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Coal Char Fragmentation During Pulverized Coal Combustion

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COAL AND CHAR FRAGMENTATION DURING PULVERIZED COAL COMBUSTION

Milestone Report

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Abstract

A series of investigations of coal and char fragmentation during pulverized coal combustion is reported for a suite of coals ranging in rank from lignite to low-volatile (lv) bituminous coal under combustion conditions similar to those found in commercial-scale boilers. Experimental measurements are described that utilize identical particle sizing characteristics to determine initial and final size distributions. Mechanistic interpretation of the data suggest that coal fragmentation is an insignificant event and that char fragmentation is controlled by char structure. Chars forming cenospheres fragment more extensively than solid chars. Among the chars that fragment, large particles produce more fine material than small particles. In all cases, coal and char fragmentation are seen to be sufficiently minor as to be relatively insignificant factors influencing fly ash size distribution, particle loading, and char burnout.

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Introduction

Char fragmentation and flyash formation during pulverized-coal combustion impact important aspects of boiler operation including radiative heat transfer, fouling and slagging propensities, and particulate removal efficiency. Flyash that escapes particle cleanup systems constitutes a significant environmental and health hazard and is the focus of substantial legislation and regulation [Wark and Warner, 1981]. These practical, environmental, health, and legal considerations have motivated a number of theoretical and experimental studies of flyash formation.

Reported mechanisms of flyash formation include (1) vaporization and recondensation of volatile components of coal ash [Flagan, 1978; Flagan and Taylor, 1980; Neville, et al., 1980; Neville and Sarofim, 1985; Quann, et al., 1982; Quann, et al., 1990; Quann and Sarofim, 1982; Quann and Sarofim, 1986], (2) fragmentation of ash due to inorganic reaction [Baxter and Mitchell, 1992; Raask, 1984; Raask, 1985], (3) convective transport of ash during rapid organic reaction [Allen and VanderSande, 1984; Baxter, et al., 1994 (to appear)], (4) structural disintegration of chars [Flagan and Sarofim, 1984], (5) shedding of ash material from the surface of chars during combustion [Allen and VanderSande, 1984; Quann, et al., 1982; Quann and Sarofim, 1982], and (6) coalescence of ash within a char particle [Allen and VanderSande, 1984; Baxter, 1992; Quann and Sarofim, 1982]. The term *fragmentation*, as used in this paper, encompasses all mechanisms that produce more than a single ash particle from a char particle and could involve any or all of the above processes.

Several mechanistic details of fragmentation are available in theoretical papers. Statistical studies ranging from number balances [Dunn-Rankin and Kerstein, 1987; Dunn-Rankin and Kerstein, 1988] to percolation models [Kang, et al., 1988; Kang, et al., 1990; Kerstein and Edwards, 1987] describe the transient development of char particle size distributions, often for a series of assumed scenarios of fragmentation. These models vary widely in their level of detail, although none describes all aspects of fragmentation and parameters used in the models do not always lend themselves to experimental measurement. While progress in this area continues, there exist no complete descriptions of fragmentation in the available literature.

Experimental techniques for studying fragmentation include both solidsampling and laser-based, in situ techniques. Typical solid-sampling studies involve size classification of flyash by a cascade of impactors. Feed material and equipment used in these studies range from mechanically classified samples of coal entrained in laminar flow facilities [Quann and Sarofim, 1982] to utility grind coal sampled from boiler ducts [Holve, 1986]. In situ techniques reported in the past [Wibberley and Wall, 1986] have also been used in laminar flow facilities. Results from various experiments appear discrepant when examined superficially. For example, the reported number of flyash particles generated per char particle varies from near one [Holve, 1986; Sarofim, et al., 1977; Wibberley and Wall, 1986] to several tens of thousands [Quann and Sarofim, 1982; Quann and Sarofim, 1986]. As will be illustrated, these discrepancies may be more superficial than actual. None of these investigations used the same analysis technique to characterize both the feed material and the flyash under combustion conditions representative of commercial boilers.

Specific objectives of this investigation are to (1) devise a fragmentation model that is sufficiently complete to analyze data collected from systems using utility grind coal as a feedstock, (2) measure experimentally the initial and final particle size distributions using the same in situ diagnostic and under conditions comparable to commercial scale operation, and (3) combine the theory and experiment to determine the extent of char fragmentation.

One of the unique aspects of these investigations is the use of the same *in situ* sizing technique to determine both char and fly ash particle sizes. Experiments are conducted in the Multifuel Combustor (MFC) using utility-grind, pulverized coal in an environment simulating that of a utility-scale boiler. Size distributions are measured immediately after coal devolatilization and at the end of char combustion (greater than 99% daf burnout as determined from tracer analysis of solid samples).

The extent of char fragmentation, as indicated by the number of fly ash particles formed per char particle, is found to depend on (in order of importance): (1) char structure, (2) initial char particle size, (3) ash content, and (4) mineral grain size distribution. The first three dependencies are clearly indicated by existing data. The fourth is postulated pending further investigation of mineral grain size distributions in these coal samples.

The analysis of the data collected from the MFC is similar to a previously published model of char fragmentation [Baxter, 1992]. This analysis is briefly reviewed here. The experimental design is also briefly reviewed. The bulk of the discussion centers on the results and their implications.

Theoretical Analysis

The fragmentation model described below relates the initial char (not coal) feedstock and final fly ash size distributions. The model is written in terms that are convenient for laboratory analyses. That is, the char particles have physical properties that can vary as a function of size but, at a given size, are described by a single-valued function. Particle-to-particle variations in physical properties *at a given size* are neglected. Also, transient developments in particle size distributions, as discussed by many of the previously cited authors, are neglected. Size distributions of the initial char and final fly ash can be related, in general, through a particle number balance.

$$\int_{d_{a1}}^{d_a} n'_a(x) dx = \int_{d_c=0}^{d_c=\infty} \int_{d_{a1}}^{d_a} g(x|y) dx n'_c(y) dy \quad (1)$$

The functions n'_a and n'_c represent particle concentration density functions for fly ash and char, respectively, with typical units of particles/(m³ μm). Dummy variables x and y are used in the integrands to represent fly ash (d_a) and char (d_c) particle diameters, respectively. Integration of n' with respect to particle diameter represents the cumulative concentration of particles with sizes between the limits of integration. Thus, the integral on the left represents the total concentration of fly ash particles with diameters larger than d_{a1} and smaller than d_a .

The function $g(x|y)$ is a conditional fly ash particle size distribution (psd); it indicates the *ultimate* size distribution of fly ash particles formed from a char particle with *initial* size y . This represents the only portion of the above equation that is not determined experimentally in this investigation.

Several published theoretical and experimental results suggest general forms of the function. One example [Quann and Sarofim, 1986] provides data from which $g(x|y)$ can be

determined for one char particle size. In that study, coal particles were mechanically sieved to a 140 μm nominal diameter and combusted at a particle temperature of about 2000 K in a 20 % O_2 environment. The number of fly ash particles generated was deduced as a function of fly ash particle size.

The function $g(x|y)$ for this literature data [Quann and Sarofim, 1986] can be generated by differentiating the cumulative size distribution with respect to particle size. This is illustrated in Figure 1. The linearity of the data when plotted in this way suggests that the data follow a power-law distribution, i.e.,

$$g(x|y) = \begin{cases} a(y)x^b, & \text{for } x_1(y) \leq x \leq x_2(y), \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where x_1 and x_2 represent the diameters of the smallest and largest fly ash particle generated, respectively. This conditional psd describes a power-law size distribution between the limits x_1 and x_2 for fly ash particles generated from each char particle of size y . Note that this functional form can only describe the results from an ensemble of initial char particles with size y . The functional form of g for a single char particle is series of Dirac delta functions.

Values for a and b of 3260 and -3.21, respectively, fit the literature data [Quann and Sarofim, 1986] with a coefficient of determination [Canavos, 1984] (r^2) greater than 0.99 (in logarithmic coordinates with x expressed in microns). The original data of Quann and Sarofim have been recast in number density form, and this correlation is compared with these recast data in Figure 1. The authors state that the smallest particles (those smaller than about 0.6 μm) are generated by vaporization-recondensation mechanisms, whereas the larger particles are believed to be generated by surface drop shedding or disintegration of char structures. If the data at sizes smaller than 0.6 μm are eliminated, values for a and b of 2370 and -2.95, respectively, fit the remaining data, also with a coefficient of determination greater than 0.99. Therefore, the functional form for $g(x|y)$ given by Eq. 2 represents at least this set of data regardless of the mechanism of fragmentation and the value of b used in the conditional psd can be assumed to be approximately -3.

Results of a percolation model of char fragmentation [Dunn-Rankin and Kerstein, 1988] provide further theoretical motivation for this functional form of this conditional pdf. This formulation has been used in other theoretical studies of the transient evolution of char particle size distributions [Kerstein and Edwards, 1987].

A mass balance on the fly ash determines the function $a(y)$, as follows:

$$m_a(y) = \int_0^{\infty} \frac{\pi}{6} \rho_a x^3 g(x|y) dx = \frac{\pi}{6} \rho_a a(y) \Delta x(y) = \omega_a(y) m_c = \omega_a(y) \frac{\pi}{6} \rho_c y^3 \quad (3)$$

where ρ represents density, ω represents ash mass fraction, and Δx represents $x_2 - x_1$. Note that the density of the *initial* char particle (ρ_c) represents the density of the total particle, not just the organic portion. Also, the density of the *final* ash particle and the ash mass fraction

in the char particle (ρ_a and ω_a , respectively) represent values of *ash*, as opposed to the mineral matter from which the ash is formed. It follows from Eq. 3 that,

$$a(y) = \frac{\omega_a(y)\rho_c y^3}{\rho_a \Delta x(y)} \quad (4)$$

For convenience in determining the upper and lower bounds of g , a parametric function $f(y)$ is designated the *fragmentation factor* and is defined as follows:

$$f(y) \equiv \frac{(\omega_a \rho_c / \rho_a)^{1/3} y}{x_2} \quad (5)$$

The numerator represents the size of the fly ash particle that obtains when all of the ash in a char particle coalesces, i.e., no fragmentation occurs. The function f equals the ratio of this hypothetical size to the size of the largest fragment actually generated from a char particle (x_2); f increases with an increase in the *extent* of fragmentation. In the limit of no fragmentation, f is unity, independent of either initial char particle size (y) or char size

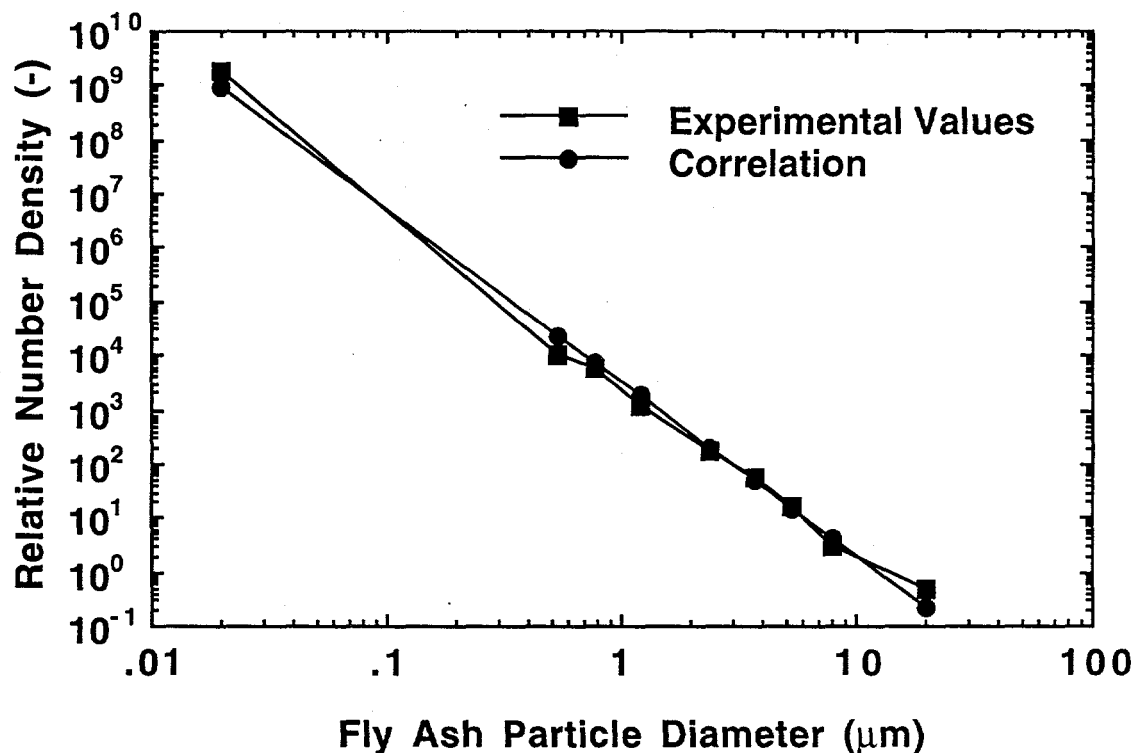


Figure 1. Power law function $g(x|y)$ correlated with the power-law size distribution. Data are from the literature [Quann and Sarofim, 1986].

dependencies in either ρ or ω . (This statement may appear to contradict the explicit dependence of f on y indicated in Eq. 5. However, in the case of no fragmentation, this explicit dependence cancels with the implied dependence of x_2 and of the physical properties on y .) In general, f is expected to be greater than or equal to 1. The parameter f indicates the extent of fragmentation in that it increases as the extent of fragmentation increases. If char were to produce a monodispersion of fly ash particles as a consequence of fragmentation, the total number of fragments produced would be equal to f^3 .

A second function $s(y)$, designated the *fragment size ratio*, is defined as

$$s(y) \equiv \frac{x_1(y)}{x_2(y)} \quad (6)$$

and represents the *mode* of fragmentation in the sense that s decreases as the range of fragment sizes produced from a char particle increases. If there is no fragmentation, both f and s are unity. As s decreases from unity toward zero, the range of sizes of fragments produced from a single char particle increases.

Equation 2 can be written in terms of the parameters f and s as

$$g(x|y) = \begin{cases} \frac{\omega_a \rho_c y^3}{\rho_c \Delta x} x^{-3} & \text{for } x_1(y) \leq x \leq x_2(y) \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

yielding

$$\int_{d_{a1}}^{d_a} g(x|y) dx = \frac{f^3}{2} \left(\frac{1-s^2}{s^2-s^3} \right) + \min \left\{ \frac{f^3}{2(1-s)} \left[\left(\frac{x_2}{\min(x_2, d_{a1})} \right)^2 - \left(\frac{1}{s} \right)^2 \right], 0 \right\} + \min \left\{ \frac{f^3}{2(1-s)} \left[1 - \left(\frac{x_2}{\max(x_1, d_a)} \right)^2 \right], 0 \right\} \quad (8)$$

where s , f and x_2 depend on y . The second term on the right side is negative for all y where $d_{a1} > x_1$ and the third term is negative for $d_a < x_2$. Otherwise, both terms are zero. If all particle sizes are included in the integration ($d_{a1} = 0$ and d_a larger than the largest char or fly ash particle in the stream), the only nonzero term on the right side of the equation is the first term, which represents the ratio of the total numbers of fly ash and char particles.

In general, both f and s depend on initial char particle size y . However, the qualitative relationship between initial char and fly ash particle size distributions is conveniently illustrated by assuming that f , s and the ratio $(\omega_a \rho_c) / \rho_a$ are independent of initial char particle size and can be treated with average values. This means the char particles are homogeneous, or size-invariant, with respect to both their physical properties and their

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$$x_2 = \left(\frac{\omega_a \rho_c}{\rho_a} \right)^{1/3} \frac{y}{f} \equiv py \quad (9)$$

and

$$x_1 = sx_2 = psy \quad (10)$$

where p is independent of y and typically has a value of order 0.5 or less. This allows the integral of the conditional psd to be expressed analytically in terms of y only. If all ash particles are included in the integration ($d_{a1} = 0$), the relationship between char and fly ash concentration distributions can be written as

$$\int_0^{d_a} n'_a(x) dx = \int_0^{d_a/(ps)} n'_c(y) \frac{f^3}{2} \left(\frac{1-s^2}{s^2-s^3} \right) dy + \int_{d_a/p}^{d_a/(ps)} n'_c(y) \frac{f^3}{2(1-s)} \left[1 - \left(\frac{py}{d^a} \right)^2 \right] dy \quad (11)$$

A linear transformation of this equation relates directly to the experimentally measured cumulative particle size distributions reported later. This transformed expression is

$$K_a(d) \equiv \int_d^{\infty} n'_a(x) dx = \int_0^{\infty} n'_a(x) dx - \int_0^d n'_a(x) dx \quad (12)$$

where the integral from 0 to ∞ is a constant (independent of d_a). A similar expression defines the function K_c for the char particles.

$$K_c(d) \equiv \int_d^{\infty} n'_c(x) dx = \int_0^{\infty} n'_c(x) dx - \int_0^d n'_c(x) dx \quad (13)$$

Limiting forms of Eq.1, other than Eq. 11, are useful to consider. If the initial char particles are monodisperse (n'_c is a Dirac delta function), the integral on the left represents the total number of fly ash particles produced per char particle. Assuming Eq. 2 as the appropriate description for g , the total number of fly ash particles generated per char particle becomes

$$g = \frac{f^3}{2} \left(\frac{1+s}{s^2} \right) \quad (14)$$

Eq. 14 indicates the dependence of the number of fly ash particles on the parameters f and s . For a given value of f , the number of fly ash particles increases dramatically as s decreases (recall that s is always less than or equal to 1). Similarly, as f increases for a given value of s , the total number of fly ash particles increases as f^3 .

The valid range of the functions f and s illustrate that this theoretical approach is applicable only to ensembles of particles, not to individual particles. For example, when the ash in an individual particle coalesces to form a single fly ash particle ($f = 1$), there is only one size fly ash particle produced ($s = 1$). However, only a fraction of the particles in an ensemble of nominally identical char particles may behave this way. Therefore, f can assume a value of unity for the ensemble without limiting the range of values s can assume. In the application of this theory in this work, the only theoretical limitations on these two parameters are that $f \geq 1$ and $s \leq 1$. The functions are independent of each other.

Experimental Conditions

The Multifuel Combustor (MFC) (Fig. 2) and a Particle Counter Sizer Velocimeter (PCSV) are the primary experimental facility and diagnostic, respectively, used in this work. The MFC provides careful control of gas temperature and composition in a long-residence-time facility. The MFC was operated at a firing rate of 0.07 MBtu/hr with overall oxygen concentrations varying from 5 to 3 mole % during char oxidation, conditions similar to commercial-scale boiler operation. Particle residence time is varied by moving the location of the coal injection lance to various ports along the length of the combustor.

The PCSV performs *in situ* measurements of particle frequency (count), size and speed at the base of the combustor. The PCSV is based on near-forward light scattering from laser beams focused at the center of the reactor flow. Two laser beams are used, one for large particles ($> 3 \mu\text{m}$) and the second for small particles. The measurements are based on individual particles passing through an approximately ellipsoidal diagnostic volume with a major axis of about 1 mm and minor axes of approximately 300 μm for one beam and 50 μm for the second. The diagnostic is discussed more fully in the literature [Holve and Self, 1979a; Holve and Self, 1979b; Holve, et al., 1981].

The accuracy of the instrument is verified by passing monosized standards through the diagnostic volume and comparing the measured particle sizes with the known actual sizes. Standards used included glass beads entrained in air and transparent discs etched in an opaque reticule. The standards varied from 0.6 to 60 μm and indicate that the PCSV reports particle sizes within one size bin or 0.1 μm of the correct size, whichever is larger.

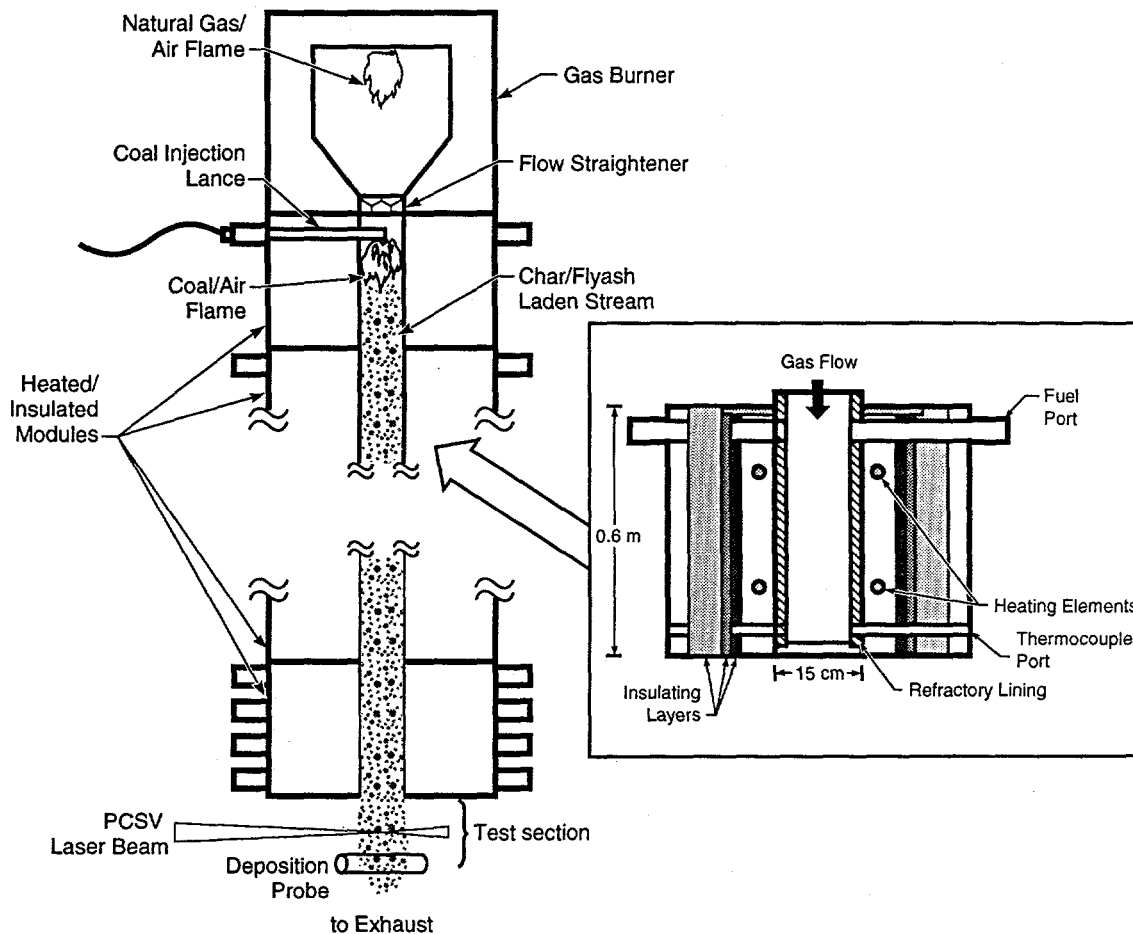


Figure 2. Schematic diagram of the Sandia Multifuel Combustor. The laser beam from the PCSV particle sizing system is illustrated in the test section of the combustor.

The precision of the data is determined by repeating measurements of coal and fly ash in the MFC under nominally identical conditions and computing coefficients of variation from the results. At least five, and as many as twelve, replicate experiments were performed for each coal at each sampling height. The coefficient of variation thus determined includes experimental uncertainty as well as actual fluctuations due, for example, to turbulent fluctuations and variations in coal feed rates. The impact of such fluctuations on the data can be minimized by computing the total mass flowrate from the measured particle concentrations and normalizing all the results to this value. Confidence intervals presented below are based on these measured coefficients of variation and standard statistical techniques.

The upper and lower detection limits of the PCSV are determined in these experiments by the points at which the agreement among the repeated tests becomes poor, as indicated by

the statistical confidence intervals. The lower limit is 0.4 - 0.7 μm and is controlled primarily by signal-to-noise levels in the detector. The upper limit is controlled by sampling statistics in this experiment. Approximately 160,000 individual particles were sampled per measurement, and each measurement was repeated 5 to 12 times. Under these conditions, the upper detection limit is about 100 μm .

Reasonably complete analyses of all the coals used in these experiments are included in the appendix. The data in the appendix include all of the coals used in the program to date. There are several samples of coal with the same name. These are distinguished by numbers, for example, Illinois #6 (2) is a different coal sample than Illinois #6 (1).

The nominal conditions under which these experiments were conducted are summarized in Table 1. Under these experimental conditions, the particles form a dilute phase in the gas, with the total particle volume fraction far less than one percent of the overall gas volume. Consequentially, the probability of particle-particle collisions producing agglomerated fly ash is vanishingly small.

Coals and Coal Properties

Table 2 summarizes the properties of the coals whose fragmentation rates were studied. The coals span a range of rank from lignite to low-volatile bituminous and a range of ash concentrations from 2.8 to 52 %, with an average value of slightly greater than 10 %. Representatives from essentially every commercially significant coal-producing region of the country are included among the coals studied. More complete analyses of the coals are provided in Appendix A. These analyses include: (1) moisture content; (2) proximate analysis; (3) ultimate analysis; (4) ash chemistry; (5) ash fusion temperatures under reducing and oxidizing environments; (6) sulfur forms; (7) particle size distributions determined by sieves; (8) particle size distributions determined by Malvern optical analyses, (9) chlorine content (for coals containing appreciable chlorine), and (10) heating value. In all cases, the data are averages of several replicated measurements.

Table 1

Typical Local Gas and Particle Properties in the MFC at the Initial Char and the Fly Ash Measurement Locations

<u>Property</u>	<u>Initial Char</u>	<u>Fly Ash</u>
Gas temperature ($^{\circ}\text{C}$)	1100	900
Oxygen mole fraction	0.06	0.04
Particle residence time τ (s)	0.2	2.1
Particle burnout (daf)	0.65	0.99+
Particle temperature ($^{\circ}\text{C}$)	1250	900

Fragmentation data for all of the coals are available. There is a great deal of similarity and consistency among the data for similar coals. Representative results illustrating trends with initial particle size, ash loading, coal type, and char structure are presented here. In the discussion below, we focus upon the important trends observed in these collections of data.

Table 2

Characteristics of utility-grind coals studied during this investigation.

Coal	Parr Values*			Ash†	Rank
	Fixed Carbon [-]	Volatile Matter [-]	Heating Value Btu/lb		
Pocahantas #3 (1)	85.8	14.2	15712	7.1	lv Bituminous
Upper Freeport [¥]	71.45	28.55	15342	21.66	mv Bituminous
Mingo Logan	64.18	35.82	15141	9.34	hv A Bituminous
Pittsburgh-Seam	59.01	40.99	15154	8.40	hv A Bituminous
Illinois #6 (3)	57.32	42.68	15023	5.62	hv A Bituminous
Pittsburgh #8 (2)	61.51	38.49	14843	6.55	hv A Bituminous
Massey Spruce	62.85	37.15	14786	8.33	hv A Bituminous
Eastern Kentucky	59.76	40.24	14724	10.15	hv A Bituminous
Pittsburgh #8 (1)	56.44	43.56	14695	10.68	hv A Bituminous
Utah Blind Canyon	51.92	48.08	14276	10.40	hv A Bituminous
Kentucky #11 [¥]	57.38	42.62	13269	22.21	hv B Bituminous
Illinois #6 (2)	56.34	43.66	13083	12.33	hv B Bituminous
SOAP [§]	57.6	42.4	12900	2.8	hv C Bituminous
Kentucky #9 [¥]	57.15	42.85	12791	14.64	hv C Bituminous
Hanna Basin	57.59	42.41	12053	11.05	hv C Bituminous
Illinois #6 (1) [¥]	55.68	44.32	11997	10.13	hv C Bituminous
Roland-Seam	52.85	47.15	11494	6.29	Subbituminous A
Decker	53.92	46.08	10726	5.11	Subbituminous A
Black Thunder	42.27	57.73	10675	6.46	Subbituminous A
Belle Ayr	49.02	50.98	10130	6.04	Subbituminous B
Wyodak	51.79	48.21	10059	6.22	Subbituminous B
Antelope	54.53	45.47	9918	5.51	Subbituminous B
Eagle Butte [¥]	51.68	48.32	9286	6.40	Subbituminous C
Beulah Lignite [¥]	51.28	48.72	8202	13.86	Lignite A
Texas Lignite [¥]	39.98	60.02	7513	51.96	Lignite A
Blends					
Eastern Blend	67.77	32.23	15312	8.67	hv A Bituminous
Pitt. #8/Decker	61.3	38.7	13599	6.96	hv B Bituminous
NIPSCO Blend (1)	54.3	45.7	12786	7.71	hv C Bituminous
NIPSCO Blend (2)	53.26	46.74	12742	7.80	hv C Bituminous
Roland/Illinois #6	54.3	45.7	12467	8.97	hv C Bituminous
Eagle Butte/Ken. #9	51.3	48.7	10592	9.39	Subbituminous A

* Fixed carbon and volatile matter are on dry, *mineral-free* (as opposed to ash-free) basis. Heating value is on a moist, mineral-free basis.

† Ash is on a dry basis.

§ Spherical Oil Agglomeration Product derived from an Illinois #6 coal.

¥ Coals obtained from PSIT as part of the original suite used in their mineral investigations.

Experimental Results and Discussion

Coal Fragmentation

Coal fragmentation (as opposed to char fragmentation) could be effected by rapid mass loss during devolatilization. The extent of coal fragmentation was analyzed in this study by comparing coal particle size probability density functions with those for char particles after devolatilization. Figure 3 illustrates cumulative particle size distribution (pdf) data for the Kentucky #9 coal. Data of these type are often presented in a histogram format. All data in this report are presented on a pdf basis. The difference can be quite large. The histogram format presents the fraction of the total data contained within some range, for example, the mass fraction of particles with sizes between two limits. The value of the ordinate is usually dimensionless, because the mass fraction is dimensionless, and changes with changes in the range of the data.

Char Fragmentation

Data derived from many coals are presented below. The discussion will first contrast a typical swelling coal (Pittsburgh #8) and a non-swelling coal (Roland coal). Results from the remainder of the coals will be presented in the context of the results from these two coals and will be shown to be consistent in their interpretation.

Cumulative size distributions for char and fly ash particles generated from the Pittsburgh #8 (2) coal are illustrated in of Fig. 3a. The mean value of the several measured distributions is indicated together with 95% confidence intervals. The coefficients of variation (standard deviation divided by mean) used in computing the confidence intervals are illustrated as a function of particle size in Fig. 3b. These experimentally determined coefficients of variation are largest at small particle sizes. Light scattering intensity is lowest for small particles and is most influenced by experimental error (detector noise, beam steering, etc.), giving rise to higher coefficients of variation.

The data illustrated in Fig. 3 are representative of all of the coals studied. Only the final results of the fragmentation analysis will be presented for the remainder of the coals studied.

The confidence intervals are largest for the submicron-sized char particles. These, however, are of little consequence to the analysis since they form fly ash particles too small to reliably detect with this technique. Over the range of char and fly ash particle sizes of interest in this study, the size distributions are determined within approximately ± 20 relative percent accuracy. The confidence intervals are much smaller over most of the range of interest.

Using these data, the fragmentation factor f is computed according to the equations indicated in the preceding discussion. The only quantity not determined from the measurements is s . Figure 4a illustrates the computed value of f for an assumed value of s of unity. This is equivalent to assuming that equal-sized fly ash particles form from a char particle of a given initial size. While this assumption is probably not realistic, it is convenient for engineering models (such as ADLVIC) that incorporate fragmentation behavior.

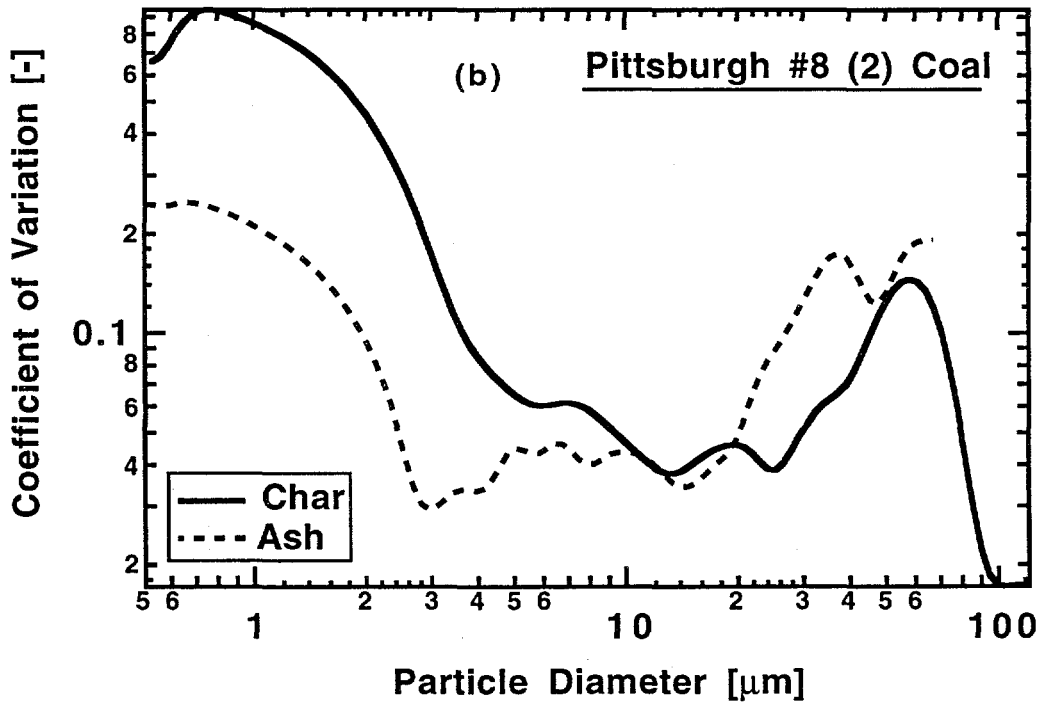
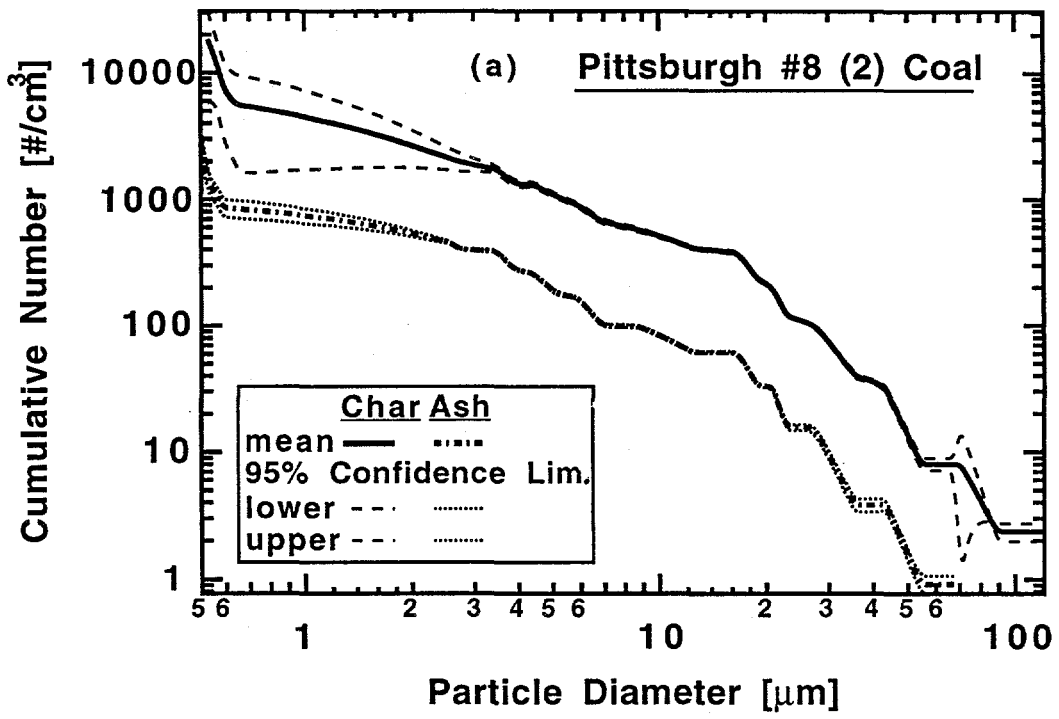


Figure 3. Cumulative particle size distributions and statistics for char and fly ash generated from the Pittsburgh #8 (2) hv A bituminous coal.

As illustrated in Fig. 4a, the value of the fragmentation factor exceeds unity only for initial char particle sizes larger than about 20 μm . The size of fragments generated by the fragmentation of these large particles is indicated by the second abscissa at the top of the figure. Fly ash particles generated through fragmentation are concentrated in the 10 μm size range.

The fragmentation factor should range from 1 to larger values, as can be seen from its definition (Eq. 5). The experimental measurements indicate a fragmentation factor as low as 0.7 in some regions of char and fly ash sizes. This is probably associated with variations in the char density and ash mass fraction and the fly ash density as a function of particle size. Reliable information concerning the particle size variation of these physical properties is not available for this coal. Therefore, the properties were assumed to be equal to their average values at all particle sizes. Considering that the fragmentation factor is derived entirely from experimental data, this small deviation of the experimental value below its theoretical limit is viewed as only a minor concern in these results.

Results from similar measurements and analyses for a Roland-seam coal are illustrated in Fig. 5. The ordinates of the two panels in Fig. 5 are scaled the same as those in Fig. 4 to allow a direct comparison. The lower-rank Roland coal is seen to fragment less extensively than the Pittsburgh #8 bituminous coal. This is consistent with our previous results and with the postulate that fragmentation is strongly influenced by char structure [Baxter, 1992]. Coals that form chars that are cenospheres or 'mesospheres' (have very large voids) are more likely to fragment because they have inherently unstable structures as they burn out. Such is the case with high volatile bituminous coals. Chars that do not form cenospheres, such as the Roland coal, are stable as the char particles burn out. The fragmentation data reflect the stability of the char structure in that there are few fragments formed per original char particle.

The comparison of the Pittsburgh #8 and Roland coals is representative of all of the coals we have tested. Data for additional coals and coal blends are illustrated in Figures 6 through 10. These data are consistent with earlier observations, i.e., the extent of fragmentation generally increases with increasing char particle size, is greater for chars that form cenospheres than for more dense chars, and decreases with increasing ash loading. While these general characteristics are consistent among all of the data, some details of the data that need further explanation.

Data for the Utah Blind Canyon coal, which is borderline between hv A and hv B bituminous, indicate little fragmentation at any particle size, much the same as the Roland and other subbituminous coals and lignites examined. When compared to the other bituminous coals, the behavior of the Blind Canyon coal appears anomalous. This is only an apparent anomaly, as can be verified by a more detailed investigation of the chemistry of the Utah Blind Canyon coal.

Figure 11 indicates the detailed chemical structure of coals from many of the same seams used in this experiments, including the Blind Canyon coal. These data are taken from published NMR spectroscopy results [Solum, et al., 1989], for coals obtained from the Argonne premium coal bank, not the samples of the coals tested here. The Blind Canyon coal in the Argonne coal bank is chemically more similar to the lower-rank subbituminous coals and lignite than it is to even to the hv B bituminous samples. There are no samples of hv C available for comparison with these data. We postulate this chemical difference is the reason for the different fragmentation behavior. Coal rank is based solely on heating value and moisture content for these coals (as determined by ASTM D388-36) and is only a crude indicator of the actual chemical structure of the raw coal.

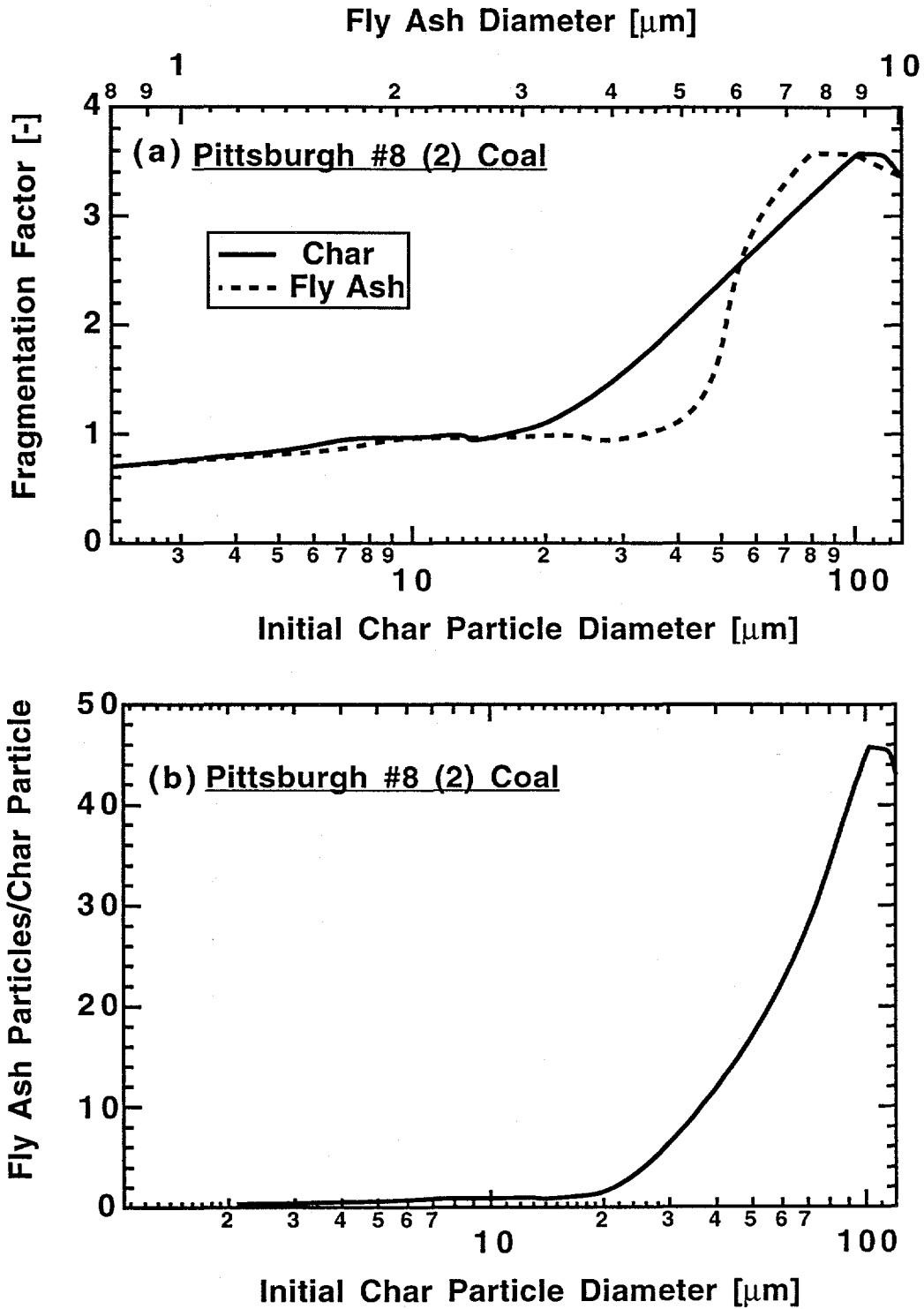


Figure 4. Variation of the fragmentation factor with initial char particle size and fly ash size (a) and the number of fly ash particles formed per char particle as a function of initial char particle size (b) for the Pittsburgh #8 hv A bituminous coal.

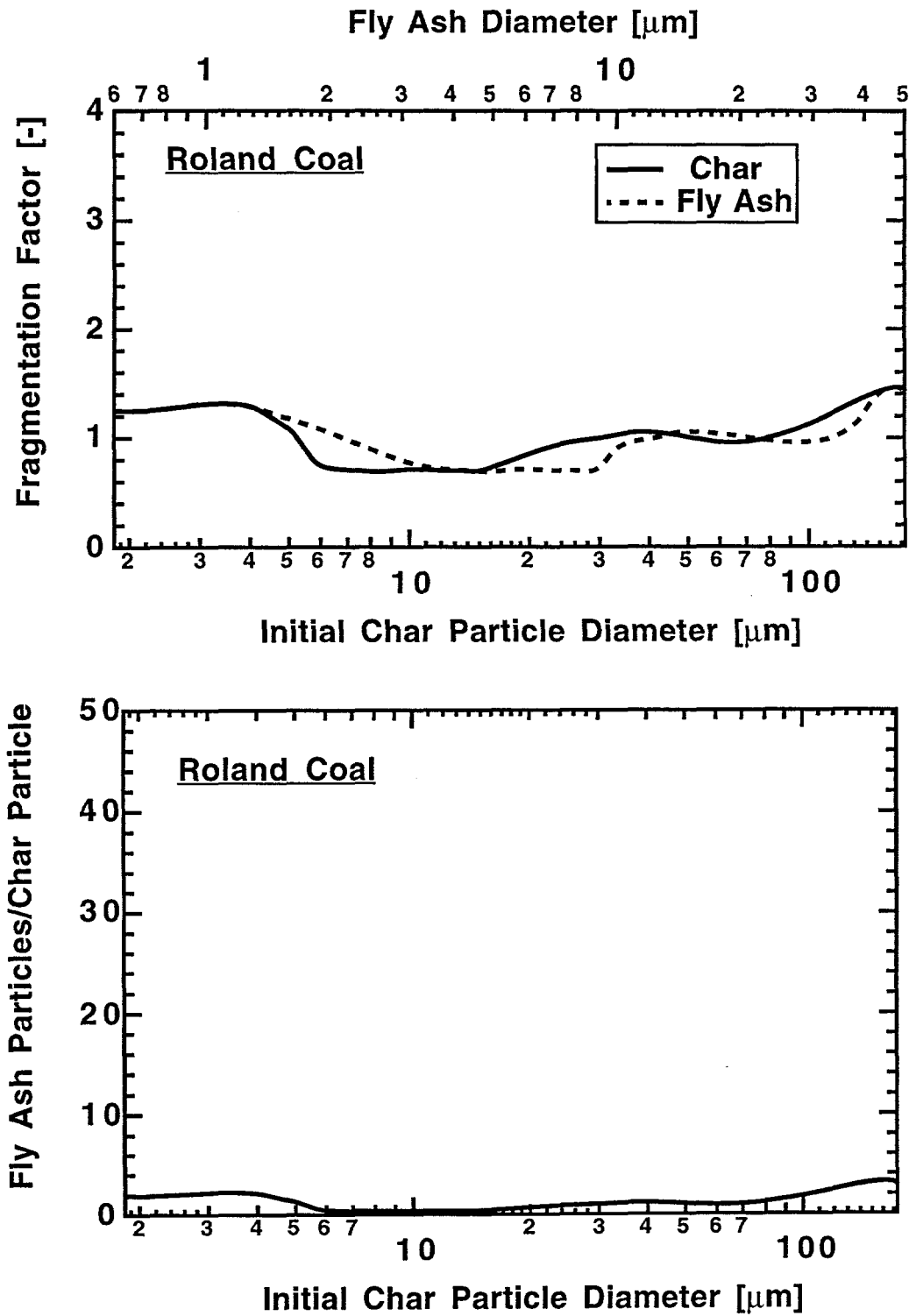


Figure 5. Variation of the fragmentation factor as a function of initial char and final fly ash particles sizes (a) and of the number of fly ash particles produced per char particle as a function of initial char particle size (b) for a Roland-seam subbituminous coal.

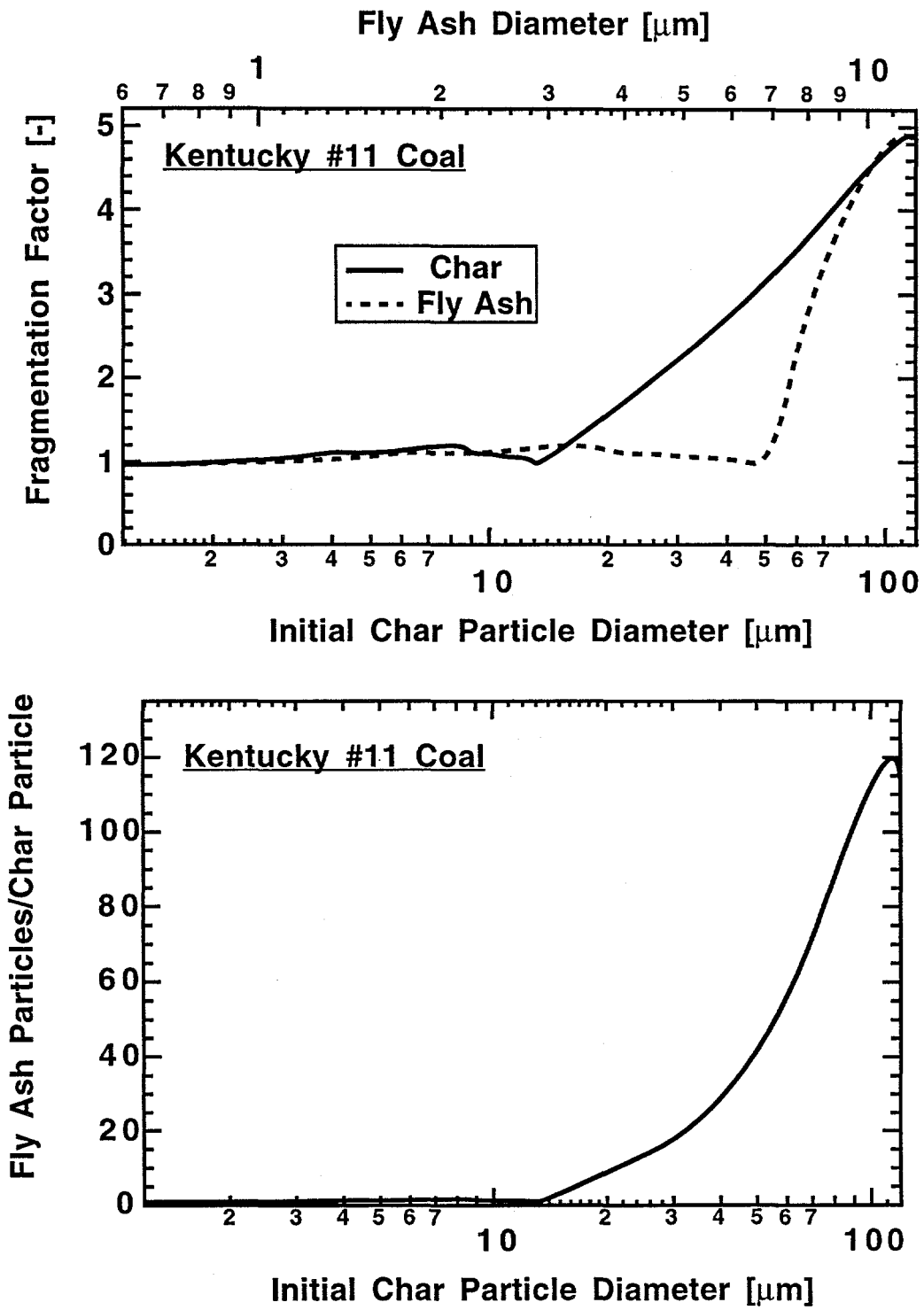


Figure 6. Variation of the fragmentation factor as a function of initial char and final fly ash particle sizes (a) and of the number of fly ash particles produced per char particle as a function of initial char particle size (b) for a Kentucky #11 hv B bituminous coal.

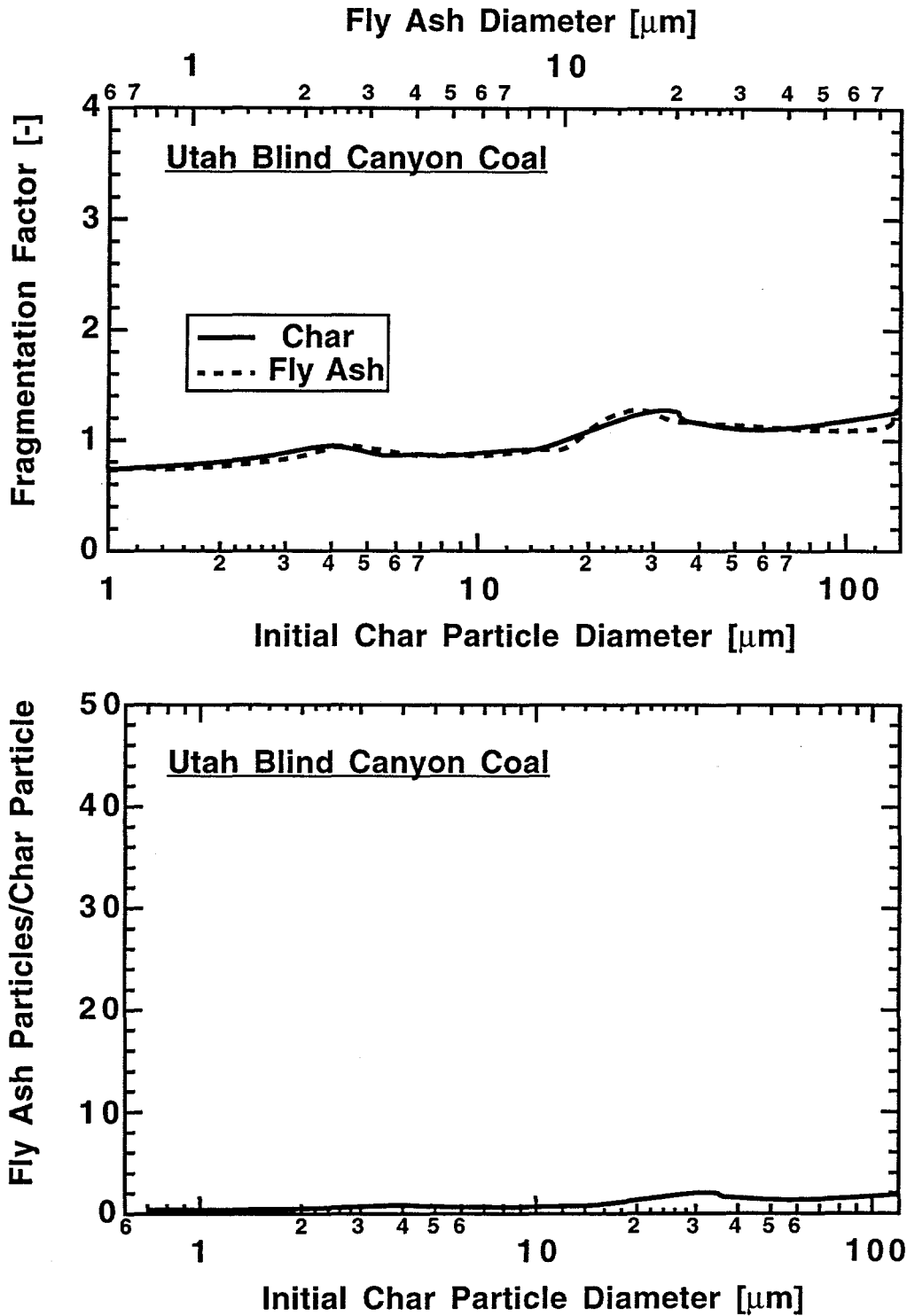


Figure 7. Variation of the fragmentation factor as a function of initial char and final fly ash particle sizes (a) and of the number of fly ash particles produced per char particle as a function of initial char particle size (b) for a Utah Blind Canyon hv A bituminous coal.

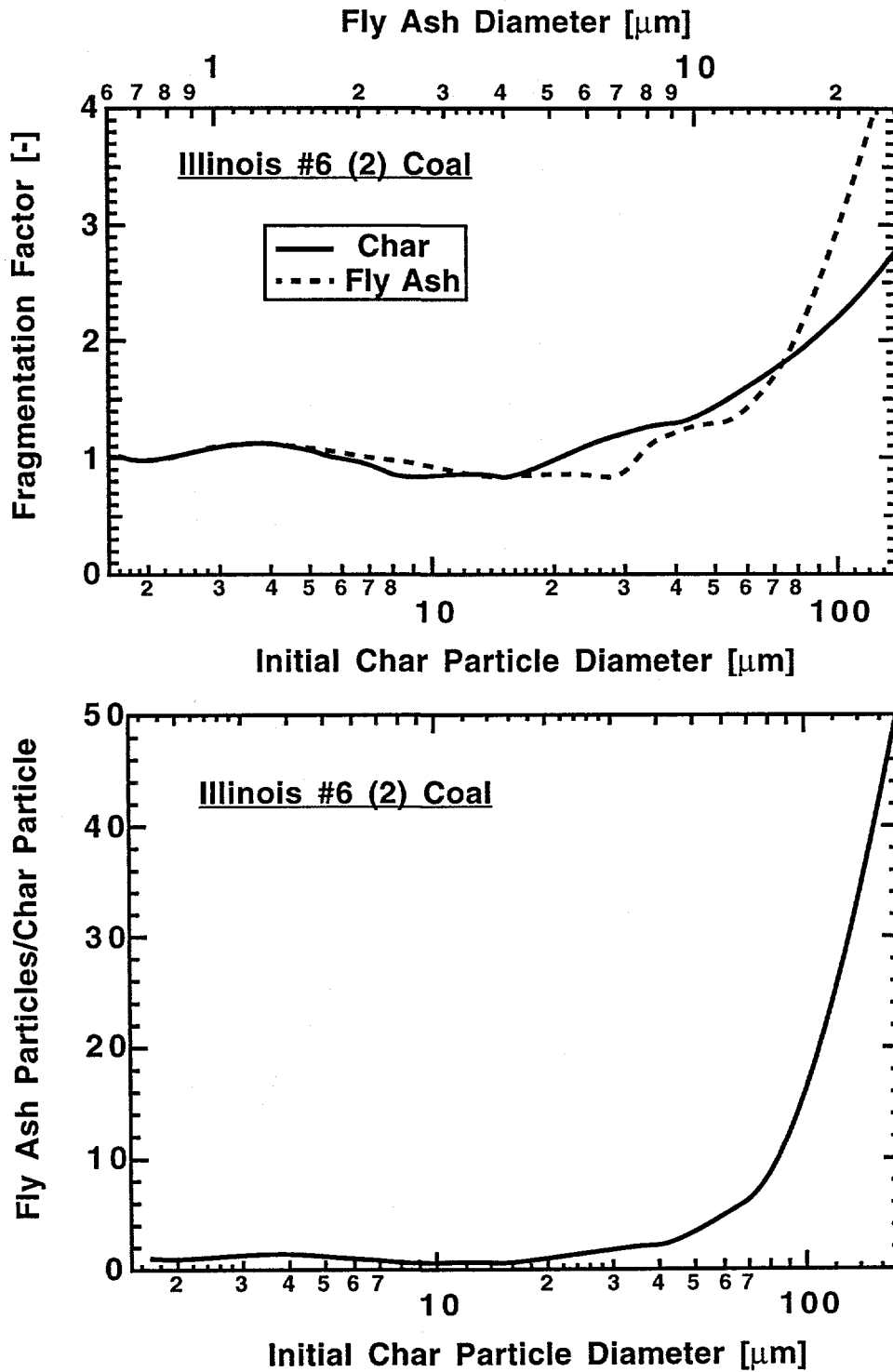


Figure 8. Variation of the fragmentation factor as a function of initial char and final fly ash particle sizes (a) and of the number of fly ash particles produced per char particle as a function of initial char particle size (b) for the Illinois #6 (2) hv B bituminous coal.

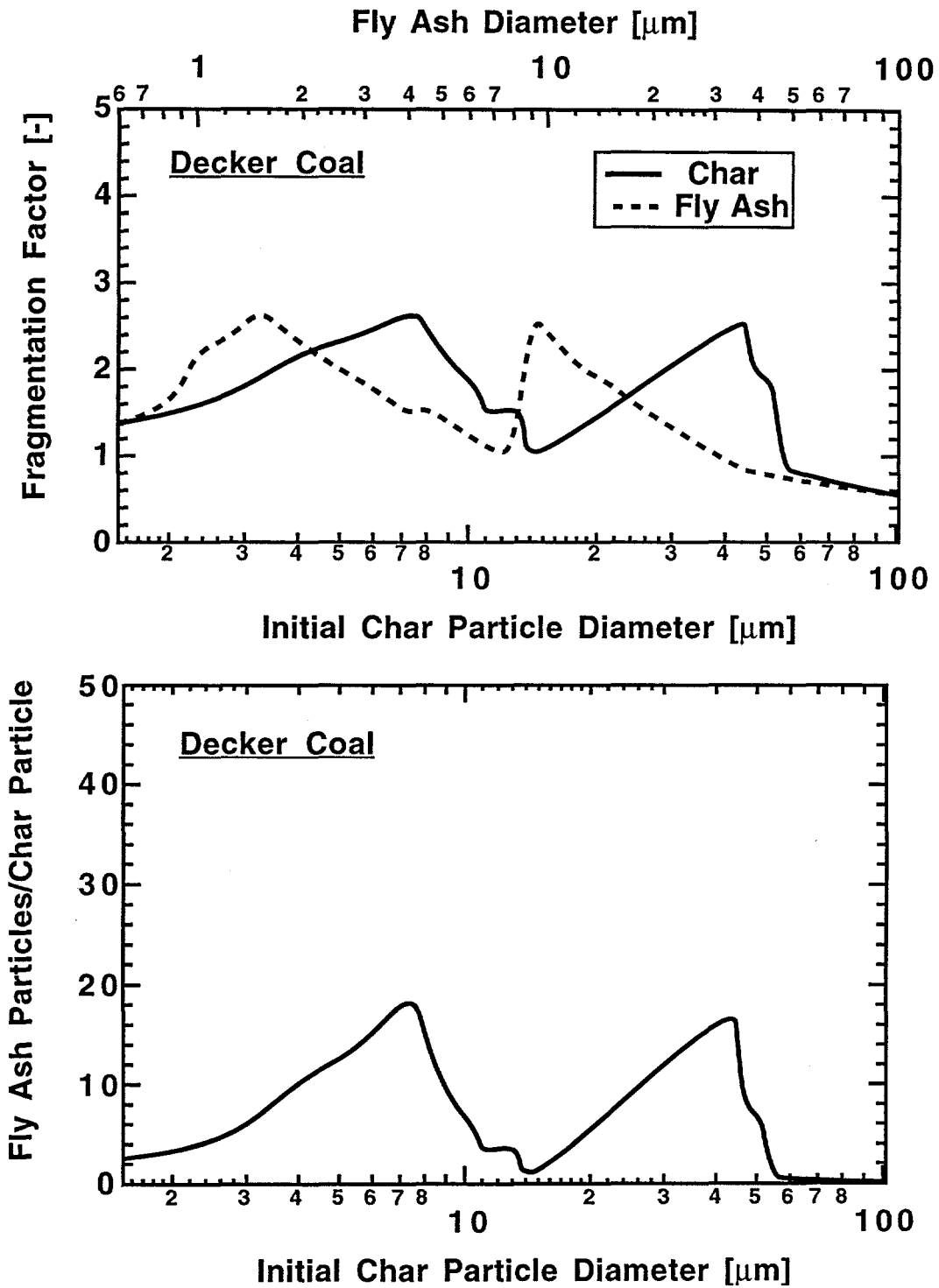


Figure 9. Variation of the fragmentation factor as a function of initial char and final fly ash particle sizes (a) and of the number of fly ash particles produced per char particle as a function of initial char particle size (b) for a Decker subbituminous A coal.

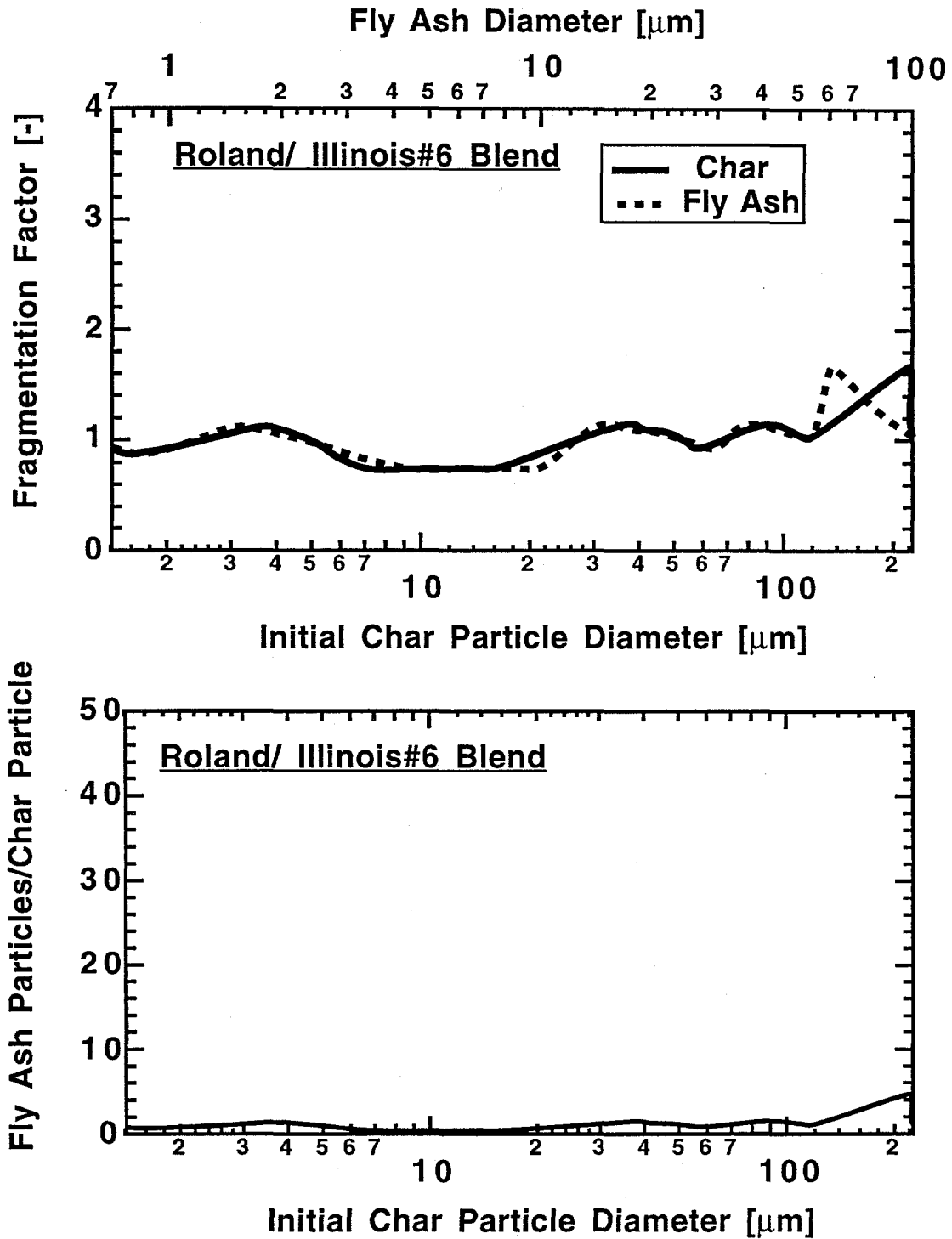


Figure 10. Variation of the fragmentation factor as a function of initial char and final fly ash particle sizes (a) and of the number of fly ash particles produced per char particle as a function of initial char particle size (b) for a blend of 70 % Roland and 30 % Illinois # 6 (2) coals.

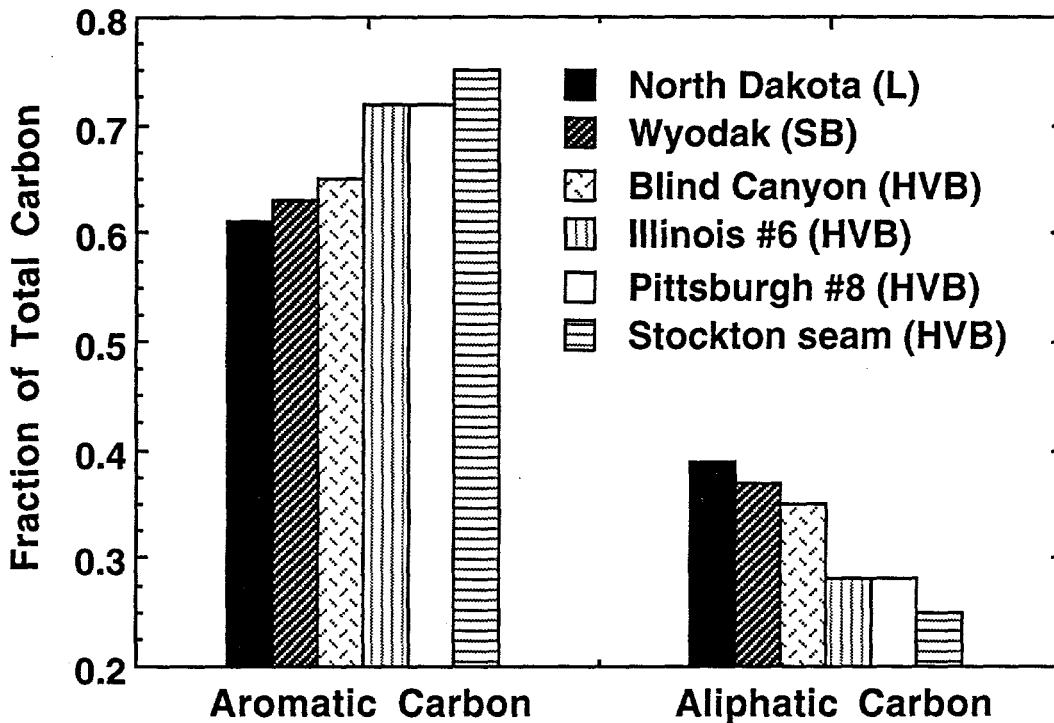


Figure 11. Comparison of the chemical composition of Argonne coal bank samples [Solum, et al., 1989] contrasting the Blind Canyon coal with coals similar to several used in these experiments.

The influence of ash loading on fragmentation behavior is minor. This can be seen by comparing results for the Kentucky #9 coal with the Illinois #6 (1) coal shown in Fig. 12 and Fig. 13. With reference to Table 2 and the appendix, these two coals are seen to be similar in most respects, with the exception that the Kentucky #9 coal has roughly 50% higher ash content than the Illinois #6 (1) coal. Comparison of the similar data for the Kentucky #9 and Illinois #6 (1) coals with the data for the Beulah lignite (Figs. 12 and 13) clearly underscores the dominant importance of coal rank on fragmentation behavior.

Conclusions

The fragmentation data investigated thus far show consistent trends in that: (1) large char particles produce far more fly ash particles than small char particles; (2) the extent of fragmentation tends to increase with increasing coal rank through hv bituminous; (3) the extent of fragmentation tends to decrease with increasing ash loading; and (4) in all cases studied thus far, the total increase in the number of particles greater than 0.6 μm in diameter by char fragmentation is less than a factor of two.

These general trends have been established for a significant number of coals over a broad range of rank, ash loading, and particle size. Our results indicate substantial agreement among experimental results previously thought to be in disagreement.

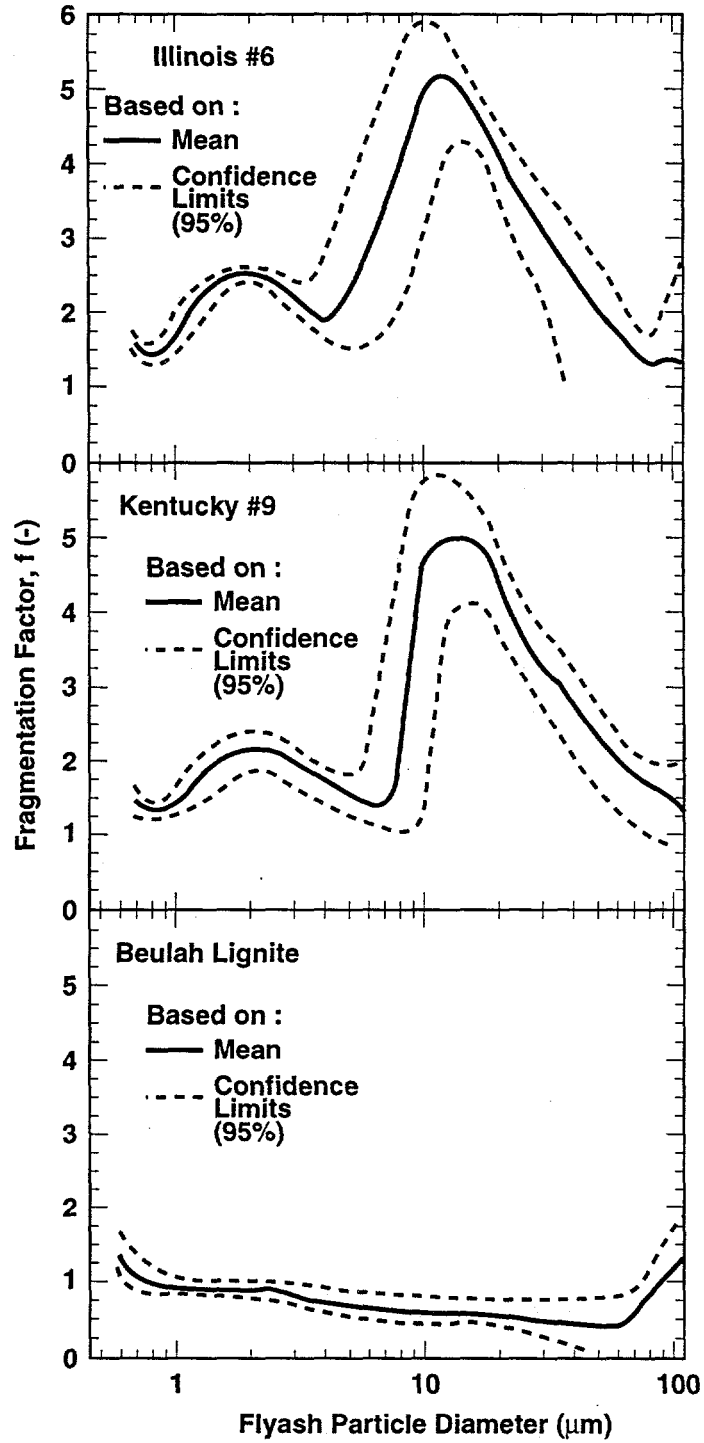


Figure 12. Variation of the fragmentation factor as a function of fly ash particle size for the Illinois #6 (1) hv C bituminous coal, the Kentucky #9 hv C bituminous coal, and the Beulah lignite.

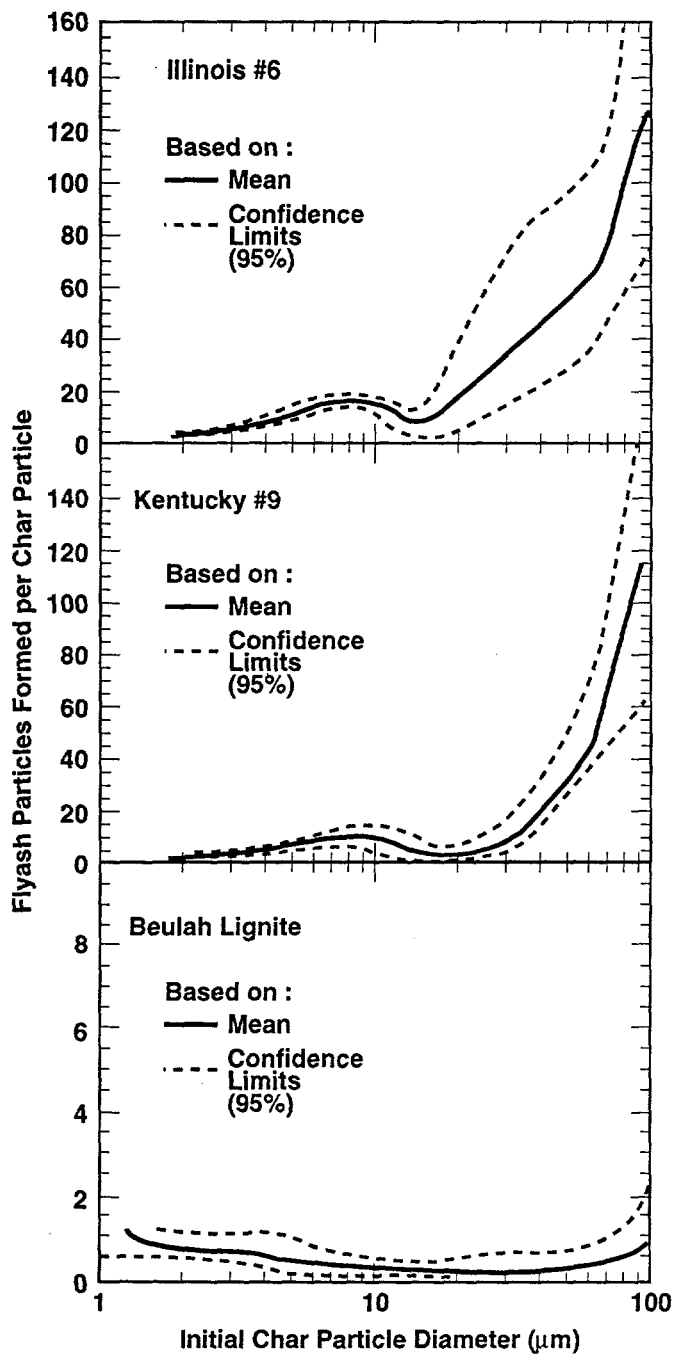


Figure 13. Variation of the number of fly ash particles produced per char particle as a function of initial char particle size for the Illinois #6 (1) hv C bituminous coal, the Kentucky #9 hv C bituminous coal, and the Beulah lignite.

In particular, the dependence of char fragmentation on char particle size had not previously been recognized when comparing results from different systems. The implications of this particle-size dependence reconcile, in part, seemingly discrepant results previously reported in the literature. This is discussed in more detail elsewhere [Baxter, 1992]. Furthermore, the current study clearly indicates that, for typical coals in typical combustion environments, the extent of fragmentation experienced at all char particle sizes is relatively minor.

Finally, based upon our extensive data sets for a broad range of coals, a mechanistic description has been developed that predicts the trends observed in the data. However, significant additional work needs to be performed to establish quantitative relationships between fly ash chemistry and the size distributions of both the char particles and the mineral grains within the char particles.

Practical Implications

Combination of the coal and char data indicate that fragmentation under typical pulverized-coal-fired conditions of particle size and oxygen concentrations: (1) is most significant for cenosphere-forming coals, (2) decreases slightly with increased ash loading, and (3) is relatively insignificant in all cases. These results have direct application to .

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APPENDIX A

Summaries of Analyses on Utility-Grind Samples of Coal

The following tables summarize the most commonly measured characteristics of the suite of utility-grind coals tested in the multifuel combustor during this project. Included among the data are the results of moisture, proximate, ultimate, ash, ash chemistry, heating value, forms of sulfur, oxidizing and reducing fusion temperature, and particle size distribution analyses. The tables summarize average results for an often large number of samples. Not all analyses were performed on all samples. For example, proximate and ultimate analyses were not performed on the samples of coals used in chemical fractionation tests. This leads to occasional small discrepancies in, for example, the sum of the oxides and the total ash content, even when undetermined ash is included in the sum of oxides.

Additional characterizations of many of the coals have been performed. These include size-resolved characterizations of the fraction of eastern and western coal in the blends, chemical fractionation results for about two thirds of the coals, and a variety of SEM-based and other individual-sample-based analyses. These additional analyses are available in published reports from this project but are not summarized here.

Blank entries indicate that no data are available. The most common examples include chlorine in ash (usually not measured), acid soluble alkali (available for small fraction of the coals), and one set of the Malvern size distribution data. The Malvern size data are reported in one of two alternative sets of ranges. Data from both ranges are rarely available. These Malvern data are for the pulverized, raw coal samples and they too have been averaged with several replicate measurements.

Table A.1

Summary of utility-grind coals studied during this investigation.

Coal	Parr Values*			Ash†	Rank
	Fixed Carbon [-]	Volatile Matter [-]	Heating Value Btu/lb		
Pocahantas #3 (1)	81.2	18.8	15750	4.5	lv Bituminous
Upper Freeport‡	71.45	28.55	15342	21.30	mv Bituminous
Mingo Logan	64.18	35.82	15141	9.34	hv A Bituminous
Pittsburgh #8 (3)	59.01	40.99	15154	9.01	hv A Bituminous
Illinois #6 (3)	57.32	42.68	15023	5.62	hv A Bituminous
Pittsburgh #8 (2)	61.51	38.49	14843	6.62	hv A Bituminous
Massey Sprouce	62.85	37.15	14786	8.33	hv A Bituminous
Eastern Kentucky	59.76	40.24	14724	10.15	hv A Bituminous
Pittsburgh #8 (1)	56.44	43.56	14695	10.68	hv A Bituminous
Utah Blind Canyon	51.92	48.08	14276	10.16	hv A Bituminous
Kentucky #11‡	57.38	42.62	13269	22.15	hv B Bituminous
Illinois #6 (2)	56.34	43.66	13083	12.21	hv B Bituminous
SOAP§	57.6	42.4	12900	3.99	hv C Bituminous
Kentucky #9‡	57.15	42.85	12791	15.64	hv C Bituminous
Hanna Basin	57.59	42.41	12053	9.99	hv C Bituminous
Illinois #6 (1)‡	55.68	44.32	11997	10.24	hv C Bituminous
Roland-Seam	52.85	47.15	11494	6.16	Subbituminous A
Decker	53.92	46.08	10726	5.12	Subbituminous A
Black Thunder	42.27	57.73	10675	6.46	Subbituminous A
Belle Ayr	49.02	50.98	10130	6.04	Subbituminous B
Wyodak	51.79	48.21	10059	6.18	Subbituminous B
Antelope	54.53	45.47	9918	5.51	Subbituminous B
Eagle Butte‡	51.68	48.32	9286	6.37	Subbituminous C
Beulah Lignite‡	51.28	48.72	8202	13.69	Lignite A
Texas Lignite‡	39.98	60.02	7513	52.18	Lignite A
Blends					
Eastern Blend	67.77	32.23	15312	8.67	hv A Bituminous
Pitt. #8/Decker	61.3	38.7	13599	6.26	hv B Bituminous
NIPSCO Blend (1)	54.3	45.7	12786	7.80	hv C Bituminous
NIPSCO Blend (2)	53.26	46.74	12742	7.71	hv C Bituminous
Roland/Illinois #6	54.3	45.7	12467	9.29	hv C Bituminous
Eagle Butte/Ken. #9	51.3	48.7	10592	8.91	Subbituminous A

* Fixed carbon and volatile matter are on dry, *mineral-free* (as opposed to ash-free) basis. Heating value is on a moist, mineral-free basis.

† Ash is on a dry basis.

§ Spherical Oil Agglomeration Product derived from an Illinois #6 coal.

‡ Coals obtained from PSIT as part of the original suite used in their mineral investigations.

Table A.2 Properties of the Pocahantas #3 coal.

Pocahantas #3							
Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	77.00	76.53	dp>600µm		+28	0.00	0.00
Volatile Matter	18.49	18.37	600µm>dp>300µm		28x48	0.70	0.70
Moisture	0.62		300µm>dp>149µm		48x100	3.67	4.37
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	14.37	18.73
C	87.52	86.98	74µm>dp>44µm		200x325	15.47	34.20
H	4.26	4.23	44µm>dp		-325	65.80	100.00
O	1.55	1.54	Size Distribution (Malvern)*				
N	1.25	1.24	Diameter % in		cum. vol.	Diameter	% in
S	0.75	0.75	(µm)	size bin	per.	(µm)	size bin
Cl	0.16	0.16	188m	0.00	100.0	118.4m2	
Ash	4.51	4.49	162m	0.05	100.0	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	0.22	99.7	88.1m2	
SiO2	1.68	37.24	121m	0.50	99.2	76m2	
Al2O3	1.07	23.73	104m	1.15	98.1	65.6m2	
TiO2	0.05	1.12	89.9m	1.90	96.2	56.6m2	
Fe2O3	0.76	16.83	77.5m	2.97	93.2	48.8m2	
CaO	0.34	7.53	66.9m	3.68	89.5	42.1m2	
MgO	0.11	2.36	57.7m	3.95	85.6	38.3m2	
K2O	0.08	1.81	49.8m	4.05	81.5	31.3m2	
Na2O	0.04	0.81	42.9m	5.55	76.0	27m2	
SO3	0.30	6.67	37.1m	6.68	69.3	23.3m2	
P2O5	0.00	0.10	32m	7.40	61.9	20.1m2	
Cl			27.6m	6.90	55.0	17.4m2	
Undetermined	0.08	1.81	23.8m	5.57	49.4	15m2	
Total	4.51	100.0	20.5m	4.77	44.7	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	4.47	40.2	11.1m2	
Pyritic	0.21		15.3m	4.70	35.5	9.6m2	
Organic	0.54		13.2m	4.82	30.7	8.3m2	
Sulfatic	0.00		11.4m	4.25	26.4	7.2m2	
Fraction Free Silica	0.04		9.8m	3.62	22.8	6.2m2	
Fraction Pyritic Iron	0.34		8.5m	2.98	19.8	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	2.75	17.1	4.8m2	
As Fired	15052	14960	6.3m	2.72	14.4	4m2	
Dulong	15282	15188	5.4m	2.70	11.7	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	2.50	9.2	3m2	
Na			4.1m	2.12	7.0	2.8m2	
Mg			3.5m	1.67	5.4	2.2m2	
Ca			3m	1.20	4.2	1.9m2	
K			2.6m	0.92	3.3	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.87	2.4	1.4m2	
Reducing Conditions			1.9m	0.70	1.7	1.2m2	
Initial Deformation	2176	1191	Size Statistics (Malvern Data Only)				
Spherical	2279	1249			Malvern	All Data	
Hemispherical	2332	1278	Dv.5	Volume Mean Diam.	25.00		
Fluid	2428	1331	Dv.9	90 % volume diameter	65.85		
Oxidizing Conditions			Dv.1	10 percentile volume diameter	5.02		
Initial Deformation	2366	1297	D4,3		30.10		
Spherical	2395	1313	D3,2	Sauter Mean Diameter	11.63		
Hemispherical	2439	1337	Span		2.37		
Fluid	2487	1364	Specific Surface Area (m ² /cc)		0.54		

*These Malvern data are for the -325 mesh size fractions.

Table A.3 Summary of Properties of the Upper Freeport Coal.

Upper Freeport							
Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	54.40	53.95	dp>600µm		+28	0.00	0.00
Volatile Matter	24.17	23.97	600µm>dp>300µm		28x48	2.63	2.63
Moisture	0.83		300µm>dp>149µm		48x100	7.33	9.97
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	20.90	30.87
C	66.46	65.91	74µm>dp>44µm		200x325	19.53	50.40
H	4.16	4.12	44µm>dp		-325	49.60	100.00
O	4.37	4.34	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	1.48	1.47	Diameter % in		cum. vol.	Diameter	% in
S	2.00	1.99	(µm)	size bin	per.	(µm)	size bin
Cl	0.19	0.19	188m		0.00	100.0	118.4m2
Ash	21.30	21.13	162m		0.00	100.0	102.1m2
Ash Chemistry	% dry fuel	% ash	140m		0.00	100.0	88.1m2
SiO2	10.93	51.29	121m		0.00	100.0	76m2
Al2O3	5.16	24.23	104m		0.00	100.0	65.6m2
TiO2	0.20	0.92	89.9m		0.12	99.9	56.6m2
Fe2O3	2.85	13.40	77.5m		0.22	99.7	48.8m2
CaO	0.53	2.47	66.9m		0.30	99.4	42.1m2
MgO	0.28	1.30	57.7m		0.93	98.4	38.3m2
K2O	0.65	3.06	49.8m		3.43	95.0	31.3m2
Na2O	0.06	0.30	42.9m		5.83	89.2	27m2
SO3	0.52	2.42	37.1m		7.73	81.4	23.3m2
P2O5	0.03	0.14	32m		8.32	73.1	20.1m2
Cl			27.6m		7.37	65.8	17.4m2
Undetermined	0.13	0.59	23.8m		6.07	59.7	15m2
Total	21.33	100.1	20.5m		5.38	54.3	12.9m2
Forms of Sulfur (% dry fuel)			17.7m		5.87	48.4	11.1m2
Pyritic	1.49		15.3m		6.38	42.1	9.6m2
Organic	0.48		13.2m		6.03	36.0	8.3m2
Sulfatic	0.11		11.4m		5.12	30.9	7.2m2
Fraction Free Silica	0.29		9.8m		3.98	26.9	6.2m2
Fraction Pyritic Iron	0.65		8.5m		3.42	23.5	5.3m2
Heating Value (Btu/lb, dry)			7.3m		3.47	20.0	4.8m2
As Fired	11830	11732	6.3m		3.75	16.3	4m2
Dulong	11987	11888	5.4m		3.60	12.7	3.4m2
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m		2.97	9.7	3m2
Na	343	343	4.1m		2.30	7.4	2.8m2
Mg	1208	1208	3.5m		1.68	5.7	2.2m2
Ca	3767	3767	3m		1.25	4.5	1.9m2
K	2292	2292	2.6m		1.07	3.4	1.6m2
Fusion Temp.	°F	°C	2.2m		0.98	2.4	1.4m2
Reducing Conditions			1.9m		1.83	0.6	1.2m2
Initial Deformation	2177	1192	Size Statistics (Malvern Data Only)				
Spherical	2317	1269				Malvern	All Data
Hemispherical	2376	1302	Dv.5	Volume Mean Diam.		16.65	
Fluid	2437	1336	Dv.9	90 % volume diameter		39.58	
Oxidizing Conditions			Dv.1	10 percentile volume diameter		4.38	
Initial Deformation	2443	1339	D4.3			19.93	
Spherical	2513	1378	D3.2	Sauter Mean Diameter		9.52	
Hemispherical	2548	1398	Span			2.12	
Fluid	2604	1429	Specific Surface Area (m ² /cc)			0.57	

*These Malvern data are for the -325 mesh size fractions.

Table A.4 Summary of Properties of the Mingo Logan Coal.

Mingo Logan

Analyses			Analyses			mass % in size bin		cum. mass %
Proximate	Dry	As Rec'd	Size Distribution		Sieves			
Fixed Carbon	57.53	56.70	dp>600µm		+28	0.00		0.00
Volatile Matter	33.13	32.65	600µm>dp>300µm		28x48	0.40		0.40
Moisture	1.44		300µm>dp>149µm		48x100	4.75		5.15
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	17.65		22.80
C	78.14	77.01	74µm>dp>44µm		200x325	19.10		41.90
H	4.94	4.87	44µm>dp		-325	58.10		100.00
O	5.28	5.20	Size Distribution (Malvern)*			Size Distribution (Malvern)*		
N	1.29	1.27	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin	cum. vol. per.
S	0.87	0.85	188m	0.00	100.0	118.4m2		
Cl	0.15	0.15	162m	0.00	100.0	102.1m2		
Ash	9.34	9.21	140m	0.00	100.0	88.1m2		
Ash Chemistry	% dry fuel	% ash	121m	0.00	100.0	76m2		
SiO2	5.14	55.07	104m	0.00	100.0	65.6m2		
Al2O3	2.80	29.96	89.9m	0.00	100.0	56.6m2		
TiO2	0.13	1.41	77.5m	0.08	99.9	48.8m2		
Fe2O3	0.60	6.38	66.9m	1.13	98.8	42.1m2		
CaO	0.10	1.07	57.7m	3.25	95.6	38.3m2		
MgO	0.10	1.02	49.8m	5.65	89.9	31.3m2		
K2O	0.27	2.91	42.9m	7.50	82.4	27m2		
Na2O	0.05	0.49	37.1m	8.95	73.5	23.3m2		
SO3	0.11	1.22	32m	8.60	64.9	20.1m2		
P2O5	0.01	0.09	27.6m	6.95	57.9	17.4m2		
Cl			23.8m	5.83	52.1	15m2		
Undetermined	0.04	0.39	20.5m	5.38	46.7	12.9m2		
Total	9.34	100.0	17.7m	5.78	40.9	11.1m2		
Forms of Sulfur (% dry fuel)			15.3m	5.93	35.0	9.6m2		
Pyritic	0.23		13.2m	5.05	29.9	8.3m2		
Organic	0.64		11.4m	4.10	25.8	7.2m2		
Sulfatic	0.00		9.8m	3.23	22.6	6.2m2		
Fraction Free Silica	0.18		8.5m	3.00	19.6	5.3m2		
Fraction Pyritic Iron	0.48		7.3m	3.10	16.5	4.8m2		
Heating Value (Btu/lb, dry)			6.3m	3.25	13.3	4m2		
As Fired	13805	13607	5.4m	2.90	10.4	3.4m2		
Dulong	14054	13852	4.7m	2.33	8.0	3m2		
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	1.80	6.2	2.8m2		
Na			3.5m	1.30	4.9	2.2m2		
Mg			3m	1.05	3.9	1.9m2		
Ca			2.6m	0.98	2.9	1.6m2		
K			2.2m	0.85	2.1	1.4m2		
Fusion Temp.	°F	°C	1.9m	2.08	0.0	1.2m2		
Reducing Conditions			Size Statistics (Malvern Data Only)					
Initial Deformation	1428	776				Malvern	All Data	
Spherical	1442	783	Dv.5	Volume Mean Diam.	19.38			
Hemispherical	1451	788	Dv.9	90 % volume diameter	43.00			
Fluid	1473	800	Dv.1	10 percentile volume diameter	4.60			
Oxidizing Conditions			D4,3		21.03			
Initial Deformation	1445	785	D3,2	Sauter Mean Diameter	10.00			
Spherical	1463	795	Span		2.00			
Hemispherical	1471	799	Specific Surface Area (m ² /cc)		0.62			
Fluid	1486	808						

*These Malvern data are for the -325 mesh size fractions.

Table A.5 Summary of Properties of the Pittsburgh #8 (3) Coal.

Pittsburgh #8 (3)			Analyses			
Analyses			Analyses			
Proximate	Dry	As Rec'd	Size Distribution	Sieves	mass % in size bin	cum. mass %
Fixed Carbon	52.64	52.06	dp>600µm	+28	0.00	0.00
Volatile Matter	38.22	37.80	600µm>dp>300µm	28x48	2.27	2.27
Moisture	1.10		300µm>dp>149µm	48x100	4.10	6.37
Ultimate	Dry	As Rec'd	149µm>dp>74µm	100x200	26.17	32.53
C	76.50	75.66	74µm>dp>44µm	200x325	22.33	54.87
H	5.07	5.02	44µm>dp	-325	45.13	100.00
O	4.29	4.24	Size Distribution (Malvern)*		Size Distribution (Malvern)*	
N	1.39	1.38	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)
S	3.52	3.48				% in size bin
Cl	0.09	0.09				cum. vol. per.
Ash	9.01	8.91	188m	0.31	99.7	118.4m2
Ash Chemistry	% dry fuel	% ash	162m	0.83	98.9	102.1m2
SiO2	3.53	39.16	140m	1.24	97.6	88.1m2
Al2O3	1.74	19.31	121m	1.59	96.0	76m2
TiO2	0.08	0.84	104m	1.70	94.3	65.6m2
Fe2O3	2.48	27.53	89.9m	1.91	92.4	56.6m2
CaO	0.41	4.56	77.5m	2.24	90.2	48.8m2
MgO	0.08	0.84	66.9m	2.69	87.5	42.1m2
K2O	0.11	1.18	57.7m	3.26	84.2	38.3m2
Na2O	0.08	0.87	49.8m	4.84	79.4	31.3m2
SO3	0.37	4.08	42.9m	6.24	73.2	27m2
P2O5	0.03	0.34	37.1m	7.04	66.1	23.3m2
Cl			32m	6.28	59.9	20.1m2
Undetermined	0.11	1.25	27.6m	4.81	55.0	17.4m2
Total	9.01	100.0	23.8m	4.35	50.7	15m2
Forms of Sulfur (% dry fuel)			20.5m	4.58	46.1	12.9m2
Pyritic	2.07		17.7m	4.74	41.4	11.1m2
Organic	1.42		15.3m	4.61	36.8	9.6m2
Sulfatic	0.03		13.2m	4.15	32.6	8.3m2
Fraction Free Silica	0.26		11.4m	3.74	28.9	7.2m2
Fraction Pyritic Iron	0.61		9.8m	3.39	25.5	6.2m2
Heating Value (Btu/lb, dry)			8.5m	3.16	22.3	5.3m2
As Fired	13728	13577	7.3m	3.01	19.3	4.8m2
Dulong	13523	13374	6.3m	2.99	16.3	4m2
Acid Sol. Alkali (ppm)	Dry	As Rec'd	5.4m	2.96	13.4	3.4m2
Na			4.7m	2.73	10.6	3m2
Mg			4.1m	2.14	8.5	2.8m2
Ca			3.5m	1.68	6.8	2.2m2
K			3m	1.30	5.5	1.9m2
Fusion Temp.	°F	°C	2.6m	1.16	4.4	1.6m2
Reducing Conditions			2.2m	1.11	3.3	1.4m2
Initial Deformation	1984	1085	1.9m	2.38	0.9	1.2m2
Spherical	2020	1104	Size Statistics (Malvern Data Only)			
Hemispherical	2080	1138			Malvern	All Data
Fluid	2245	1229	Dv.5	Volume Mean Diam.	25.04	
Oxidizing Conditions			Dv.9	90 % volume diameter	63.86	
Initial Deformation	2387	1308	Dv.1	10 percentile volume diameter	4.51	
Spherical	2448	1342	D4,3		30.11	
Hemispherical	2496	1369	D3,2	Sauter Mean Diameter	10.70	
Fluid	2542	1394	Span		2.56	
			Specific Surface Area (m ² /cc)		0.66	

*These Malvern data are for the -325 mesh size fractions.

Table A.6 Summary of Properties of the Illinois #6 (3) Coal.

Illinois #6(3)

Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	58.15	56.51	dp>600µm		+28	0.00	0.00
Volatile Matter	36.24	35.22	600µm>dp>300µm		28x48	0.15	0.15
Moisture	2.81		300µm>dp>149µm		48x100	2.50	2.65
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	14.10	16.75
C	78.18	75.98	74µm>dp>44µm		200x325	19.75	36.50
H	5.02	4.87	44µm>dp		-325	63.50	100.00
O	8.25	8.02	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	1.62	1.57	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	0.95	0.92					
Cl	0.38	0.37	188m	0.00	100.0	118.4m2	
Ash	5.62	5.46	162m	0.08	99.9	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	0.10	99.8	88.1m2	
SiO2	2.98	53.00	121m	0.10	99.7	76m2	
Al2O3	1.36	24.18	104m	0.10	99.6	65.6m2	
TiO2	0.07	1.28	89.9m	0.23	99.4	56.6m2	
Fe2O3	0.64	11.44	77.5m	1.20	98.2	48.8m2	
CaO	0.12	2.19	66.9m	2.95	95.3	42.1m2	
MgO	0.06	1.03	57.7m	5.40	89.9	38.3m2	
K2O	0.13	2.39	49.8m	7.88	82.0	31.3m2	
Na2O	0.14	2.41	42.9m	8.90	73.1	27m2	
SO3	0.11	2.00	37.1m	9.13	64.0	23.3m2	
P2O5	0.01	0.24	32m	8.13	55.8	20.1m2	
Cl			27.6m	6.55	49.3	17.4m2	
Undetermined	-0.01	-0.17	23.8m	5.85	43.4	15m2	
Total	5.62	100.0	20.5m	5.70	37.7	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	5.73	32.0	11.1m2	
Pyritic	0.36		15.3m	5.38	26.6	9.6m2	
Organic	0.57		13.2m	4.33	22.3	8.3m2	
Sulfatic	0.02		11.4m	3.58	18.7	7.2m2	
Fraction Free Silica	0.32		9.8m	2.98	15.8	6.2m2	
Fraction Pyritic Iron	0.70		8.5m	2.70	13.1	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	2.53	10.5	4.8m2	
As Fired	14516	14108	6.3m	2.30	8.2	4m2	
Dulong	13879	13489	5.4m	2.03	6.2	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.78	4.4	3m2	
Na			4.1m	1.23	3.2	2.8m2	
Mg			3.5m	1.08	2.1	2.2m2	
Ca			3m	0.70	1.4	1.9m2	
K			2.6m	0.48	1.0	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.35	0.6	1.4m2	
Reducing Conditions			1.9m	0.73	-0.1	1.2m2	
Initial Deformation	1081	583	Size Statistics (Malvern Data Only)				
Spherical	1183	639				Malvern	All Data
Hemispherical	1228	664	Dv.5	Volume Mean Diam.		24.13	
Fluid	1271	688	Dv.9	90 % volume diameter		49.83	
Oxidizing Conditions			Dv.1	10 percentile volume diameter		6.08	
Initial Deformation	1232	666	D4,3			27.03	
Spherical	1258	681	D3,2	Sauter Mean Diameter		13.40	
Hemispherical	1280	693	Span			1.80	
Fluid	1308	709	Specific Surface Area (m ² /cc)			0.45	

*These Malvern data are for the -325 mesh size fractions.

Table A.7 Summary of Properties of the Pittsburgh #8 (2) Coal.

Analyses			Analyses					
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %	
Fixed Carbon	56.87	55.92	dp>600µm		+28	0.00	0.00	
Volatile Matter	36.58	35.97	600µm>dp>300µm		28x48	0.27	0.27	
Moisture	1.67		300µm>dp>149µm		48x100	1.40	1.67	
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	27.83	29.50	
C	78.62	77.31	74µm>dp>44µm		200x325	30.83	60.33	
H	5.14	5.06	44µm>dp		-325	39.67	100.00	
O	6.51	6.41	Size Distribution (Malvern)*			Size Distribution (Malvern)*		
N	1.50	1.48	Diameter % in		cum. vol.	Diameter	% in	
S	1.57	1.54	(µm)	size bin	per.	(µm)	size bin	
Cl	0.10	0.09				per.		
Ash	6.63	6.51	188m	0.00	100.0	118.4m2	0.08	
Ash Chemistry	% dry fuel	% ash	162m	0.00	100.0	102.1m2	0.15	
SiO2	3.16	47.70	140m	0.00	100.0	88.1m2	0.18	
Al2O3	1.60	24.08	121m	0.00	100.0	76m2	0.13	
TiO2	0.07	1.05	104m	0.00	100.0	65.6m2	1.33	
Fe2O3	1.11	16.81	89.9m	0.25	99.8	56.6m2	5.30	
CaO	0.23	3.46	77.5m	0.40	99.4	48.8m2	9.88	
MgO	0.06	0.84	66.9m	0.35	99.0	42.1m2	11.45	
K2O	0.12	1.75	57.7m	1.05	98.0	38.3m2	10.03	
Na2O	0.03	0.45	49.8m	5.35	92.6	31.3m2	8.03	
SO3	0.20	2.99	42.9m	9.45	83.2	27m2	8.00	
P2O5	0.04	0.62	37.1m	12.60	70.6	23.3m2	8.88	
Cl			32m	11.95	58.6	20.1m2	7.23	
Undetermined	0.01	0.23	27.6m	8.55	50.1	17.4m2	4.43	
Total	6.62	100.0	23.8m	6.60	43.5	15m2	3.70	
Forms of Sulfur (% dry fuel)			20.5m	6.00	37.5	12.9m2	4.40	
Pyritic	0.69		17.7m	6.35	31.1	11.1m2	3.90	
Organic	0.82		15.3m	6.40	24.7	9.6m2	2.88	
Sulfatic	0.05		13.2m	5.25	19.5	8.3m2	1.63	
Fraction Free Silica	0.24		11.4m	4.05	15.4	7.2m2	1.45	
Fraction Pyritic Iron	0.74		9.8m	2.85	12.6	6.2m2	1.50	
Heating Value (Btu/lb, dry)			8.5m	2.25	10.3	5.3m2	1.33	
As Fired	13994	13761	7.3m	2.00	8.3	4.8m2	1.20	
Dulong	14184	13947	6.3m	1.80	6.5	4m2	0.93	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	5.4m	1.65	4.9	3.4m2	0.88	
Na			4.7m	1.35	3.5	3m2	0.70	
Mg			4.1m	0.90	2.6	2.8m2	0.30	
Ca			3.5m	0.80	1.8	2.2m2	0.13	
K			3m	0.50	1.3	1.9m2	0.00	
Fusion Temp.	°F	°C	2.6m	0.35	1.0	1.6m2	0.05	
Reducing Conditions			2.2m	0.25	0.7	1.4m2	0.00	
Initial Deformation	2109	1154	1.9m	0.55	0.2	1.2m2	0.00	
Spherical	2268	1242	Size Statistics (Malvern Data Only)					
Hemispherical	2383	1306				Malvern	All Data	
Fluid	2481	1360	Dv.5	Volume Mean Diam.		24.78		
Oxidizing Conditions			Dv.9	90 % volume diameter		44.78		
Initial Deformation	2472	1356	Dv.1	10 percentile volume diameter		18.55		
Spherical	2519	1382	D4,3			25.52		
Hemispherical	2550	1399	D3,2	Sauter Mean Diameter		14.80		
Fluid	2604	1429	Span			1.48		
			Specific Surface Area (m ² /cc)				0.39	

*These Malvern data are for the -325 mesh size fractions.

Table A.8 Summary of Properties of the Massey Spruce Coal.

Massey Spruce

Analyses			Analyses			
Proximate	Dry	As Rec'd	Size Distribution	Sieves	mass % in size bin	cum. mass %
Fixed Carbon	56.99	55.69	dp>600µm	+28		
Volatile Matter	34.68	33.89	600µm>dp>300µm	28x48		
Moisture	2.28		300µm>dp>149µm	48x100		
Ultimate	Dry	As Rec'd	149µm>dp>74µm	100x200		
C	77.89	76.11	74µm>dp>44µm	200x325		
H	5.04	4.93	44µm>dp	-325		
O	6.26	6.12	Size Distribution (Malvern)*		Size Distribution (Malvern)*	
N	1.43	1.40	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)
S	1.05	1.03				% in size bin
Cl						cum. vol. per.
Ash	8.33	8.14	188m			118.4m2
Ash Chemistry	% dry fuel	% ash	162m			102.1m2
SiO2	4.61	55.35	140m			88.1m2
Al2O3	2.18	26.22	121m			76m2
TiO2	0.10	1.23	104m			65.6m2
Fe2O3	0.97	11.62	89.9m			56.6m2
CaO	0.12	1.42	77.5m			48.8m2
MgO	0.07	0.86	66.9m			42.1m2
K2O	0.19	2.28	57.7m			38.3m2
Na2O	0.02	0.29	49.8m			31.3m2
SO3	0.15	1.76	42.9m			27m2
P2O5	0.01	0.08	37.1m			23.3m2
Cl			32m			20.1m2
Undetermined	-0.09	-1.11	27.6m			17.4m2
Total	8.33	100.0	23.8m			15m2
Forms of Sulfur (% dry fuel)			20.5m			12.9m2
Pyritic	0.49		17.7m			11.1m2
Organic	0.53		15.3m			9.6m2
Sulfatic	0.03		13.2m			8.3m2
Fraction Free Silica	0.29		11.4m			7.2m2
Fraction Pyritic Iron	0.63		9.8m			6.2m2
Heating Value (Btu/lb, dry)			8.5m			5.3m2
As Fired	13768	13454	7.3m			4.8m2
Dulong	14012	13692	6.3m			4m2
Acid Sol. Alkali (ppm)	Dry	As Rec'd	5.4m			3.4m2
Na			4.7m			3m2
Mg			4.1m			2.8m2
Ca			3.5m			2.2m2
K			3m			1.9m2
Fusion Temp.	°F	°C	2.6m			1.6m2
Reducing Conditions			2.2m			1.4m2
Initial Deformation			1.9m			1.2m2
Spherical			Size Statistics (Malvern Data Only)			
Hemispherical					Malvern	All Data
Fluid			Dv.5	Volume Mean Diam.		
Oxidizing Conditions			Dv.9	90 % volume diameter		
Initial Deformation			Dv.1	10 percentile volume diameter		
Spherical			D4,3			
Hemispherical			D3,2	Sauter Mean Diameter		
Fluid			Span			
			Specific Surface Area (m ² /cc)			

*These Malvern data are for the -325 mesh size fractions.

Table A.9 Summary of Properties of the Eastern Kentucky Coal.

Eastern Kentucky

Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	53.00	52.28	dp>600µm		+28	0.00	0.00
Volatile Matter	36.87	36.37	600µm>dp>300µm		28x48	0.05	0.05
Moisture	1.36		300µm>dp>149µm		48x100	1.43	1.48
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	32.50	33.98
C	74.82	73.80	74µm>dp>44µm		200x325	30.15	64.13
H	4.97	4.90	44µm>dp		-325	35.88	100.00
O	7.57	7.47	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	1.46	1.44	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	0.97	0.96	188m	0.00	100.0	118.4m2	0.05
Cl	0.09	0.09	162m	0.05	100.0	102.1m2	0.13
Ash	10.15	10.02	140m	0.05	99.9	88.1m2	0.15
Ash Chemistry	% dry fuel	% ash	121m	0.05	99.9	76m2	0.23
SiO2	5.86	57.67	104m	0.05	99.8	65.6m2	1.98
Al2O3	3.09	30.39	89.9m	0.18	99.6	56.6m2	5.58
TiO2	0.21	2.06	77.5m	0.63	99.0	48.8m2	9.70
Fe2O3	0.49	4.83	66.9m	1.48	97.5	42.1m2	10.70
CaO	0.12	1.15	57.7m	2.98	94.6	38.3m2	8.63
MgO	0.04	0.41	49.8m	5.85	88.7	31.3m2	6.40
K2O	0.10	0.99	42.9m	8.43	80.3	27m2	6.98
Na2O	0.02	0.17	37.1m	9.73	70.6	23.3m2	8.98
SO3	0.13	1.28	32m	9.08	61.5	20.1m2	7.55
P2O5	0.01	0.13	27.6m	7.48	54.0	17.4m2	4.28
Cl			23.8m	6.40	47.6	15m2	3.30
Undetermined	0.09	0.91	20.5m	5.73	41.9	12.9m2	4.13
Total	10.15	100.0	17.7m	5.35	36.5	11.1m2	4.35
Forms of Sulfur (% dry fuel)			15.3m	5.30	31.2	9.6m2	3.90
Pyritic	0.31		13.2m	4.95	26.3	8.3m2	2.40
Organic	0.66		11.4m	4.18	22.1	7.2m2	1.63
Sulfatic	0.00		9.8m	3.33	18.8	6.2m2	1.68
Fraction Free Silica	0.21		8.5m	2.75	16.0	5.3m2	1.78
Fraction Pyritic Iron	0.78		7.3m	2.50	13.5	4.8m2	1.60
Heating Value (Btu/lb, dry)			6.3m	2.48	11.1	4m2	1.40
As Fired	13226	13046	5.4m	2.43	8.6	3.4m2	1.15
Dulong	13418	13235	4.7m	2.13	6.5	3m2	0.93
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	1.65	4.9	2.8m2	0.45
Na			3.5m	1.35	3.5	2.2m2	0.15
Mg			3m	0.93	2.6	1.9m2	0.00
Ca			2.6m	0.65	1.9	1.6m2	0.00
K			2.2m	0.58	1.4	1.4m2	0.00
Fusion Temp.	°F	°C	1.9m	0.60	0.8	1.2m2	0.00
Reducing Conditions			Size Statistics (Malvern Data Only)				
Initial Deformation	2949	1620				Malvern	All Data
Spherical	2980	1638	Dv.5	Volume Mean Diam.		23.48	
Hemispherical	2992	1644	Dv.9	90 % volume diameter		47.54	
Fluid	3000	1649	Dv.1	10 percentile volume diameter		6.28	
Oxidizing Conditions			D4,3			25.23	
Initial Deformation	2960	1627	D3,2	Sauter Mean Diameter		13.04	
Spherical	2996	1647	Span			1.75	
Hemispherical	3000	1649	Specific Surface Area (m ² /cc)			0.45	
Fluid	3000	1649					

*These Malvern data are for the -325 mesh size fractions.

Table A.10 Summary of Properties of the Pittsburgh #8 (1) Coal.

Pittsburgh #8 (1)

Analyses			Analyses			
Proximate	Dry	As Rec'd	Size Distribution	Sieves	mass % in size bin	cum. mass %
Fixed Carbon	49.16	48.66	dp>600µm	+28	0.00	0.00
Volatile Matter	40.16	39.75	600µm>dp>300µm	28x48	0.20	0.20
Moisture	1.02		300µm>dp>149µm	48x100	0.80	1.00
Ultimate	Dry	As Rec'd	149µm>dp>74µm	100x200	22.10	23.10
C	71.51	70.78	74µm>dp>44µm	200x325	34.80	57.90
H	5.03	4.98	44µm>dp	-325	42.10	100.00
O	6.76	6.69	Size Distribution (Malvern)*		Size Distribution (Malvern)*	
N	1.24	1.23	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)
S	4.78	4.73				% in size bin
Cl						cum. vol. per.
Ash	10.68	10.57	188m			118.4m2
Ash Chemistry	% dry fuel	% ash	162m			102.1m2
SiO2	4.42	41.40	140m			88.1m2
Al2O3	2.19	20.51	121m			76m2
TiO2	0.10	0.89	104m			65.6m2
Fe2O3	3.10	29.03	89.9m			56.6m2
CaO	0.22	2.07	77.5m			48.8m2
MgO	0.08	0.78	66.9m			42.1m2
K2O	0.18	1.73	57.7m			38.3m2
Na2O	0.04	0.40	49.8m			31.3m2
SO3	0.25	2.33	42.9m			27m2
P2O5	0.02	0.15	37.1m			23.3m2
Cl			32m			20.1m2
Undetermined	0.08	0.71	27.6m			17.4m2
Total	10.68	100.0	23.8m			15m2
Forms of Sulfur (% dry fuel)			20.5m			12.9m2
Pyritic	1.81		17.7m			11.1m2
Organic	2.82		15.3m			9.6m2
Sulfatic	0.15		13.2m			8.3m2
Fraction Free Silica	0.26		11.4m			7.2m2
Fraction Pyritic Iron	0.73		9.8m			6.2m2
Heating Value (Btu/lb, dry)			8.5m			5.3m2
As Fired	13004	12871	7.3m			4.8m2
Dulong	13190	13055	6.3m			4m2
Acid Sol. Alkali (ppm)	Dry	As Rec'd	5.4m			3.4m2
Na			4.7m			3m2
Mg			4.1m			2.8m2
Ca			3.5m			2.2m2
K			3m			1.9m2
Fusion Temp.	°F	°C	2.6m			1.6m2
Reducing Conditions			2.2m			1.4m2
Initial Deformation	1917	1047	1.9m			1.2m2
Spherical	1980	1082	Size Statistics (Malvern Data Only)			
Hemispherical	2154	1179			Malvern	All Data
Fluid	2232	1222	Dv.5	Volume Mean Diam.		
Oxidizing Conditions			Dv.9	90 % volume diameter		
Initial Deformation	2438	1337	Dv.1	10 percentile volume diameter		
Spherical	2502	1372	D4,3			
Hemispherical	2518	1381	D3,2	Sauter Mean Diameter		
Fluid	2532	1389	Span			
			Specific Surface Area (m ² /cc)			

*These Malvern data are for the -325 mesh size fractions.

Table A.11 Summary of Properties of the Utah Blind Canyon Coal.

Utah Blind Canyon

Analyses			Analyses					
Proximate	Dry	As Rec'd	Size Distribution	Sieves	mass % in size bin	cum. mass %		
Fixed Carbon	45.59	44.12	dp>600µm	+28	0.00	0.00		
Volatile Matter	43.92	42.50	600µm>dp>300µm	28x48	0.33	0.33		
Moisture	3.24		300µm>dp>149µm	48x100	5.90	6.23		
Ultimate	Dry	As Rec'd	149µm>dp>74µm	100x200	24.90	31.13		
C	72.62	70.27	74µm>dp>44µm	200x325	21.43	52.57		
H	5.50	5.32	44µm>dp	-325	47.43	100.00		
O	9.57	9.26	Size Distribution (Malvern)*		Size Distribution (Malvern)*			
N	1.33	1.29	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin	cum. vol. per.
S	0.46	0.44	188m	0.00	100.0	118.4m2		
Cl	0.04	0.04	162m	0.00	100.0	102.1m2		
Ash	10.51	10.17	140m	0.00	100.0	88.1m2		
Ash Chemistry	% dry fuel	% ash	121m	0.00	100.0	76m2		
SiO2	6.06	57.69	104m	0.00	100.0	65.6m2		
Al2O3	1.92	18.32	89.9m	0.08	99.9	56.6m2		
TiO2	0.10	0.96	77.5m	0.28	99.7	48.8m2		
Fe2O3	0.43	4.11	66.9m	0.63	99.0	42.1m2		
CaO	0.64	6.13	57.7m	1.35	97.7	38.3m2		
MgO	0.19	1.84	49.8m	3.68	94.0	31.3m2		
K2O	0.12	1.16	42.9m	7.55	86.5	27m2		
Na2O	0.45	4.32	37.1m	9.68	76.8	23.3m2		
SO3	0.48	4.57	32m	9.13	67.7	20.1m2		
P2O5	0.03	0.33	27.6m	7.45	60.2	17.4m2		
Cl			23.8m	6.28	53.9	15m2		
Undetermined	0.06	0.58	20.5m	5.78	48.2	12.9m2		
Total	10.51	100.0	17.7m	5.93	42.2	11.1m2		
Forms of Sulfur (% dry fuel)			15.3m	6.05	36.2	9.6m2		
Pyritic	0.08		13.2m	5.50	30.7	8.3m2		
Organic	0.37		11.4m	4.60	26.1	7.2m2		
Sulfatic	0.00		9.8m	3.68	22.4	6.2m2		
Fraction Free Silica	0.52		8.5m	3.15	19.3	5.3m2		
Fraction Pyritic Iron	0.24		7.3m	3.00	16.3	4.8m2		
Heating Value (Btu/lb, dry)			6.3m	2.95	13.3	4m2		
As Fired	13108	12684	5.4m	2.78	10.5	3.4m2		
Dulong	13247	12819	4.7m	2.35	8.2	3m2		
Acid Sol. Alkali (ppm)			4.1m	1.70	6.5	2.8m2		
Na			3.5m	1.45	5.0	2.2m2		
Mg			3m	1.05	4.0	1.9m2		
Ca			2.6m	0.88	3.1	1.6m2		
K			2.2m	0.83	2.3	1.4m2		
Fusion Temp.			1.9m	1.20	1.1	1.2m2		
Reducing Conditions			Size Statistics (Malvern Data Only)					
Initial Deformation	2178	1192			Malvern	All Data		
Spherical	2246	1230	Dv.5	Volume Mean Diam.	20.25			
Hemispherical	2369	1298	Dv.9	90 % volume diameter	42.45			
Fluid	2641	1449	Dv.1	10 percentile volume diameter	4.95			
Oxidizing Conditions			D4,3		22.58			
Initial Deformation	2220	1216	D3,2	Sauter Mean Diameter	10.88			
Spherical	2265	1241	Span		1.88			
Hemispherical	2400	1316	Specific Surface Area (m ² /cc)		0.58			
Fluid	2675	1468						

*These Malvern data are for the -325 mesh size fractions.

Table A.12 Summary of Properties of the Kentucky #11 Coal.

Kentucky #11

Analyses			Analyses			Analyses		
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin		cum. mass %
Fixed Carbon	42.82	41.14	dp>600µm		+28	0.00		0.00
Volatile Matter	34.97	33.60	600µm>dp>300µm		28x48	0.20		0.20
Moisture	3.91		300µm>dp>149µm		48x100	2.70		2.90
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	15.40		18.30
C	59.15	56.84	74µm>dp>44µm		200x325	22.70		41.00
H	4.44	4.26	44µm>dp		-325	59.00		100.00
O	8.25	7.93	Size Distribution (Malvern)*			Size Distribution (Malvern)*		
N	1.16	1.11	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin	cum. vol. per.
S	4.78	4.60	188m	0.00	100.0	118.4m2		
Cl	0.03	0.03	162m	0.00	100.0	102.1m2		
Ash	22.15	21.28	140m	0.00	100.0	88.1m2		
Ash Chemistry	% dry fuel	% ash	121m	0.00	100.0	76m2		
SiO2	10.14	45.76	104m	0.00	100.0	65.6m2		
Al2O3	4.06	18.33	89.9m	0.15	99.9	56.6m2		
TiO2	0.19	0.84	77.5m	0.45	99.4	48.8m2		
Fe2O3	4.70	21.23	66.9m	0.80	98.6	42.1m2		
CaO	0.95	4.30	57.7m	1.60	97.0	38.3m2		
MgO	0.24	1.11	49.8m	3.85	93.2	31.3m2		
K2O	0.48	2.17	42.9m	6.65	86.5	27m2		
Na2O	0.08	0.36	37.1m	9.55	77.0	23.3m2		
SO3	1.02	4.61	32m	9.90	67.1	20.1m2		
P2O5	0.04	0.20	27.6m	8.15	58.9	17.4m2		
Cl	0.02	0.09	23.8m	6.85	52.1	15m2		
Undetermined	0.23	1.02	20.5m	6.20	45.9	12.9m2		
Total	22.16	100.0	17.7m	6.20	39.7	11.1m2		
Forms of Sulfur (% dry fuel)			15.3m	6.35	33.3	9.6m2		
Pyritic	2.99		13.2m	5.70	27.6	8.3m2		
Organic	1.59		11.4m	4.75	22.8	7.2m2		
Sulfatic	0.20		9.8m	3.50	19.3	6.2m2		
Fraction Free Silica	0.40		8.5m	2.90	16.5	5.3m2		
Fraction Pyritic Iron	0.80		7.3m	2.80	13.6	4.8m2		
Heating Value (Btu/lb, dry)			6.3m	2.75	10.9	4m2		
As Fired	10524	10112	5.4m	2.60	8.3	3.4m2		
Dulong	10909	10482	4.7m	2.20	6.1	3m2		
Acid Sol. Alkali (ppm)			4.1m	1.55	4.5	2.8m2		
Na	400	400	3.5m	1.15	3.4	2.2m2		
Mg	1037	1037	3m	0.85	2.5	1.9m2		
Ca	4981	4981	2.6m	0.70	1.8	1.6m2		
K	3578	3578	2.2m	0.55	1.3	1.4m2		
Fusion Temp.			1.9m	1.25	0.0	1.2m2		
			Size Statistics (Malvern Data Only)					
Reducing Conditions						Malvern	All Data	
Initial Deformation	2238	1226	Dv.5 Volume Mean Diam.			19.55		
Spherical	2270	1243	Dv.9 90 % volume diameter			39.75		
Hemispherical	2310	1266	Dv.1 10 percentile volume diameter			5.20		
Fluid	2352	1289	D4,3			21.75		
Oxidizing Conditions			D3,2 Sauter Mean Diameter			11.25		
Initial Deformation	2314	1268	Span			1.80		
Spherical	2354	1290	Specific Surface Area (m ² /cc)			0.55		
Hemispherical	2404	1318						
Fluid	2446	1341						

*These Malvern data are for the -325 mesh size fractions.

Table A.13 Summary of Properties of the Illinois #6 (2) Coal.

Illinois #6 (2)

Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	48.34	46.30	dp>600µm		+28	0.00	0.00
Volatile Matter	39.46	37.79	600µm>dp>300µm		28x48	0.00	0.00
Moisture	4.22		300µm>dp>149µm		48x100	1.78	1.78
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	25.20	26.98
C	68.12	65.24	74µm>dp>44µm		200x325	25.88	52.85
H	4.74	4.54	44µm>dp		-325	47.15	100.00
O	9.91	9.49	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	1.22	1.17	Diameter. % in		cum. vol.	Diameter	% in
S	3.72	3.57	(µm)	size bin	per.	(µm)	size bin
Cl	0.08	0.08	188m	0.00	100.0	118.4m2	
Ash	12.21	11.69	162m	0.02	100.0	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	0.07	99.9	88.1m2	
SiO2	5.94	48.66	121m	0.08	99.8	76m2	
Al2O3	2.20	18.00	104m	0.08	99.8	65.6m2	
TiO2	0.11	0.87	89.9m	0.08	99.7	56.6m2	
Fe2O3	2.23	18.31	77.5m	0.42	99.3	48.8m2	
CaO	0.58	4.78	66.9m	1.72	97.5	42.1m2	
MgO	0.12	1.02	57.7m	3.88	93.7	38.3m2	
K2O	0.25	2.08	49.8m	6.70	87.0	31.3m2	
Na2O	0.12	1.02	42.9m	9.10	77.9	27m2	
SO3	0.55	4.53	37.1m	9.83	68.0	23.3m2	
P2O5	0.03	0.21	32m	9.15	58.9	20.1m2	
Cl			27.6m	7.75	51.1	17.4m2	
Undetermined	0.12	0.94	23.8m	6.55	44.6	15m2	
Total	12.26	100.4	20.5m	5.88	38.7	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	5.65	33.0	11.1m2	
Pyritic	1.06		15.3m	5.38	27.7	9.6m2	
Organic	2.21		13.2m	4.70	23.0	8.3m2	
Sulfatic	0.54		11.4m	3.73	19.2	7.2m2	
Fraction Free Silica	0.45		9.8m	2.95	16.3	6.2m2	
Fraction Pyritic Iron	0.44		8.5m	2.52	13.8	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	2.32	11.4	4.8m2	
As Fired	12059	11550	6.3m	2.18	9.3	4m2	
Dulong	12228	11712	5.4m	2.07	7.2	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.75	5.4	3m2	
Na			4.1m	1.38	4.1	2.8m2	
Mg			3.5m	1.07	3.0	2.2m2	
Ca			3m	0.85	2.1	1.9m2	
K			2.6m	0.58	1.6	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.42	1.1	1.4m2	
Reducing Conditions			1.9m	0.50	0.6	1.2m2	
Initial Deformation	1996	1091	Size Statistics (Malvern Data Only)				
Spherical	2054	1123				Malvern	All Data
Hemispherical	2177	1192	Dv.5	Volume Mean Diam.		25.65	
Fluid	2367	1297	Dv.9	90 % volume diameter		50.57	
Oxidizing Conditions			Dv.1	10 percentile volume diameter		6.52	
Initial Deformation	2291	1255	D4,3			27.65	
Spherical	2331	1277	D3,2	Sauter Mean Diameter		13.97	
Hemispherical	2360	1293	Span			1.73	
Fluid	2480	1360	Specific Surface Area (m ² /cc)			0.44	

*These Malvern data are for the -325 mesh size fractions.

Table A.14 Summary of Properties of the SOAP.

Spherical Oil Agglomerate							
Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	53.04	47.15	dp>600µm		+28	0.27	0.27
Volatiles Matter	42.98	38.20	600µm>dp>300µm		28x48	23.40	23.67
Moisture	11.10		300µm>dp>149µm		48x100	6.57	30.23
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	3.77	34.00
C	74.63	66.34	74µm>dp>44µm		200x325	1.80	35.80
H	5.21	4.63	44µm>dp		-325	64.20	100.00
O	11.86	10.54	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	1.20	1.06	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	3.07	2.73	188m	0.00	100.0	118.4m2	
Cl	0.06	0.05	162m	0.00	100.0	102.1m2	
Ash	3.99	3.54	140m	0.00	100.0	88.1m2	
Ash Chemistry	% dry fuel	% ash	121m	0.00	100.0	76m2	
SiO2	1.25	31.44	104m	0.00	100.0	65.6m2	
Al2O3	0.66	16.66	89.9m	0.00	100.0	56.6m2	
TiO2	0.08	2.09	77.5m	0.00	100.0	48.8m2	
Fe2O3	1.52	38.03	66.9m	0.00	100.0	42.1m2	
CaO	0.11	2.72	57.7m	0.02	100.0	38.3m2	
MgO	0.04	1.06	49.8m	0.03	100.0	31.3m2	
K2O	0.07	1.86	42.9m	0.10	99.9	27m2	
Na2O	0.04	1.02	37.1m	0.53	99.3	23.3m2	
SO3	0.15	3.66	32m	0.92	98.4	20.1m2	
P2O5	0.01	0.14	27.6m	2.05	96.4	17.4m2	
Cl			23.8m	3.80	92.6	15m2	
Undetermined	0.05	1.26	20.5m	5.17	87.4	12.9m2	
Total	3.98	99.9	17.7m	6.22	81.2	11.1m2	
Forms of Sulfur (% dry fuel)			15.3m	7.15	74.0	9.6m2	
Pyritic	0.03		13.2m	7.83	66.2	8.3m2	
Organic	2.19		11.4m	8.40	57.8	7.2m2	
Sulfatic	0.85		9.8m	8.33	49.5	6.2m2	
Fraction Free Silica	0.20		8.5m	7.73	41.7	5.3m2	
Fraction Pyritic Iron	0.02		7.3m	6.95	34.8	4.8m2	
Heating Value (Btu/lb, dry)			6.3m	6.53	28.2	4m2	
As Fired	13656	12139	5.4m	6.18	22.1	3.4m2	
Dulong	13289	11813	4.7m	5.53	16.5	3m2	
Acid Sol. Alkali (ppm)			4.1m	4.47	12.1	2.8m2	
Na			3.5m	3.17	8.9	2.2m2	
Mg			3m	2.23	6.7	1.9m2	
Ca			2.6m	1.73	4.9	1.6m2	
K			2.2m	1.43	3.5	1.4m2	
Fusion Temp.			1.9m	2.58	0.9	1.2m2	
	°F	°C	Size Statistics (Malvern Data Only)				
Reducing Conditions			Dv.5		Volume Mean Diam.	Malvern	All Data
Initial Deformation	2108	1153	Dv.9		90 % volume diameter	8.98	
Spherical	2257	1236	Dv.1		10 percentile volume diameter	19.92	
Hemispherical	2344	1284	D4,3			3.40	
Fluid	2394	1312	D3,2		Sauter Mean Diameter	10.42	
Oxidizing Conditions			Span			6.47	
Initial Deformation	2442	1339	Specific Surface Area (m ³ /cc)			1.85	
Spherical	2531	1388				0.83	
Hemispherical	2569	1409					
Fluid	2600	1426					

*These Malvern data are for the -325 mesh size fractions.

Table A.15 Summary of Properties of the Kentucky #9 Coal.

Kentucky #9							
Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	46.77	43.34	dp>600µm		+28	0.00	0.00
Volatile Matter	37.56	34.80	600µm>dp>300µm		28x48	0.13	0.13
Moisture	7.34		300µm>dp>149µm		48x100	2.05	2.18
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	13.98	16.15
C	64.85	60.09	74µm>dp>44µm		200x325	24.60	40.75
H	4.60	4.26	44µm>dp		-325	59.25	100.00
O	9.22	8.55	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	1.61	1.49	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	4.00	3.71					cum. vol. per.
Cl	0.06	0.05	188m	0.00	100.0	118.4m2	
Ash	15.64	14.49	162m	0.00	100.0	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	0.02	100.0	88.1m2	
SiO2	7.12	45.54	121m	0.03	100.0	76m2	
Al2O3	3.08	19.71	104m	0.02	99.9	65.6m2	
TiO2	0.15	0.98	89.9m	0.07	99.9	56.6m2	
Fe2O3	3.61	23.09	77.5m	0.33	99.5	48.8m2	
CaO	0.50	3.22	66.9m	1.23	98.3	42.1m2	
MgO	0.16	1.05	57.7m	2.92	95.4	38.3m2	
K2O	0.39	2.47	49.8m	5.38	90.0	31.3m2	
Na2O	0.14	0.87	42.9m	7.83	82.2	27m2	
SO3	0.57	3.62	37.1m	9.22	73.0	23.3m2	
P2O5	0.02	0.14	32m	9.33	63.6	20.1m2	
Cl	0.03	0.17	27.6m	8.38	55.2	17.4m2	
Undetermined	-0.12	-0.77	23.8m	7.28	48.0	15m2	
Total	15.65	100.1	20.5m	6.35	41.6	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	5.83	35.8	11.1m2	
Pyritic	1.70		15.3m	5.72	30.1	9.6m2	
Organic	1.89		13.2m	5.37	24.7	8.3m2	
Sulfatic	0.41		11.4m	4.45	20.2	7.2m2	
Fraction Free Silica	0.34		9.8m	3.48	16.8	6.2m2	
Fraction Pyritic Iron	0.59		8.5m	2.80	14.0	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	2.42	11.5	4.8m2	
As Fired	11611	10759	6.3m	2.28	9.3	4m2	
Dulong	15493	14356	5.4m	2.13	7.1	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.85	5.3	3m2	
Na	694	694	4.1m	1.47	3.8	2.8m2	
Mg	830	830	3.5m	1.15	2.7	2.2m2	
Ca	2835	2835	3m	0.87	1.8	1.9m2	
K	2225	2225	2.6m	0.57	1.2	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.38	0.8	1.4m2	
Reducing Conditions			1.9m	0.37	0.5	1.2m2	
Initial Deformation	1979	1082	Size Statistics (Malvern Data Only)				
Spherical	2041	1116				Malvern	All Data
Hemispherical	2170	1188	Dv.5	Volume Mean Diam.		23.57	
Fluid	2339	1282	Dv.9	90 % volume diameter		47.35	
Oxidizing Conditions			Dv.1	10 percentile volume diameter		6.53	
Initial Deformation	2323	1273	D4,3			26.15	
Spherical	2414	1323	D3,2	Sauter Mean Diameter		13.80	
Hemispherical	2469	1354	Span			1.77	
Fluid	2526	1385	Specific Surface Area (m ² /cc)			0.44	

*These Malvern data are for the -325 mesh size fractions.

Table A.16 Summary of Properties of the Hanna Basin Coal.

Hanna Basin						
Analyses			Analyses			
Proximate	Dry	As Rec'd	Size Distribution	Sieves	mass % in size bin	cum. mass %
Fixed Carbon	50.36	45.35	dp>600µm	+28	0.00	0.00
Volatile Matter	39.49	35.55	600µm>dp>300µm	28x48	0.00	0.00
Moisture	9.96		300µm>dp>149µm	48x100	6.30	6.30
Ultimate	Dry	As Rec'd	149µm>dp>74µm	100x200	25.40	31.70
C	67.12	60.44	74µm>dp>44µm	200x325	24.60	56.30
H	4.79	4.31	44µm>dp	-325	43.70	100.00
O	16.02	14.42	Size Distribution (Malvern)*		Size Distribution (Malvern)*	
N	1.26	1.13	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)
S	0.65	0.58	188m	0.00	100.0	118.4m2
Cl	0.03	0.02	162m	0.05	100.0	102.1m2
Ash	9.99	9.00	140m	0.10	99.9	88.1m2
Ash Chemistry	% dry fuel	% ash	121m	0.15	99.7	76m2
SiO2	3.63	36.34	104m	0.20	99.5	65.6m2
Al2O3	1.49	14.94	89.9m	0.15	99.4	56.6m2
TiO2	0.07	0.75	77.5m	0.45	98.9	48.8m2
Fe2O3	0.82	8.21	66.9m	1.90	97.0	42.1m2
CaO	2.20	22.01	57.7m	4.25	92.8	38.3m2
MgO	0.33	3.26	49.8m	7.45	85.3	31.3m2
K2O	0.08	0.82	42.9m	10.35	75.0	27m2
Na2O	0.09	0.87	37.1m	10.80	64.2	23.3m2
SO3	1.07	10.76	32m	10.05	54.1	20.1m2
P2O5	0.07	0.66	27.6m	8.30	45.8	17.4m2
Cl			23.8m	6.30	39.5	15m2
Undetermined	0.10	1.01	20.5m	5.40	34.1	12.9m2
Total	9.95	99.6	17.7m	5.15	29.0	11.1m2
Forms of Sulfur (% dry fuel)			15.3m	5.05	23.9	9.6m2
Pyritic	0.19		13.2m	4.60	19.3	8.3m2
Organic	0.43		11.4m	3.45	15.9	7.2m2
Sulfatic	0.03		9.8m	2.70	13.2	6.2m2
Fraction Free Silica	0.38		8.5m	2.15	11.0	5.3m2
Fraction Pyritic Iron	0.19		7.3m	1.90	9.1	4.8m2
Heating Value (Btu/lb, dry)			6.3m	1.70	7.4	4m2
As Fired	11921	10734	5.4m	1.60	5.8	3.4m2
Dulong	11517	10370	4.7m	1.40	4.4	3m2
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	1.20	3.2	2.8m2
Na			3.5m	0.95	2.3	2.2m2
Mg			3m	0.75	1.5	1.9m2
Ca			2.6m	0.50	1.0	1.6m2
K			2.2m	0.35	0.7	1.4m2
Fusion Temp.	°F	°C	1.9m	0.25	0.4	1.2m2
Reducing Conditions			Size Statistics (Malvern Data Only)			
Initial Deformation	2186	1196			Malvern	All Data
Spherical	2245	1229	Dv.5	Volume Mean Diam.	29.70	
Hemispherical	2276	1246	Dv.9	90 % volume diameter	54.20	
Fluid	2338	1281	Dv.1	10 percentile volume diameter	7.85	
Oxidizing Conditions			D4,3		31.15	
Initial Deformation	2275	1246	D3,2	Sauter Mean Diameter	16.15	
Spherical	2316	1269	Span		1.55	
Hemispherical	2349	1287	Specific Surface Area (m ² /cc)		0.38	
Fluid	2452	1344				

*These Malvern data are for the -325 mesh size fractions.

Table A.17 Summary of Properties of the Illinois #6 (1) Coal.

Illinois #6 (1)

Analyses			Analyses			Analyses		
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin		cum. mass %
Fixed Carbon	48.90	43.69	dp>600µm		+28	0.00		0.00
Volatile Matter	40.83	36.48	600µm>dp>300µm		28x48	0.05		0.05
Moisture	10.65		300µm>dp>149µm		48x100	1.75		1.80
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	14.50		16.30
C	68.50	61.20	74µm>dp>44µm		200x325	27.30		43.60
H	5.04	4.50	44µm>dp		-325	57.65		101.25
O	10.40	9.29	Size Distribution (Malvern)*			Size Distribution (Malvern)*		
N	1.44	1.29	Diameter % in		cum. vol.	Diameter	% in	cum. vol.
S	4.33	3.87	(µm)	size bin	per.	(µm)	size bin	per.
Cl	0.10	0.09	188m	0.00	100.0	118.4m2	0.05	100.0
Ash	10.24	9.15	162m	0.03	100.0	102.1m2	0.15	99.9
Ash Chemistry	% dry fuel	% ash	140m	0.08	99.9	88.1m2	0.15	99.9
SiO2	4.75	46.35	121m	0.10	99.8	76m2	0.10	99.9
Al2O3	1.71	16.74	104m	0.10	99.7	65.6m2	1.65	98.4
TiO2	0.09	0.88	89.9m	0.10	99.6	56.6m2	5.40	94.6
Fe2O3	2.10	20.49	77.5m	0.45	99.2	48.8m2	9.55	90.5
CaO	0.53	5.15	66.9m	1.50	97.7	42.1m2	10.95	89.1
MgO	0.08	0.78	57.7m	3.45	94.2	38.3m2	9.55	90.5
K2O	0.21	2.01	49.8m	6.15	88.1	31.3m2	7.75	92.3
Na2O	0.13	1.28	42.9m	8.93	79.1	27m2	8.20	91.8
SO3	0.51	4.95	37.1m	10.63	68.5	23.3m2	9.55	90.5
P2O5	0.02	0.16	32m	10.45	58.1	20.1m2	7.55	92.5
Cl	0.02	0.16	27.6m	8.88	49.2	17.4m2	4.15	95.9
Undetermined	0.10	0.96	23.8m	7.25	41.9	15m2	3.65	96.4
Total	10.23	99.9	20.5m	6.20	35.7	12.9m2	4.90	95.1
Forms of Sulfur (% dry fuel)			17.7m	6.00	29.7	11.1m2	4.20	95.8
Pyritic	1.20		15.3m	5.83	23.9	9.6m2	3.00	97.0
Organic	2.78		13.2m	5.05	18.9	8.3m2	1.60	98.4
Sulfatic	0.36		11.4m	3.88	15.0	7.2m2	1.20	98.8
Fraction Free Silica	0.46		9.8m	2.80	12.2	6.2m2	1.55	98.5
Fraction Pyritic Iron	0.72		8.5m	2.20	10.0	5.3m2	1.35	98.7
Heating Value (Btu/lb, dry)			7.3m	1.93	8.1	4.8m2	1.15	98.9
As Fired	12182	10885	6.3m	1.85	6.2	4m2	0.80	99.2
Dulong	12457	11131	5.4m	1.63	4.6	3.4m2	0.75	99.3
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.28	3.3	3m2	0.70	99.3
Na	2256	2256	4.1m	1.00	2.3	2.8m2	0.10	99.9
Mg	1766	1766	3.5m	0.80	1.5	2.2m2	0.10	99.9
Ca	5977	5977	3m	0.55	0.9	1.9m2	0.00	100.0
K	2380	2380	2.6m	0.33	0.6	1.6m2	0.00	100.0
Fusion Temp.	°F	°C	2.2m	0.23	0.4	1.4m2	0.00	100.0
Reducing Conditions			1.9m	0.20	0.2	1.2m2	0.00	100.0
Initial Deformation	1939	1060	Size Statistics (Malvern Data Only)					
Spherical	1995	1090				Malvern		All Data
Hemispherical	2110	1154	Dv.5	Volume Mean Diam.		25.63		
Fluid	2287	1253	Dv.9	90 % volume diameter		47.92		
Oxidizing Conditions			Dv.1	10 percentile volume diameter		8.17		
Initial Deformation	2266	1241	D4,3			27.10		
Spherical	2291	1255	D3,2	Sauter Mean Diameter		15.72		
Hemispherical	2346	1285	Span			1.57		
Fluid	2491	1366	Specific Surface Area (m ² /cc)			0.37		

*These Malvern data are for the -325 mesh size fractions.

Table A.18 Summary of Properties of the Roland Coal.

Roland								
Analyses			Analyses					
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %	
Fixed Carbon	48.45	43.46	dp>600µm		+28	0.00	0.00	
Volatile Matter	45.39	40.72	600µm>dp>300µm		28x48	0.80	0.80	
Moisture	10.29		300µm>dp>149µm		48x100	1.80	2.60	
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	26.50	29.10	
C	69.94	62.74	74µm>dp>44µm		200x325	28.97	58.07	
H	4.76	4.27	44µm>dp		-325	41.93	100.00	
O	17.79	15.96	Size Distribution (Malvern)*					
N	0.91	0.82	Diameter % in		cum. vol.	Diameter	% in	
S	0.40	0.36	(µm)	size bin	per.	(µm)	size bin	
Cl	0.03	0.03						
Ash	6.16	5.53	188m	0.00	100.0	118.4m2		
Ash Chemistry	% dry fuel	% ash	162m	0.00	100.0	102.1m2		
SiO2	1.87	30.42	140m	0.00	100.0	88.1m2		
Al2O3	0.91	14.81	121m	0.00	100.0	76m2		
TiO2	0.07	1.12	104m	0.00	100.0	65.6m2		
Fe2O3	0.44	7.22	89.9m	0.03	100.0	56.6m2		
CaO	1.28	20.72	77.5m	0.18	99.8	48.8m2		
MgO	0.31	5.08	66.9m	1.00	98.8	42.1m2		
K2O	0.02	0.38	57.7m	2.50	96.3	38.3m2		
Na2O	0.12	1.95	49.8m	4.75	91.6	31.3m2		
SO3	1.00	16.16	42.9m	7.30	84.3	27m2		
P2O5	0.07	1.08	37.1m	9.20	75.1	23.3m2		
Cl			32m	9.20	65.9	20.1m2		
Undetermined	0.07	1.07	27.6m	7.28	58.6	17.4m2		
Total	6.16	100.0	23.8m	5.60	53.0	15m2		
Forms of Sulfur (% dry fuel)			20.5m	5.05	47.9	12.9m2		
Pyritic	0.07		17.7m	5.25	42.7	11.1m2		
Organic	0.27		15.3m	5.48	37.2	9.6m2		
Sulfatic	0.00		13.2m	5.03	32.2	8.3m2		
Fraction Free Silica	0.27		11.4m	4.10	28.1	7.2m2		
Fraction Pyritic Iron	0.13		9.8m	3.38	24.7	6.2m2		
Heating Value (Btu/lb, dry)			8.5m	3.10	21.6	5.3m2		
As Fired	11877	10655	7.3m	3.13	18.5	4.8m2		
Dulong	11762	10551	6.3m	3.18	15.3	4m2		
Acid Sol. Alkali (ppm)	Dry	As Rec'd	5.4m	3.08	12.2	3.4m2		
Na			4.7m	2.73	9.5	3m2		
Mg			4.1m	2.25	7.3	2.8m2		
Ca			3.5m	1.73	5.5	2.2m2		
K			3m	1.25	4.3	1.9m2		
Fusion Temp.	°F	°C	2.6m	1.03	3.3	1.6m2		
Reducing Conditions			2.2m	0.83	2.4	1.4m2		
Initial Deformation	2066	1130	1.9m	1.23	1.2	1.2m2		
Spherical	2113	1156	Size Statistics (Malvern Data Only)					
Hemispherical	2131	1166				Malvern	All Data	
Fluid	2188	1198	Dv.5	Volume Mean Diam.		20.20		
Oxidizing Conditions			Dv.9	90 % volume diameter		44.78		
Initial Deformation	2132	1167	Dv.1	10 percentile volume diameter		4.55		
Spherical	2177	1191	D4,3			22.93		
Hemispherical	2202	1205	D3,2	Sauter Mean Diameter		10.40		
Fluid	2271	1244	Span			1.98		
			Specific Surface Area (m ² /cc)				0.61	

*These Malvern data are for the -325 mesh size fractions.

Table A.19 Summary of Properties of the Decker Coal.

Decker									
Analyses			Analyses						
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %		
Fixed Carbon	51.45	42.46	dp>600µm		+28	0.00	0.00		
Volatile Matter	43.45	35.86	600µm>dp>300µm		28x48	0.10	0.10		
Moisture	17.48		300µm>dp>149µm		48x100	4.00	4.10		
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	23.97	28.07		
C	72.04	59.45	74µm>dp>44µm		200x325	25.03	53.10		
H	4.97	4.10	44µm>dp		-325	46.90	100.00		
O	16.36	13.50	Size Distribution (Malvern)*				Size Distribution (Malvern)*		
N	1.00	0.82	Diameter % in		cum. vol.	Diameter	% in	cum. vol.	
S	0.53	0.43	(µm)	size bin	per.	(µm)	size bin	per.	
Cl	0.02	0.02	188m	0.36	99.6	118.4m2			
Ash	5.12	4.23	162m	0.95	98.7	102.1m2			
Ash Chemistry	% dry fuel	% ash	140m	1.41	97.3	88.1m2			
SiO2	1.32	25.78	121m	1.78	95.5	76m2			
Al2O3	0.87	16.96	104m	1.89	93.6	65.6m2			
TiO2	0.06	1.15	89.9m	1.96	91.7	56.6m2			
Fe2O3	0.33	6.42	77.5m	2.05	89.6	48.8m2			
CaO	0.74	14.51	66.9m	2.48	87.1	42.1m2			
MgO	0.16	3.14	57.7m	3.40	83.7	38.3m2			
K2O	0.02	0.47	49.8m	5.38	78.4	31.3m2			
Na2O	0.41	7.99	42.9m	7.54	70.8	27m2			
SO3	1.07	20.83	37.1m	9.31	61.5	23.3m2			
P2O5	0.05	0.93	32m	9.10	52.4	20.1m2			
Cl			27.6m	7.10	45.3	17.4m2			
Undetermined	0.09	1.82	23.8m	5.41	39.9	15m2			
Total	5.12	100.0	20.5m	4.73	35.2	12.9m2			
Forms of Sulfur (% dry fuel)			17.7m	4.95	30.2	11.1m2			
Pyritic	0.16		15.3m	5.19	25.0	9.6m2			
Organic	0.33		13.2m	4.65	20.4	8.3m2			
Sulfatic	0.04		11.4m	3.71	16.7	7.2m2			
Fraction Free Silica	0.02		9.8m	2.75	13.9	6.2m2			
Fraction Pyritic Iron	0.61		8.5m	2.33	11.6	5.3m2			
Heating Value (Btu/lb, dry)			7.3m	2.28	9.3	4.8m2			
As Fired	12424	10253	6.3m	2.23	7.1	4m2			
Dulong	12315	10162	5.4m	2.01	5.1	3.4m2			
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.53	3.6	3m2			
Na			4.1m	1.01	2.5	2.8m2			
Mg			3.5m	0.79	1.8	2.2m2			
Ca			3m	0.54	1.2	1.9m2			
K			2.6m	0.31	0.9	1.6m2			
Fusion Temp.	°F	°C	2.2m	0.31	0.6	1.4m2			
Reducing Conditions			1.9m	0.49	0.1	1.2m2			
Initial Deformation	2056	1124	Size Statistics (Malvern Data Only)						
Spherical	2143	1173				Malvern	All Data		
Hemispherical	2161	1183	Dv.5	Volume Mean Diam.		31.06			
Fluid	2194	1201	Dv.9	90 % volume diameter		64.68			
Oxidizing Conditions			Dv.1	10 percentile volume diameter		7.63			
Initial Deformation	2333	1278	D4,3			34.15			
Spherical	2457	1347	D3,2	Sauter Mean Diameter		15.80			
Hemispherical	2472	1356	Span			1.76			
Fluid	2495	1368	Specific Surface Area (m ² /cc)			0.40			

*These Malvern data are for the -325 mesh size fractions.

Table A.20 Summary of Properties of the Black Thunder Coal.

Black Thunder

Analyses			Analyses			Analyses		
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin		cum. mass %
Fixed Carbon	39.28	30.91	dp>600µm		+28	0.00		0.00
Volatile Matter	54.26	42.70	600µm>dp>300µm		28x48	0.30		0.30
Moisture	21.30		300µm>dp>149µm		48x100	7.70		8.00
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	30.80		38.80
C	69.90	55.01	74µm>dp>44µm		200x325	19.20		58.00
H	5.05	3.97	44µm>dp		-325	42.00		100.00
O	17.09	13.45	Size Distribution (Malvern)*			Size Distribution (Malvern)*		
N	0.94	0.74	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin	cum. vol. per.
S	0.48	0.38	188m	0.00	100.0	118.4m2		
Cl	0.08	0.06	162m	0.05	100.0	102.1m2		
Ash	6.46	5.08	140m	0.05	99.9	88.1m2		
Ash Chemistry	% dry fuel	% ash	121m	0.05	99.9	76m2		
SiO2	1.96	30.31	104m	0.05	99.8	65.6m2		
Al2O3	1.05	16.27	89.9m	0.15	99.7	56.6m2		
TiO2	0.08	1.27	77.5m	1.10	98.6	48.8m2		
Fe2O3	0.33	5.04	66.9m	3.05	95.5	42.1m2		
CaO	1.36	21.07	57.7m	5.85	89.7	38.3m2		
MgO	0.31	4.74	49.8m	8.55	81.1	31.3m2		
K2O	0.02	0.35	42.9m	9.40	71.7	27m2		
Na2O	0.09	1.41	37.1m	9.30	62.4	23.3m2		
SO3	1.13	17.46	32m	7.85	54.6	20.1m2		
P2O5	0.06	0.91	27.6m	6.05	48.5	17.4m2		
Cl			23.8m	5.35	43.2	15m2		
Undetermined	0.08	1.17	20.5m	5.50	37.7	12.9m2		
Total	6.46	100.0	17.7m	5.65	32.0	11.1m2		
Forms of Sulfur (% dry fuel)			15.3m	5.30	26.7	9.6m2		
Pyritic	0.08		13.2m	4.25	22.5	8.3m2		
Organic	0.40		11.4m	3.45	19.0	7.2m2		
Sulfatic	0.00		9.8m	2.95	16.1	6.2m2		
Fraction Free Silica	0.19		8.5m	2.70	13.4	5.3m2		
Fraction Pyritic Iron	0.31		7.3m	2.50	10.9	4.8m2		
Heating Value (Btu/lb, dry)			6.3m	2.30	8.6	4m2		
As Fired	12815	10085	5.4m	2.05	6.5	3.4m2		
Dulong	11993	9438	4.7m	1.70	4.8	3m2		
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	1.20	3.6	2.8m2		
Na			3.5m	1.05	2.6	2.2m2		
Mg			3m	0.70	1.9	1.9m2		
Ca			2.6m	0.50	1.4	1.6m2		
K			2.2m	0.40	1.0	1.4m2		
Fusion Temp.	°F	°C	1.9m	0.80	0.2	1.2m2		
Reducing Conditions			Size Statistics (Malvern Data Only)					
Initial Deformation	2121	1161				Malvern	All Data	
Spherical	2152	1178	Dv.5	Volume Mean Diam.		24.75		
Hemispherical	2172	1189	Dv.9	90 % volume diameter		50.10		
Fluid	2210	1210	Dv.1	10 percentile volume diameter		6.05		
Oxidizing Conditions			D4,3			27.35		
Initial Deformation	2154	1179	D3,2	Sauter Mean Diameter		13.50		
Spherical	2192	1200	Span			1.75		
Hemispherical	2209	1209	Specific Surface Area (m ² /cc)			0.46		
Fluid	2269	1243						

*These Malvern data are for the -325 mesh size fractions.

Table A.21 Summary of Properties of the Belle Ayr Coal.

Belle Ayr

Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	45.78	34.49	dp>600µm		+28	0.00	0.00
Volatile Matter	48.19	36.31	600µm>dp>300µm		28x48	0.50	0.50
Moisture	24.65		300µm>dp>149µm		48x100	9.25	9.75
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	24.65	34.40
C	70.27	52.94	74µm>dp>44µm		200x325	17.15	51.55
H	5.05	3.80	44µm>dp		-325	48.45	100.00
O	17.27	13.01	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	0.90	0.68	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	0.44	0.33					
Cl	0.05	0.04	188m	0.00	100.0	118.4m2	
Ash	6.04	4.55	162m	0.03	100.0	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	0.08	99.9	88.1m2	
SiO2	1.74	28.81	121m	0.05	99.9	76m2	
Al2O3	0.85	14.13	104m	0.03	99.8	65.6m2	
TiO2	0.08	1.40	89.9m	0.23	99.6	56.6m2	
Fe2O3	0.31	5.08	77.5m	1.10	98.5	48.8m2	
CaO	1.43	23.68	66.9m	2.70	95.8	42.1m2	
MgO	0.25	4.10	57.7m	4.95	90.9	38.3m2	
K2O	0.01	0.23	49.8m	7.10	83.8	31.3m2	
Na2O	0.08	1.31	42.9m	7.85	75.9	27m2	
SO3	1.13	18.78	37.1m	7.90	68.0	23.3m2	
P2O5	0.06	1.04	32m	7.03	61.0	20.1m2	
Cl			27.6m	5.90	55.1	17.4m2	
Undetermined	0.09	1.43	23.8m	5.63	49.5	15m2	
Total	6.04	100.0	20.5m	5.83	43.6	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	5.88	37.8	11.1m2	
Pyritic	0.07		15.3m	5.60	32.2	9.6m2	
Organic	0.37		13.2m	4.65	27.5	8.3m2	
Sulfatic	0.00		11.4m	4.08	23.4	7.2m2	
Fraction Free Silica	0.26		9.8m	3.63	19.8	6.2m2	
Fraction Pyritic Iron	0.28		8.5m	3.33	16.5	5.3m2	
Heating Value (Btu/lb. dry)			7.3m	3.03	13.5	4.8m2	
As Fired	12781	9630	6.3m	2.78	10.7	4m2	
Dulong	12027	9063	5.4m	2.43	8.3	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	2.08	6.2	3m2	
Na			4.1m	1.78	4.4	2.8m2	
Mg			3.5m	1.23	3.2	2.2m2	
Ca			3m	0.88	2.3	1.9m2	
K			2.6m	0.78	1.5	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.50	1.0	1.4m2	
Reducing Conditions			1.9m	1.13	-0.1	1.2m2	
Initial Deformation	1075	579	Size Statistics (Malvern Data Only)				
Spherical	1098	592				Malvern	All Data
Hemispherical	1107	597	Dv.5	Volume Mean Diam.		20.65	
Fluid	1125	607	Dv.9	90 % volume diameter		48.88	
Oxidizing Conditions			Dv.1	10 percentile volume diameter		5.20	
Initial Deformation	1070	577	D4,3			25.13	
Spherical	1098	592	D3,2	Sauter Mean Diameter		11.65	
Hemispherical	1109	598	Span			2.10	
Fluid	1126	608	Specific Surface Area (m ² /cc)			0.53	

*These Malvern data are for the -325 mesh size fractions.

Table A.22 Summary of Properties of the Wyodak Coal.

Wyodak

Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	48.27	38.74	dp>600µm		+28	0.00	0.00
Volatile Matter	45.50	36.52	600µm>dp>300µm		28x48	0.00	0.00
Moisture	19.74		300µm>dp>149µm		48x100	4.08	4.08
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	19.53	23.60
C	69.76	55.99	74µm>dp>44µm		200x325	20.38	43.98
H	4.95	3.97	44µm>dp		-325	56.03	100.00
O	17.49	14.04	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	0.97	0.77	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	0.56	0.45	188m	0.00	100.0	118.4m2	0.08
Cl	0.04	0.03	162m	0.05	100.0	102.1m2	0.13
Ash	6.18	4.96	140m	0.08	99.9	88.1m2	0.15
Ash Chemistry	% dry fuel	% ash	121m	0.13	99.8	76m2	0.10
SiO2	1.61	26.06	104m	0.13	99.6	65.6m2	0.38
Al2O3	0.86	13.96	89.9m	0.13	99.5	56.6m2	3.45
TiO2	0.08	1.29	77.5m	0.45	99.1	48.8m2	7.43
Fe2O3	0.33	5.35	66.9m	1.45	97.6	42.1m2	9.40
CaO	1.51	24.40	57.7m	3.18	94.4	38.3m2	9.35
MgO	0.26	4.28	49.8m	5.58	88.9	31.3m2	8.50
K2O	0.01	0.19	42.9m	8.18	80.7	27m2	8.20
Na2O	0.05	0.86	37.1m	9.88	70.8	23.3m2	8.10
SO3	1.29	20.82	32m	9.75	61.1	20.1m2	6.75
P2O5	0.06	0.99	27.6m	7.98	53.1	17.4m2	5.15
Cl			23.8m	6.18	46.9	15m2	4.90
Undetermined	0.11	1.80	20.5m	5.30	41.6	12.9m2	5.35
Total	6.18	100.0	17.7m	5.45	36.2	11.1m2	4.58
Forms of Sulfur (% dry fuel)			15.3m	5.68	30.5	9.6m2	3.70
Pyritic	0.12		13.2m	5.40	25.1	8.3m2	2.68
Organic	0.40		11.4m	4.45	20.6	7.2m2	2.18
Sulfatic	0.04		9.8m	3.45	17.2	6.2m2	2.13
Fraction Free Silica	0.21		8.5m	2.88	14.3	5.3m2	1.90
Fraction Pyritic Iron	0.43		7.3m	2.58	11.7	4.8m2	1.53
Heating Value (Btu/lb, dry)			6.3m	2.43	9.3	4m2	1.28
As Fired	11927	9573	5.4m	2.20	7.1	3.4m2	1.13
Dulong	11881	9536	4.7m	1.90	5.2	3m2	0.88
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	1.15	4.1	2.8m2	0.45
Na			3.5m	1.08	3.0	2.2m2	0.10
Mg			3m	0.83	2.2	1.9m2	0.00
Ca			2.6m	0.53	1.6	1.6m2	0.00
K			2.2m	0.40	1.2	1.4m2	0.00
Fusion Temp.	°F	°C	1.9m	0.53	0.7	1.2m2	0.00
Reducing Conditions			Size Statistics (Malvern Data Only)				
Initial Deformation	2161	1183				Malvern	All Data
Spherical	2214	1212	Dv.5	Volume Mean Diam.		23.10	
Hemispherical	2236	1224	Dv.9	90 % volume diameter		45.41	
Fluid	2288	1253	Dv.1	10 percentile volume diameter		6.29	
Oxidizing Conditions			D4,3			25.04	
Initial Deformation	2154	1179	D3,2	Sauter Mean Diameter		13.66	
Spherical	2204	1207	Span			1.71	
Hemispherical	2231	1222	Specific Surface Area (m ² /cc)			0.44	
Fluid	2285	1252					

*These Malvern data are for the -325 mesh size fractions.

Table A.23 Summary of Properties of the Antelope Coal.

Antelope

Analyses			Analyses					
Proximate	Dry	As Rec'd	Size Distribution	Sieves	mass % in size bin	cum. mass %		
Fixed Carbon	51.22	39.49	dp>600µm	+28	0.50	0.50		
Volatile Matter	43.27	33.36	600µm>dp>300µm	28x48	12.00	12.50		
Moisture	22.90		300µm>dp>149µm	48x100	31.40	43.90		
Ultimate	Dry	As Rec'd	149µm>dp>74µm	100x200	18.90	62.80		
C	68.38	52.72	74µm>dp>44µm	200x325	37.20	100.00		
H	4.89	3.77	44µm>dp	-325	0.00	100.00		
O	19.74	15.22	Size Distribution (Malvern)*		Size Distribution (Malvern)*			
N	1.03	0.79	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin	cum. vol. per.
S	0.42	0.32	188m			118.4m2		
Cl	0.03	0.02	162m			102.1m2		
Ash	5.51	4.25	140m			88.1m2		
Ash Chemistry	% dry fuel	% ash	121m			76m2		
SiO2	1.38	25.03	104m			65.6m2		
Al2O3	0.63	11.36	89.9m			56.6m2		
TiO2	0.04	0.66	77.5m			48.8m2		
Fe2O3	0.45	8.18	66.9m			42.1m2		
CaO	1.59	28.88	57.7m			38.3m2		
MgO	0.31	5.60	49.8m			31.3m2		
K2O	0.01	0.25	42.9m			27m2		
Na2O	0.09	1.57	37.1m			23.3m2		
SO3	0.97	17.65	32m			20.1m2		
P2O5	0.04	0.81	27.6m			17.4m2		
Cl			23.8m			15m2		
Undetermined	0.00	0.01	20.5m			12.9m2		
Total	5.51	100.0	17.7m			11.1m2		
Forms of Sulfur (% dry fuel)			15.3m			9.6m2		
Pyritic	0.02		13.2m			8.3m2		
Organic	0.40		11.4m			7.2m2		
Sulfatic	0.00		9.8m			6.2m2		
Fraction Free Silica	0.32		8.5m			5.3m2		
Fraction Pyritic Iron	0.06		7.3m			4.8m2		
Heating Value (Btu/lb, dry)			6.3m			4m2		
As Fired	12271	9461	5.4m			3.4m2		
Dulong	11465	8840	4.7m			3m2		
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m			2.8m2		
Na			3.5m			2.2m2		
Mg			3m			1.9m2		
Ca			2.6m			1.6m2		
K			2.2m			1.4m2		
Fusion Temp.	°F	°C	1.9m			1.2m2		
Reducing Conditions			Size Statistics (Malvern Data Only)					
Initial Deformation	2323	1273			Malvern	All Data		
Spherical	2355	1291	Dv.5	Volume Mean Diam.				
Hemispherical	2381	1305	Dv.9	90 % volume diameter				
Fluid	2411	1322	Dv.1	10 percentile volume diameter				
Oxidizing Conditions			D4,3					
Initial Deformation	2349	1287	D3,2	Sauter Mean Diameter				
Spherical	2369	1298	Span					
Hemispherical	2383	1306	Specific Surface Area (m ² /cc)					
Fluid	2402	1317						

*These Malvern data are for the -325 mesh size fractions.

Table A.24 Summary of Properties of the Eagle Butte Coal.

Eagle Butte							
Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	47.95	37.26	dp>600µm		+28	0.00	0.00
Volatile Matter	45.67	35.48	600µm>dp>300µm		28x48	0.27	0.27
Moisture	22.30		300µm>dp>149µm		48x100	2.70	2.97
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	17.50	20.47
C	66.89	51.97	74µm>dp>44µm		200x325	22.60	43.07
H	4.89	3.80	44µm>dp		-325	56.93	100.00
O	20.20	15.70	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	1.17	0.91	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	0.47	0.37	188m	0.00	100.0	118.4m2	
Cl	0.03	0.02	162m	0.00	100.0	102.1m2	
Ash	6.37	4.95	140m	0.02	100.0	88.1m2	
Ash Chemistry	% dry fuel	% ash	121m	0.03	100.0	76m2	
SiO2	1.78	28.00	104m	0.03	99.9	65.6m2	
Al2O3	0.90	14.16	89.9m	0.08	99.8	56.6m2	
TiO2	0.05	0.83	77.5m	0.27	99.6	48.8m2	
Fe2O3	0.39	6.09	66.9m	0.88	98.7	42.1m2	
CaO	1.60	25.09	57.7m	1.87	96.8	38.3m2	
MgO	0.38	5.95	49.8m	3.78	93.0	31.3m2	
K2O	0.02	0.26	42.9m	6.80	86.2	27m2	
Na2O	0.12	1.84	37.1m	9.47	76.8	23.3m2	
SO3	1.04	16.38	32m	10.13	66.6	20.1m2	
P2O5	0.04	0.67	27.6m	8.87	57.8	17.4m2	
Cl			23.8m	7.38	50.4	15m2	
Undetermined	0.05	0.73	20.5m	6.47	43.9	12.9m2	
Total	6.37	100.0	17.7m	6.32	37.6	11.1m2	
Forms of Sulfur (% dry fuel)			15.3m	6.32	31.3	9.6m2	
Pyritic	0.06		13.2m	5.75	25.5	8.3m2	
Organic	0.40		11.4m	4.82	20.7	7.2m2	
Sulfatic	0.01		9.8m	3.75	17.0	6.2m2	
Fraction Free Silica	0.24		8.5m	3.03	13.9	5.3m2	
Fraction Pyritic Iron	0.19		7.3m	2.68	11.3	4.8m2	
Heating Value (Btu/lb, dry)			6.3m	2.48	8.8	4m2	
As Fired	11516	8947	5.4m	2.25	6.5	3.4m2	
Dulong	11211	8711	4.7m	1.88	4.6	3m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	1.30	3.3	2.8m2	
Na	822	822	3.5m	1.00	2.3	2.2m2	
Mg	1891	1891	3m	0.70	1.6	1.9m2	
Ca	7250	7250	2.6m	0.48	1.2	1.6m2	
K	75	75	2.2m	0.32	0.8	1.4m2	
Fusion Temp.	°F	°C	1.9m	0.27	0.6	1.2m2	
Reducing Conditions			Size Statistics (Malvern Data Only)				
Initial Deformation	2223	1217			Malvern	All Data	
Spherical	2254	1234	Dv.5	Volume Mean Diam.	21.37		
Hemispherical	2261	1239	Dv.9	90 % volume diameter	42.02		
Fluid	2273	1245	Dv.1	10 percentile volume diameter	6.20		
Oxidizing Conditions			D4,3		23.20		
Initial Deformation	2184	1196	D3,2	Sauter Mean Diameter	12.98		
Spherical	2214	1212	Span		1.68		
Hemispherical	2229	1221	Specific Surface Area (m ² /cc)		0.47		
Fluid	2249	1231					

*These Malvern data are for the -325 mesh size fractions.

Table A.25 Summary of Properties of the Beulah Lignite.

Beulah

Analyses			Analyses			Analyses		
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin		cum. mass %
Fixed Carbon	43.44	32.96	dp>600µm		+28	0.06		0.06
Volatile Matter	42.95	32.59	600µm>dp>300µm		28x48	2.88		2.94
Moisture	24.13		300µm>dp>149µm		48x100	12.81		15.75
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	22.60		38.35
C	60.97	46.26	74µm>dp>44µm		200x325	17.20		55.55
H	4.07	3.09	44µm>dp		-325	45.29		100.84
O	18.50	14.04	Size Distribution (Malvern)*			Size Distribution (Malvern)*		
N	1.02	0.77	Diameter % in		cum. vol.	Diameter		% in
S	1.81	1.38	(µm)	size bin	per.	(µm)	size bin	per.
Cl	0.04	0.03	188m	0.18	99.8	118.4m2	0.08	99.9
Ash	13.69	10.39	162m	0.49	99.3	102.1m2	0.14	99.9
Ash Chemistry	% dry fuel	% ash	140m	0.72	98.6	88.1m2	0.14	99.9
SiO2	2.87	20.93	121m	0.92	97.7	76m2	0.10	99.9
Al2O3	1.89	13.78	104m	0.98	96.7	65.6m2	0.00	100.0
TiO2	0.06	0.41	89.9m	1.20	95.5	56.6m2	1.62	98.4
Fe2O3	1.65	12.08	77.5m	1.53	94.0	48.8m2	4.78	95.2
CaO	2.21	16.13	66.9m	1.92	92.1	42.1m2	6.62	93.4
MgO	0.60	4.40	57.7m	2.69	89.4	38.3m2	7.14	92.9
K2O	0.03	0.22	49.8m	4.01	85.4	31.3m2	7.04	93.0
Na2O	0.88	6.41	42.9m	5.41	79.9	27m2	7.14	92.9
SO3	3.32	24.27	37.1m	6.32	73.6	23.3m2	7.30	92.7
P2O5	0.00	0.00	32m	6.37	67.3	20.1m2	6.40	93.6
Cl			27.6m	5.98	61.3	17.4m2	5.42	94.6
Undetermined	0.19	1.38	23.8m	5.70	55.6	15m2	5.60	94.4
Total	13.69	100.0	20.5m	5.48	50.1	12.9m2	6.12	93.9
Forms of Sulfur (% dry fuel)			17.7m	5.33	44.8	11.1m2	5.34	94.7
Pyritic	0.47		15.3m	5.29	39.5	9.6m2	4.64	95.4
Organic	1.18		13.2m	4.99	34.5	8.3m2	3.90	96.1
Sulfatic	0.16		11.4m	4.64	29.8	7.2m2	3.68	96.3
Fraction Free Silica	0.10		9.8m	4.12	25.7	6.2m2	3.64	96.4
Fraction Pyritic Iron	0.37		8.5m	3.67	22.1	5.3m2	3.10	96.9
Heating Value (Btu/lb, dry)			7.3m	3.38	18.7	4.8m2	2.40	97.6
As Fired	10040	7617	6.3m	3.31	15.4	4m2	2.14	97.9
Dulong	10003	7590	5.4m	3.18	12.2	3.4m2	2.22	97.8
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	2.90	9.3	3m2	2.06	97.9
Na	7357	7357	4.1m	2.47	6.8	2.8m2	0.74	99.3
Mg	3321	3321	3.5m	1.82	5.0	2.2m2	0.42	99.6
Ca	14036	14036	3m	1.33	3.7	1.9m2	0.00	100.0
K	152	152	2.6m	1.11	2.6	1.6m2	0.04	100.0
Fusion Temp.	°F	°C	2.2m	0.91	1.6	1.4m2	0.00	100.0
Reducing Conditions			1.9m	1.79	-0.1	1.2m2	0.00	100.0
Initial Deformation	2026	1108	Size Statistics (Malvern Data Only)					
Spherical	2149	1176				Malvern		All Data
Hemispherical	2175	1190	Dv.5	Volume Mean Diam.		18.46		
Fluid	2191	1199	Dv.9	90 % volume diameter		49.66		
Oxidizing Conditions			Dv.1	10 percentile volume diameter		4.44		
Initial Deformation	2290	1255	D4,3			23.49		
Spherical	2359	1293	D3,2	Sauter Mean Diameter		10.24		
Hemispherical	2365	1296	Span			2.35		
Fluid	2388	1309	Specific Surface Area (m³/cc)			0.62		

*These Malvern data are for the -325 mesh size fractions.

Table A.26 Summary of Properties of the Texas (San Miguel) Lignite.

Texas (San Miguel)							
Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	
Fixed Carbon	17.51	14.27	dp>600µm		+28	0.00	
Volatile Matter	30.41	24.78	600µm>dp>300µm		28x48	2.40	
Moisture	18.50		300µm>dp>149µm		48x100	9.83	
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	18.28	
C	29.43	23.99	74µm>dp>44µm		200x325	17.23	
H	3.20	2.61	44µm>dp		-325	52.28	
O	12.95	10.55	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	0.51	0.41	Diameter % in		cum. vol.	Diameter	% in
S	1.75	1.43	(µm)	size bin	per.	(µm)	size bin
Cl	0.08	0.06	188m		0.00	100.0	118.4m2
Ash	52.18	42.53	162m		0.00	100.0	102.1m2
Ash Chemistry	% dry fuel	% ash	140m		0.00	100.0	88.1m2
SiO2	34.36	65.85	121m		0.00	100.0	76m2
Al2O3	10.13	19.41	104m		0.00	100.0	65.6m2
TiO2	0.45	0.87	89.9m		0.08	99.9	56.6m2
Fe2O3	0.87	1.66	77.5m		0.13	99.8	48.8m2
CaO	1.56	2.99	66.9m		0.15	99.6	42.1m2
MgO	0.25	0.48	57.7m		0.22	99.4	38.3m2
K2O	0.98	1.88	49.8m		1.02	98.4	31.3m2
Na2O	1.35	2.60	42.9m		2.78	95.6	27m2
SO3	1.47	2.82	37.1m		4.85	90.8	23.3m2
P2O5	0.00	0.01	32m		6.48	84.3	20.1m2
Cl	0.01	0.02	27.6m		6.97	77.3	17.4m2
Undetermined	0.74	1.42	23.8m		6.90	70.4	15m2
Total	52.17	100.0	20.5m		6.68	63.7	12.9m2
Forms of Sulfur (% dry fuel)			17.7m		6.70	57.0	11.1m2
Pyritic	0.29		15.3m		6.73	50.3	9.6m2
Organic	1.35		13.2m		6.45	43.8	8.3m2
Sulfatic	0.10		11.4m		5.95	37.9	7.2m2
Fraction Free Silica	0.56		9.8m		5.12	32.8	6.2m2
Fraction Pyritic Iron	0.41		8.5m		4.45	28.3	5.3m2
Heating Value (Btu/lb, dry)			7.3m		4.05	24.3	4.8m2
As Fired	5076	4137	6.3m		3.95	20.3	4m2
Dulong	5334	4347	5.4m		3.78	16.5	3.4m2
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m		3.42	13.1	3m2
Na	8788	8788	4.1m		2.88	10.2	2.8m2
Mg	1156	1156	3.5m		2.13	8.1	2.2m2
Ca	7628	7628	3m		1.58	6.5	1.9m2
K	5862	5862	2.6m		1.37	5.2	1.6m2
Fusion Temp.	°F	°C	2.2m		1.30	3.9	1.4m2
Reducing Conditions			1.9m		2.33	1.5	1.2m2
Initial Deformation	2349	1287	Size Statistics (Malvern Data Only)				
Spherical	2458	1348	Dv.5		Volume Mean Diam.	14.76	Malvern
Hemispherical	2580	1416	Dv.9		90 % volume diameter	34.26	All Data
Fluid	2759	1515	Dv.1		10 percentile volume diameter	3.89	
Oxidizing Conditions			D4,3			17.45	
Initial Deformation	2338	1281	D3,2		Sauter Mean Diameter	8.39	
Spherical	2433	1334	Span			2.06	
Hemispherical	2576	1413	Specific Surface Area (m ² /cc)			0.76	
Fluid	2762	1517					

*These Malvern data are for the -325 mesh size fractions.

Table A.27 Summary of Properties of the Eastern Blend.

Eastern Blend

Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	61.06	60.62	dp>600µm		+28	0.00	0.00
Volatile Matter	30.27	30.05	600µm>dp>300µm		28x48	0.00	0.00
Moisture	0.72		300µm>dp>149µm		48x100	1.30	1.30
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	26.30	27.60
C	77.95	77.39	74µm>dp>44µm		200x325	26.30	53.90
H	4.79	4.76	44µm>dp		-325	46.10	100.00
O	5.51	5.47	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	1.43	1.42	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	1.65	1.64					
Cl			188m			118.4m2	
Ash	8.67	8.61	162m			102.1m2	
Ash Chemistry	% dry fuel	% ash	140m			88.1m2	
SiO2	4.25	49.03	121m			76m2	
Al2O3	2.13	24.53	104m			65.6m2	
TiO2	0.09	1.00	89.9m			56.6m2	
Fe2O3	1.48	17.03	77.5m			48.8m2	
CaO	0.20	2.31	66.9m			42.1m2	
MgO	0.07	0.86	57.7m			38.3m2	
K2O	0.17	1.99	49.8m			31.3m2	
Na2O	0.03	0.36	42.9m			27m2	
SO3	0.17	1.92	37.1m			23.3m2	
P2O5	0.03	0.37	32m			20.1m2	
Cl			27.6m			17.4m2	
Undetermined	0.05	0.60	23.8m			15m2	
Total	8.67	100.0	20.5m			12.9m2	
Forms of Sulfur (% dry fuel)			17.7m			11.1m2	
Pyritic	0.89		15.3m			9.6m2	
Organic	0.75		13.2m			8.3m2	
Sulfatic	0.01		11.4m			7.2m2	
Fraction Free Silica	0.25		9.8m			6.2m2	
Fraction Pyritic Iron	0.75		8.5m			5.3m2	
Heating Value (Btu/lb, dry)			7.3m			4.8m2	
As Fired	13933	13833	6.3m			4m2	
Dulong			5.4m			3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m			3m2	
Na			4.1m			2.8m2	
Mg			3.5m			2.2m2	
Ca			3m			1.9m2	
K			2.6m			1.6m2	
Fusion Temp.	°F	°C	2.2m			1.4m2	
Reducing Conditions			1.9m			1.2m2	
Initial Deformation	2133	1167	Size Statistics (Malvern Data Only)				
Spherical	2429	1332			Malvern	All Data	
Hemispherical	2449	1343	Dv.5	Volume Mean Diam.			
Fluid	2500	1371	Dv.9	90 % volume diameter			
Oxidizing Conditions			Dv.1	10 percentile volume diameter			
Initial Deformation	2497	1369	D4.3				
Spherical	2574	1412	D3,2	Sauter Mean Diameter			
Hemispherical	2602	1428	Span				
Fluid	2632	1444	Specific Surface Area (m ² /cc)				

*These Malvern data are for the -325 mesh size fractions.

Table A.28 Summary of Properties of the Pittsburgh #8 - Decker Blend.

Pittsburgh #8-Decker Blend

Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	53.05	49.44	dp>600µm		+28	0.00	0.00
Volatile Matter	41.23	38.42	600µm>dp>300µm		28x48	0.03	0.03
Moisture	6.81		300µm>dp>149µm		48x100	2.83	2.87
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	25.53	28.40
C	72.94	67.98	74µm>dp>44µm		200x325	26.90	55.30
H	5.34	4.98	44µm>dp		-325	44.73	100.03
O	13.11	12.22	Size Distribution (Malvern)*		Size Distribution (Malvern)*		
N	1.28	1.19	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	1.04	0.97	188m	1.83	98.2	118.4m2	
Cl	0.07	0.06	162m	4.39	93.8	102.1m2	
Ash	6.26	5.84	140m	5.51	88.3	88.1m2	
Ash Chemistry	% dry fuel	% ash	121m	5.36	82.9	76m2	
SiO2	2.42	38.68	104m	3.92	79.0	65.6m2	
Al2O3	1.29	20.56	89.9m	2.77	76.2	56.6m2	
TiO2	0.06	1.03	77.5m	3.74	72.5	48.8m2	
Fe2O3	0.73	11.71	66.9m	4.46	68.1	42.1m2	
CaO	0.48	7.67	57.7m	4.80	63.3	38.3m2	
MgO	0.11	1.68	49.8m	5.54	57.7	31.3m2	
K2O	0.07	1.18	42.9m	6.08	51.6	27m2	
Na2O	0.21	3.38	37.1m	7.15	44.5	23.3m2	
SO3	0.65	10.39	32m	6.53	38.0	20.1m2	
P2O5	0.04	0.70	27.6m	5.22	32.7	17.4m2	
Cl			23.8m	4.18	28.6	15m2	
Undetermined	0.04	0.62	20.5m	3.63	24.9	12.9m2	
Total	6.11	97.6	17.7m	3.50	21.4	11.1m2	
Forms of Sulfur (% dry fuel)			15.3m	3.51	17.9	9.6m2	
Pyritic	0.41		13.2m	3.24	14.7	8.3m2	
Organic	0.61		11.4m	2.72	12.0	7.2m2	
Sulfatic	0.08		9.8m	2.09	9.9	6.2m2	
Fraction Free Silica	0.20		8.5m	1.65	8.3	5.3m2	
Fraction Pyritic Iron	0.68		7.3m	1.46	6.8	4.8m2	
Heating Value (Btu/lb, dry)			6.3m	1.40	5.4	4m2	
As Fired	13357	12448	5.4m	1.34	4.1	3.4m2	
Dulong	12948	12066	4.7m	1.21	2.9	3m2	
Acid Sol. Alkali (ppm)			4.1m	0.86	2.0	2.8m2	
Na			3.5m	0.67	1.3	2.2m2	
Mg			3m	0.69	0.6	1.9m2	
Ca			2.6m	0.34	0.3	1.6m2	
K			2.2m	0.29	0.0	1.4m2	
Fusion Temp.			1.9m	0.54	-0.5	1.2m2	
Reducing Conditions			Size Statistics (Malvern Data Only)				
Initial Deformation	2139	1171				Malvern	All Data
Spherical	2201	1205	Dv.5	Volume Mean Diam.		53.26	
Hemispherical	2243	1228	Dv.9	90 % volume diameter		80.51	
Fluid	2342	1283	Dv.1	10 percentile volume diameter		24.72	
Oxidizing Conditions			D4,3			51.78	
Initial Deformation	2319	1271	D3,2	Sauter Mean Diameter		24.84	
Spherical	2338	1281	Span			1.31	
Hemispherical	2388	1309	Specific Surface Area (m ² /cc)			0.33	
Fluid	2443	1339					

*These Malvern data are for the -325 mesh size fractions.

Table A.29 Summary of Properties of the NIPSCO Blend (1).

NIPSCO Blend (1)

Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	48.70	44.13	dp>600µm		+28	0.00	0.00
Volatile Matter	43.51	39.43	600µm>dp>300µm		28x48	0.53	0.53
Moisture	9.38		300µm>dp>149µm		48x100	8.60	9.13
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	28.87	38.00
C	70.31	63.71	74µm>dp>44µm		200x325	19.67	57.67
H	5.39	4.89	44µm>dp		-325	42.33	100.00
O	14.74	13.35	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	1.22	1.10	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	0.53	0.48					
Cl	0.06	0.05	188m	1.56	98.4	118.4m2	
Ash	7.80	7.06	162m	3.84	94.6	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	5.22	89.4	88.1m2	
SiO2	3.27	41.91	121m	5.92	83.5	76m2	
Al2O3	1.68	21.54	104m	5.40	78.1	65.6m2	
TiO2	0.10	1.32	89.9m	5.44	72.6	56.6m2	
Fe2O3	0.37	4.79	77.5m	5.25	67.4	48.8m2	
CaO	1.17	15.00	66.9m	5.10	62.3	42.1m2	
MgO	0.20	2.61	57.7m	4.90	57.4	38.3m2	
K2O	0.09	1.17	49.8m	5.80	51.6	31.3m2	
Na2O	0.08	0.97	42.9m	6.16	45.4	27m2	
SO3	1.11	14.18	37.1m	6.47	38.9	23.3m2	
P2O5	0.05	0.69	32m	5.89	33.0	20.1m2	
Cl			27.6m	4.49	28.5	17.4m2	
Undetermined	0.11	1.36	23.8m	3.58	25.0	15m2	
Total	8.23	105.5	20.5m	3.54	21.4	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	3.23	18.2	11.1m2	
Pyritic	0.07		15.3m	3.00	15.2	9.6m2	
Organic	0.49		13.2m	2.55	12.6	8.3m2	
Sulfatic	0.00		11.4m	2.03	10.6	7.2m2	
Fraction Free Silica	0.23		9.8m	1.60	9.0	6.2m2	
Fraction Pyritic Iron	0.23		8.5m	1.39	7.6	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	1.26	6.4	4.8m2	
As Fired	12979	11761	6.3m	1.22	5.1	4m2	
Dulong	12451	11282	5.4m	1.15	4.0	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.00	3.0	3m2	
Na			4.1m	0.76	2.2	2.8m2	
Mg			3.5m	0.60	1.6	2.2m2	
Ca			3m	0.44	1.2	1.9m2	
K			2.6m	0.32	0.9	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.30	0.6	1.4m2	
Reducing Conditions			1.9m	0.55	0.0	1.2m2	
Initial Deformation	1513	823	Size Statistics (Malvern Data Only)				
Spherical	1549	843				Malvern	All Data
Hemispherical	1610	877	Dv.5	Volume Mean Diam.		143.33	
Fluid	1673	912	Dv.9	90 % volume diameter		84.47	
Oxidizing Conditions			Dv.1	10 percentile volume diameter		21.74	
Initial Deformation	1554	846	D4,3			54.68	
Spherical	1579	860	D3,2	Sauter Mean Diameter		26.56	
Hemispherical	1629	887	Span			1.30	
Fluid	1688	920	Specific Surface Area (m ² /cc)			0.30	

*These Malvern data are for the -325 mesh size fractions.

Table A.30 Summary of Properties of the NIPSCO Blend (2).

Analyses			Analyses			
Proximate	Dry	As Rec'd	Size Distribution	Sieves	mass % in size bin	cum. mass %
Fixed Carbon	49.69	42.64	dp>600µm	+28	0.00	0.00
Volatile Matter	42.61	36.57	600µm>dp>300µm	28x48	0.35	0.35
Moisture	14.17		300µm>dp>149µm	48x100	7.65	8.00
Ultimate	Dry	As Rec'd	149µm>dp>74µm	100x200	21.90	29.90
C	73.93	63.45	74µm>dp>44µm	200x325	19.85	49.75
H	4.96	4.25	44µm>dp	-325	50.25	100.00
O	11.70	10.04	Size Distribution (Malvern)*		Size Distribution (Malvern)*	
N	1.06	0.91	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)
S	0.59	0.51	188m	0.00	100.0	118.4m2
Cl	0.08	0.06	162m	0.00	100.0	102.1m2
Ash	7.71	6.61	140m	0.00	100.0	88.1m2
Ash Chemistry	% dry fuel	% ash	121m	0.03	100.0	76m2
SiO2	2.99	38.84	104m	0.00	100.0	65.6m2
Al2O3	1.63	21.22	89.9m	0.05	99.9	56.6m2
TiO2	0.10	1.27	77.5m	0.50	99.4	48.8m2
Fe2O3	0.40	5.17	66.9m	2.10	97.3	42.1m2
CaO	0.93	12.13	57.7m	4.90	92.4	38.3m2
MgO	0.19	2.53	49.8m	7.58	84.9	31.3m2
K2O	0.10	1.35	42.9m	8.45	76.4	27m2
Na2O	0.07	0.96	37.1m	8.33	68.1	23.3m2
SO3	1.15	14.91	32m	7.40	60.7	20.1m2
P2O5	0.06	0.76	27.6m	6.30	54.4	17.4m2
Cl			23.8m	5.75	48.6	15m2
Undetermined	0.07	0.87	20.5m	5.60	43.0	12.9m2
Total	7.71	100.0	17.7m	5.73	37.3	11.1m2
Forms of Sulfur (% dry fuel)			15.3m	5.50	31.8	9.6m2
Pyritic	0.07		13.2m	4.55	27.2	8.3m2
Organic	0.53		11.4m	3.83	23.4	7.2m2
Sulfatic	0.00		9.8m	3.35	20.1	6.2m2
Fraction Free Silica	0.18		8.5m	3.08	17.0	5.3m2
Fraction Pyritic Iron	0.20		7.3m	2.90	14.1	4.8m2
Heating Value (Btu/lb, dry)			6.3m	2.73	11.4	4m2
As Fired	13821	11863	5.4m	2.43	8.9	3.4m2
Dulong	12942	11108	4.7m	2.08	6.9	3m2
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	1.63	5.2	2.8m2
Na			3.5m	1.23	4.0	2.2m2
Mg			3m	0.93	3.1	1.9m2
Ca			2.6m	0.83	2.3	1.6m2
K			2.2m	0.68	1.6	1.4m2
Fusion Temp.	°F	°C	1.9m	1.58	0.0	1.2m2
Reducing Conditions			Size Statistics (Malvern Data Only)			
Initial Deformation	1147	619			Malvern	All Data
Spherical	1174	634	Dv.5	Volume Mean Diam.	21.45	
Hemispherical	1207	653	Dv.9	90 % volume diameter	47.13	
Fluid	1241	672	Dv.1	10 percentile volume diameter	5.05	
Oxidizing Conditions			D4,3		24.28	
Initial Deformation	1180	638	D3,2	Sauter Mean Diameter	11.30	
Spherical	1194	645	Span		1.95	
Hemispherical	1225	663	Specific Surface Area (m ² /cc)		0.56	
Fluid	1257	680				

*These Malvern data are for the -325 mesh size fractions.

Table A.31 Summary of Properties of the Roland-Illinois #6 Blend.

Roland/Illinois #6 (2) Blend

Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
Fixed Carbon	46.43	43.36	dp>600µm		+28	0.00	0.00
Volatile Matter	44.25	41.33	600µm>dp>300µm		28x48	0.27	0.27
Moisture	6.60		300µm>dp>149µm		48x100	1.77	2.03
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	30.10	32.13
C	68.58	64.06	74µm>dp>44µm		200x325	28.70	60.83
H	4.73	4.42	44µm>dp		-325	39.17	100.00
O	14.70	13.73	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	1.09	1.02	Diameter % in		cum. vol.	Diameter	% in
S	1.56	1.46	(µm)	size bin	per.	(µm)	size bin
Cl	0.03	0.03	188m	1.93	98.1	118.4m2	
Ash	9.29	8.67	162m	4.75	93.3	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	6.18	87.2	88.1m2	
SiO2	3.54	38.12	121m	6.74	80.4	76m2	
Al2O3	1.49	16.04	104m	6.16	74.3	65.6m2	
TiO2	0.09	0.95	89.9m	5.16	69.1	56.6m2	
Fe2O3	1.12	12.01	77.5m	4.68	64.4	48.8m2	
CaO	1.07	11.49	66.9m	5.14	59.3	42.1m2	
MgO	0.27	2.94	57.7m	5.49	53.8	38.3m2	
K2O	0.11	1.16	49.8m	6.56	47.2	31.3m2	
Na2O	0.13	1.35	42.9m	6.57	40.7	27m2	
SO3	1.48	15.96	37.1m	6.14	34.5	23.3m2	
P2O5	0.06	0.64	32m	5.03	29.5	20.1m2	
Cl			27.6m	3.56	25.9	17.4m2	
Undetermined	-0.06	-0.65	23.8m	2.86	23.1	15m2	
Total	9.29	100.0	20.5m	2.83	20.2	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	2.83	17.4	11.1m2	
Pyritic	0.58		15.3m	2.63	14.8	9.6m2	
Organic	0.86		13.2m	2.18	12.6	8.3m2	
Sulfatic	0.06		11.4m	1.75	10.9	7.2m2	
Fraction Free Silica	0.36		9.8m	1.46	9.4	6.2m2	
Fraction Pyritic Iron	0.70		8.5m	1.37	8.0	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	1.33	6.7	4.8m2	
As Fired	12752	11911	6.3m	1.31	5.4	4m2	
Dulong	11835	11054	5.4m	1.23	4.2	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.07	3.1	3m2	
Na			4.1m	0.80	2.3	2.8m2	
Mg			3.5m	0.68	1.6	2.2m2	
Ca			3m	0.50	1.1	1.9m2	
K			2.6m	0.40	0.7	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.34	0.4	1.4m2	
Reducing Conditions			1.9m	0.53	-0.1	1.2m2	
Initial Deformation	2044	1118	Size Statistics (Malvern Data Only)				
Spherical	2119	1160				Malvern	All Data
Hemispherical	2195	1202	Dv.5	Volume Mean Diam.		60.03	
Fluid	2300	1260	Dv.9	90 % volume diameter		88.28	
Oxidizing Conditions			Dv.1	10 percentile volume diameter		26.59	
Initial Deformation	2181	1194	D4,3			58.48	
Spherical	2208	1209	D3,2	Sauter Mean Diameter		29.87	
Hemispherical	2286	1252	Span			1.26	
Fluid	2378	1304	Specific Surface Area (m ² /cc)			0.30	

*These Malvern data are for the -325 mesh size fractions.

Table A.32 Summary of Properties of the Eagle Butte - Kentucky #9 Blend.

Eagle Butte/Kentucky #9 Blend									
Analyses			Analyses						
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %		
Fixed Carbon	46.53	37.12	dp>600µm		+28	0.00	0.00		
Volatile Matter	43.90	35.02	600µm>dp>300µm		28x48	0.00	0.00		
Moisture	20.23		300µm>dp>149µm		48x100	8.00	8.00		
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	21.50	29.50		
C	68.32	54.50	74µm>dp>44µm		200x325	18.60	48.10		
H	4.76	3.80	44µm>dp		-325	51.90	100.00		
O	14.50	11.57	Size Distribution (Malvern)*						
N	1.11	0.89	Diameter (µm)		% in size bin	cum. vol. per.	Diameter (µm)	% in size bin	cum. vol. per.
S	1.74	1.39	188m	0.00	100.0	118.4m2			
Cl	0.00	0.00	162m	0.00	100.0	102.1m2			
Ash	8.91	7.11	140m	0.05	100.0	88.1m2			
Ash Chemistry	% dry fuel	% ash	121m	0.05	99.9	76m2			
SiO2	2.63	29.55	104m	0.05	99.9	65.6m2			
Al2O3	1.29	14.44	89.9m	0.05	99.8	56.6m2			
TiO2	0.09	1.01	77.5m	0.15	99.7	48.8m2			
Fe2O3	1.21	13.57	66.9m	1.15	98.5	42.1m2			
CaO	1.31	14.70	57.7m	3.10	95.4	38.3m2			
MgO	0.32	3.54	49.8m	6.10	89.3	31.3m2			
K2O	0.10	1.12	42.9m	8.80	80.5	27m2			
Na2O	0.11	1.27	37.1m	9.25	71.3	23.3m2			
SO3	1.84	20.67	32m	8.60	62.7	20.1m2			
P2O5	0.02	0.28	27.6m	7.15	55.5	17.4m2			
Cl			23.8m	5.70	49.8	15m2			
Undetermined	0.01	0.08	20.5m	5.50	44.3	12.9m2			
Total	8.93	100.2	17.7m	5.85	38.5	11.1m2			
Forms of Sulfur (% dry fuel)			15.3m	5.70	32.8	9.6m2			
Pyritic	0.55		13.2m	5.20	27.6	8.3m2			
Organic	0.88		11.4m	4.25	23.3	7.2m2			
Sulfatic	0.31		9.8m	3.60	19.7	6.2m2			
Fraction Free Silica	0.26		8.5m	3.25	16.5	5.3m2			
Fraction Pyritic Iron	0.49		7.3m	2.95	13.5	4.8m2			
Heating Value (Btu/lb, dry)			6.3m	2.70	10.8	4m2			
As Fired	11876	9473	5.4m	2.40	8.4	3.4m2			
Dulong	11835	9441	4.7m	2.10	6.3	3m2			
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	1.90	4.4	2.8m2			
Na			3.5m	1.30	3.1	2.2m2			
Mg			3m	1.10	2.0	1.9m2			
Ca			2.6m	0.70	1.3	1.6m2			
K			2.2m	0.45	0.9	1.4m2			
Fusion Temp.	°F	°C	1.9m	0.30	0.6	1.2m2			
Reducing Conditions			Size Statistics (Malvern Data Only)						
Initial Deformation	1999	1093				Malvern	All Data		
Spherical	2106	1152	Dv.5	Volume Mean Diam.		23.90			
Hemispherical	2142	1172	Dv.9	90 % volume diameter		50.60			
Fluid	2233	1223	Dv.1	10 percentile volume diameter		6.00			
Oxidizing Conditions			D4,3			27.15			
Initial Deformation	2188	1198	D3,2	Sauter Mean Diameter		13.45			
Spherical	2212	1211	Span			1.85			
Hemispherical	2239	1226	Specific Surface Area (m ² /cc)			0.45			
Fluid	2320	1271							

*These Malvern data are for the -325 mesh size fractions.

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