Generation*. U.S. Department of Health and Human Services, NIOSH RI 9645.

Organiscak, J. A., Page, S. J., and Jankowski, R. A. (1992). *Relationship of Coal Seam Parameters and Airborne Respirable Dust at Longwalls*, U.S. Department of Interior, Bureau of Mines RI 9425.

Page, S. J. (2000). Relationships Between Electrostatic Charging Characteristics, Moisture Content, and Airborne Dust Generation for Subbituminous and Bituminous Coals, *Aerosol Sci. Technol.* 32:249–267.

Page, S. J., Organiscak, J. A., and Quattro, J. (1993). Coal Proximate Analysis Correlation with Airborne Respirable Dust, *Fuel* 72:965–970.

Polat, M., Chander, S., and Hogg, R. (1991). Characterization of Freshly Generated Airborne Dust of Quartz. In *Proc. of Int. Symp. on Respirable Dust in the Mineral Ind.*, October 17–19, 1990, Pittsburgh, PA, edited by R. L. Franz. SME, Littleton, CO, pp. 267–274.

Potts, J. D., McCawley, M. J., and Jankowski, R. A. (1990). Thoracic Dust Exposures on Longwall and Continuous Mining Sections, *J. Appl Occup. Environ. Hyg.* 5:440–447.

Raistrick, A., and Marshall, C. E. (1939). *The Nature and Origin of Coal and Coal Seams*, English Universities Press Ltd., London.

Ramani, R. V., Mutmansky, J. M., Bhaskar, R., and Qin, J. (1987). *Fundamental Studies on the Relationship Between Quartz Levels in the Host Material and the Respirable Dust Generated During Mining*, U.S. Department of Interior, Bureau of Mines OFR 36-88, NTIS PB 88-214325/AS, Vol. I.

Schuhmann, R. (1940). Principles of Comminution, I-Size Distribution and Standard Calculations. American Institute of Mining, Metallurgical, and Petroleum Engineers, TO 1189, *Mining Technology* (July) 1–11.

Srikanth, R., Zhao, R., and Ramani, R. V. (1995). Relationships Between Coal Properties and Respirable Dust Generation. In *Proc. 7th U.S. Mine Ventilation Symposium*, June 5–7. SME, Lexington, KY, pp. 301–309.

Stecklein, G. L. (1982). *Basic Research on Coal Fragmentation and Dust Entrainment*, vol., 1, San Antonio, TX, Soutwest Research Institute, U.S. Department of Interior, Bureau of Mines OFR 215(1)-83.

Taggart, A. F. (1945). *Handbook of Mineral Dressing, Section 19–Sampling and Testing*, John Wiley, New York, pp. 33–35.

U.S. Congress. (1969). *Federal Coal Mine Health and Safety Act of 1969*, Public Law 91-1173.

Wheeler, R. V. (1921). Sulfur in Coal, *Colliery Guardian*, p. 1596.

Williams, K. L., and Timko, R. J. (1984). *Performance Evaluation of a Real-Time Aerosol Monitor*, U.S. Department of Interior, Bureau of Mines IC 8968.

Yancey, H. F., and Fraser, T. (1929). *Coal-Washing Investigations: Methods and Tests*, U.S. Department of Commerce, Bureau of Mines Bulletin 300, pp. 21–22.

Yu, C. P., and Chandra, K. (1978). Deposition of Charged Particles from Laminar Flows in Rectangular and Cylindrical Channels by Image Force, *J. Aerosol Sci.* 9:175–180.