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Release of Inorganic Material During Coal Devolatilization

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Release of Inorganic Material During Coal Devolatilization

Milestone Report

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Abstract

Experimental results presented in this paper indicate that coal devolatilization products convectively remove a fraction of the nonvolatile components of inorganic material atomically dispersed in the coal matrix. Results from three facilities burning six different coals illustrate this mechanism of ash transformation and release from coal particles. Titanium is chosen to illustrate this type of mass release from coal particles on the basis of its low volatility and mode of occurrence in the coal. During moderate rates of devolatilization (10^4 K/s heating rate), no significant loss of titanium is noted. At more rapid rates of heating/devolatilization (10^5 K/s) a consistent but minor (3-4 %) loss of titanium is noted. During rapid devolatilization (5×10^5 K/s and higher), significant (10-20 %) amounts of titanium leave the coal. The loss of titanium monitored in coals ranging in rank from subbituminous to high-volatile bituminous coals and under conditions typical of pulverized-coal combustion. The amount of titanium lost during devolatilization exhibits a complex rank dependence. These results imply that other atomically dispersed material (alkali and alkaline earth elements) may undergo similar mechanisms of transformation and release.

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Introduction

Among the issues determining the design, operation, and efficiency of past and present coal conversion technologies, the behavior of mineral matter plays a significant, some say dominant, role [Raask, 1985]. Development of new coal conversion technology will undoubtedly benefit greatly from an improved understanding of this issue. Recent literature documents progress toward this goal [Barta, et al., 1991; Baxter and DeSollar, 1993 (in press); Borio and Levasseur, 1991; Brekke, et al., 1991; Srinivasachar, et al., 1990; Srinivasachar, et al., 1992]. While experimental and theoretical approaches differ, these investigations reach the consensus that a general understanding of inorganic behavior requires consideration of the mineralogy and modes of occurrence of the coal inorganic material in addition to its elemental composition. This is in contrast to 'indices' of coal behavior that rely on algebraic relationships between elemental descriptions of the coal inorganic material. Also, the transformations of this inorganic material during combustion are as important in determining the fate of the material as is the elemental composition. Unlike the elemental composition, these transformations depend on the temperature and composition of the gases through which the particle passes.

Granular minerals dominate the inorganic material of most bituminous and many subbituminous coals and lignites. Inorganic material atomically dispersed in the coal matrix or dissolved in pore water occurs in increasing amounts in U.S. coals with decreasing coal rank. We refer to both types of material as inorganic matter in this discussion. The term *mineral matter* refers to actual minerals that are granular but may or may not be crystalline. The term *ash* refers to the product of the inorganic material after combustion and applies to both entrained particles (fly ash) and ash deposits. Inorganic matter within a coal particle has one of two fates. It either contributes to the formation of a residual fly ash particle or leaves the original coal particle in the form of a gas or a condensed phase.

The two mechanisms by which inorganic material leaves a particle most commonly indicated in the literature are fragmentation and vaporization [Desrosiers, et al., 1978; Flagan, 1978; Helble, et al., 1986; Kang, et al., 1988; Linak and Peterson, 1986; Markowski, et al., 1980; Neville, et al., 1980; Neville and Sarofim, 1985; Ramsden, 1969; Sarofim, et al., 1977; Schafer, 1979a; Schafer, 1979b; Schulz, et al., 1975; Taylor and Flagan, 1982]. In this context, fragmentation includes shedding of surface particles during combustion, collapse of char structures into several individual pieces, and physical fracturing of individual inorganic mineral grains resulting in formation of separate fly ash particles. Vaporization, in this context, refers to the formation of a near-equilibrium gas partial pressure of a species over its condensed phase and the subsequent transport of this species into the bulk gas stream. Other investigators have documented the loss of nonvolatile materials, including titanium, from coal during rapid heating (10^5 - 10^6 K/s) high temperature (2000-2800 K) devolatilization experiments. These experiments combined relatively inert particles with pulverized coal particles and based mass balances on the concentration of inert particles in the sampled solids [Gat, et al., 1984]. The extent to which material was released from the particles discussed in this paper increased monotonically with increasing particle burnout. All inorganic material inherent in the coal was released to a measurable extent.

Recent experiments indicate an additional mechanism for the release of material from pyrite and other reactive inorganic grains [Baxter and Mitchell, 1992]. These experiments, coupled with observations of inorganic grain fragmentation during particle heating and reaction [Baxter, 1990], indicate that under some conditions the granular inorganic material may contribute more significantly to the small portion of the particle size distributions than previously recognized.

The results reported below indicate that another additional mechanism of mass release from coal during combustion primarily involved with the atomically dispersed or very fine-grained inorganic material complements those discussed above. The mechanism involves the convective transport and removal of atomically dispersed or fine-grained inorganic material during coal devolatilization. In the discussion below, analyses of nonvolatile, atomically dispersed or fine-grained material (titanium) inherent in the coal illustrate this mechanism and its dependence on coal type and rate of devolatilization.

Fuel Characteristics, Equipment, and Procedures

The suite of size-classified coals used in these experiments is indicated in rank order in Table 1, together with several selected properties. Several different size ranges were used in the experiments with the size-classified coals. More detailed information on the sizes used and the properties of specific size ranges is presented later. Similar information on the suite of utility-grind coals is indicated in Table 2. Note that both suites range in rank from lignite to lv bituminous and include representatives from a wide variety of geographical locations. All are U.S. coals and several are beneficiated. There are also several blends among the coals considered. All of these coals were examined in this work. Detailed data from a few are used to illustrate the major points of the discussion, whereas the remainder of the data are presented in summary form. Additional details on the properties of several of these coals are provided in the detailed discussion of results.

The rate of devolatilization of coal particles is of particular interest in this work. The rate of devolatilization is controlled by particle heating rate, which is in turn controlled by gas temperature, reactor environment, and particle size. Reactor conditions are described shortly. Figure 1 illustrates typical measured size distributions for the utility-grind coals used in this work. More detailed size and physical property information for the utility-grind coals is found in Appendix A. Each of the coals is nominally 70 % through 200 mesh, with overall size distributions relatively similar in all cases. The size and heating rate of the particles is typical of those commonly found in utility applications. The coals used in the CCL and CDL are size- and gravity-classified.

The coals with PSOC ID numbers in Table 1 were sampled, size-classified, and stored in inert gas environments to prevent slow oxidation (weathering) of the pyrite with time. Such weathering of pyrite at modest temperatures can occur rapidly, with significant formation of sulfates within a few days [Steger and Desjardins, 1978] and significant rate enhancements from both the presence of moisture in the air and interactions with coal and coal-bound minerals [Shyu, et al., 1981]. The remaining coals were pulverized and stored in various containers with no attempt to prevent oxidation. In all cases, samples of the coals were analyzed at several stages of experimentation to determine the fraction of pyritic iron.

In the experiments, coal samples are entrained in a laminar flow reactors in the Sandia Coal Devolatilization Laboratory (CDL) and the Coal Combustion Laboratory (CCL) and in the turbulent

flow of the Multifuel Combustor (MFC). In all cases, partially reacted solids are sampled at various stages of burning using helium-quench sampling probes. Schematic diagrams these reactors and their sampling systems are presented in Figures 2 through 6. The CCL is an up-fired reactor that uses a vitiated flow as the entrainment fluid for the particles. The CDL reactor is similar in design to the CCL except that it is down-fired and uses electrically heated inert entrainment gases (N_2) rather than a vitiated flow. Both the CCL and the CDL are relatively short residence time facilities (< 300 ms) that entrain size-classified particles in a dilute stream with the gases. The MFC is a down-fired, pilot-scale combustor with longer residence time capabilities (0 – 5 s), comparable to or in excess of those achieved in commercial-scale equipment. In these experiments, the utility grind coal was fired in the MFC at rates (g/cm^2 sec) similar to those achieved in commercial-scale operations. Further details of the reactors and their diagnostics are available elsewhere [Baxter, 1992; Baxter and Mitchell, 1992; Fletcher, 1989].

Table 1

Characteristic properties of size-classified coals studied during this investigation.

Coal	PSOC # or other	Parr Values*			Ash† [-]	Rank
		Fixed Carbon [-]	Volatile Matter [-]	Heating Value Btu/lb		
Pocahontas #3	1508-D	83.8	16.2	15642	7.4	Iv Bituminous
Lower Kittanning	1516-D	81.4	18.6	15488	10.3	Iv Bituminous
Pittsburgh #8	1451-D	61.2	38.8	14682	13.7	hv A Bituminous
Pittsburgh #8	EPRI-C2	54.9	45.1	13752	8.7	hv B Bituminous
Pittsburgh #8	EPRI-C1	55.2	44.8	13643	11.8	hv B Bituminous
Kentucky #9	EPRI-MC	54.2	45.8	12939	10.3	hv C Bituminous
SOAP§		57.6	42.4	12900	2.8	hv C Bituminous
Pittsburgh #8	EPRI-RM	54.9	45.1	12867	33.7	hv C Bituminous
Illinois #6	1493-D	57.1	42.9	12832	15.2	hv C Bituminous
Hiawatha	1502-D	55.8	44.2	12678	9.0	hv C Bituminous
Kentucky #9	EPRI-RM	54.6	45.4	12286	15.0	hv C Bituminous
Blue #1	1445-D	52.1	47.9	12107	4.6	hv C Bituminous
Dietz	1488-D	56.1	43.9	10000	5.4	Subbituminous B
Smith-Roland	1520-D	38.0	62.0	9177	12.4	Subbituminous C
Lower Wilcox	1443-D	21.8	78.2	8459	21.4	Subbituminous C
Beulah	1507-D	54.3	45.7	7747	12.5	Lignite 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 Illinois #6 coal.

Table 2

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)	85.8	14.2	15712	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 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	10.16	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.

Figure 1. Particle size distributions of the five typical utility grind coals used in the MFC. Each curve indicates the mass of total coal with a diameter below the given value. Data are derived from both optical and sieve techniques. All coals meet the typical boiler specification of 70 % through 200 mesh (70 % less than 74 μm).

Figure 2. Schematic diagram of the laminar flow reactor, in Sandia's Coal Combustion Laboratory (CCL), used in these experiments. Coal particles entrained in the hot, vitiated gas flow upward as they proceed through the stages of heat-up, devolatilization and heterogeneous oxidation.

Figure 3. Schematic diagram of the laminar rapid-quench sampling system used in these experiments in each of the coal reactors. The openings in the filter are 1 μm in diameter.

Figure 4. Schematic diagram of the laminar flow reactor, in Sandia's Coal Devolatilization Laboratory (CDL), used in these experiments. The reactor is down-fired and uses electrically heated inert gas as the entrainment medium.

From Helium
quench probe

► 70% of gas flow
0% of char
(to primary tar filter)

▼
30% of gas flow
100% of char
(to cyclone separators)

Figure 5. Schematic diagram of an aerodynamic, sample-separation portion of the sampling system associated with the CDL. Solids and vapors (tars) are separated in flight in the sampling system.

Figure 6. Schematic diagram of the Sandia Multifuel Combustor. A sampling system similar to that illustrated in Figure 3 is used with the MFC.

Elemental ash analyses are obtained for each of the solid samples. The inorganic elements in samples from the CDL and CCL were analyzed by Coors Analytical Laboratories using an inductively coupled plasma (ICAP) according to ASTM Procedure D 3682 with the following revisions: (1) a lithium metaborate and lithium tetraborate flux was used for the fusion, and (2) concentrations are determined using the ICAP. Samples from the MFC were analyzed by the chemical analysis laboratories of CONSOL Inc., Library, PA, using the standard ASTM Procedure (D 3682).

The experimental facilities used in this investigation include the coal devolatilization laboratory (CDL), the coal combustion laboratory (CCL), and the multifuel combustor (MFC). All are located at the Combustion Research Facility of Sandia National Laboratories. These facilities are

described in some detail in the literature [Baxter, 1992; Baxter and Mitchell, 1992; Fletcher, 1989]. They provide a capability to study the effect of devolatilization rate on mineral matter transformations over a wide range of controlled conditions. A brief, functional description of the facilities and their capabilities, as used in this investigation, is given here.

The CDL includes a laminar, electrically heated flow reactor and an *in situ*, particle-sizing, two-color pyrometer. The flow reactor entrains size- and aerodynamically classified samples of coal. An isokinetic, helium-quench probe samples the entrained particles at residence times up to about 300 ms. The pyrometer system obtains single-particle temperature, velocity, and size measurements at each sampling location. Inductively coupled atomic absorption spectroscopy characterizes the elemental composition of the inorganic constituents of the particles. Additional analyses characterize the elemental compositions of the organic portion, particle density and pore size distributions, surface areas, etc. Maximum gas temperatures vary up to approximately 1250 K, producing initial particle heating rates up to about 10^4 K/s. Particles are injected at room temperature and experience an initial rapid increase in temperature. Maximum particle temperatures attained in the CDL are approximately 1150 K. Inert gas environments used in the flow section and sampling systems of the CDL, preclude oxidation of the samples.

The CCL resembles the CDL in design and scale. The primary differences involve the vitiated, oxygen-bearing flow in the CCL. The vitiated flow of the CCL allows initial particle heating rates as high as 5×10^5 K/s and, consequently, more rapid rates of devolatilization than are obtained in the CDL. Initial gas temperatures reach approximately 1800 K in all experiments. Particles combust under in two environments, one containing 6 and the other 12 mole percent oxygen. Otherwise, the gas environments are identical. Particles enter the reactor at room temperature. Maximum particle temperature attained in the CCL is approximately 1950 K and particle residence times are as long as 150 ms.

The MFC simulates conditions in a commercial-scale boiler. Utility-grind coal (70 % through 200 mesh) is used in the facility and particle residence times of 3 seconds or longer are obtainable. Mass-average particle diameters are 20-30 μm . Firing rates and particle loadings in the MFC are matched to those of commercial-scale boilers. Gas and particle temperatures and heatup rates are also chosen to match those of commercial-scale boilers. Maximum particle temperatures exceed 2000 K and particle residence times are as long as 3 s. In most experiments, devolatilization rates in the MFC exceed those in either the CDL or CCL.

All three laboratories capture solid samples from the reacting flow using Nuclepore® polycarbonate filters with 1 μm openings and total diameters of either 76 or 142 mm. The sampling efficiency of particles greater than 1.2 μm in diameter exceeds 99.9 % whereas the sampling efficiency of particles less than 0.8 μm in diameter is less than 0.1%. This filtration system separates particles on the basis of their absolute, as opposed to aerodynamic, diameters. The collection system in the CDL separates tars from solid particles prior to collecting the solid particles on the filter.

The fractional loss of any element from the particle at time i is determined from a combination of the overall mass loss and the change in the mass fraction of that element, as follows

$$R_i(t) = 1 - \left(\frac{m(t)}{m_o} \right) \left(\frac{x_i(t)}{x_{io}} \right) \quad (1)$$

where R_j represents the cumulative fraction of the original mass of element j released from the particle up to time t , m is the overall mass of the particle, and x is the mass fraction of element j in the particle. Subscript o represents a value in the raw coal (residence time of 0 ms). All other values are time dependent, as indicated.

Overall mass loss is computed by averaging the results of tracer techniques and mass balances (where feasible). Silica and alumina were found to be the best tracers in most cases. Mass loss calculated from the concentrations of these materials in the coal were in close agreement with both each other and with the measured change in mass between coal and char samples. There was no indication of a change in the silica to alumina ratio during combustion. The variance of the overall mass loss was calculated from the independent measurements of mass loss (mass balance and tracers) and from replicated experiments. This variance is used to compute the variance for individual points.

Statistical variation in the value of R arises from sample-to-sample variations and experimental error in three experimentally determined values in Eq. 1: the overall mass loss at time t ($m(t)/m_o$); the original fraction of element j in the coal particle (x_{oj}); and the time-dependent fraction of element j in a coal particle ($x(t)_j$). The total variance in R at a given residence time can be estimated from these three sources as follows [Papoulis, 1984]:

$$\sigma_{R_i}^2 = \sigma_{m_i/m_o}^2 \left(\frac{\partial f_i}{\partial m_i/m_o} \right)^2 + \sigma_{x_i}^2 \left(\frac{\partial f_i}{\partial x_i} \right)^2 + \sigma_{x_o}^2 \left(\frac{\partial f_i}{\partial x_o} \right)^2 \quad (2)$$

or

$$\sigma_{R_i}^2 = \sigma_{m_i/m_o}^2 \left(\frac{\langle x_i \rangle}{\langle x_o \rangle} \right)^2 + \sigma_{x_i}^2 \left(\left\langle \frac{m_i}{m_o} \right\rangle \frac{1}{\langle x_o \rangle} \right)^2 + \sigma_{x_o}^2 \left(\left\langle \frac{m_i}{m_o} \right\rangle \frac{\langle x_i \rangle}{\langle x_o \rangle^2} \right)^2 \quad (3)$$

where angle brackets represent mean values, σ^2 represents a variance, and the remaining symbols have been previously defined. All quantities are time dependent except those bearing a subscript o . This approach can be used to estimate variances on a point-by-point basis. Variances in groups of data, i.e., all points after coal devolatilization, can be calculated using standard statistical techniques [Canavos, 1984]. The statistical analyses of the data are based on these variances.

Results and Discussion

Figures 7 through 9 illustrate the data and trends for the fractional overall mass loss (dashed lines scaled by the right ordinate) and the fractional titanium loss (solid lines scaled by the left ordinate)

as a function of particle residence time in the CDL and CCL with respect to the Illinois #6 coal (PSOC 1493d). Because the CDL data are obtained in an oxygen-free environment, all of the mass loss indicated in Figs. 7(a) and 7(b) is attributable to devolatilization. The overall mass loss indicated in Fig. 8 includes both devolatilization and oxidation results. The separation between devolatilization and heterogeneous oxidation mass loss occurs at about 45 ms.

The least rapid rates of devolatilization among the data from the size-classified coals are experienced by the small (75-106 μm) particles in the CDL, where maximum gas temperatures range from 1050 to 1250 K. In these experiments, mass loss during devolatilization can be resolved. These are the only data presented that include solid samples collected *during* devolatilization.

The data illustrated in Fig. 8 were collected in the CCL under conditions of more rapid devolatilization than is attained in the CDL. The data differ only in the bulk gas oxygen composition, with results from environments containing 6 and 12 mole percent oxygen being presented in Figure 8(a) and 8(b), respectfully. The difference in gas composition has little impact on the rate of devolatilization. The bulk gas temperatures in the 6 and 12 % oxygen environments are essentially identical and the particles are not exposed to oxygen during devolatilization due to the combustion of the surrounding volatile cloud. Therefore, the differences in the rates of devolatilization are minimal in these two gas environments.

The data illustrated in Fig. 9 were collected under conditions inducing the most rapid rates of devolatilization among the CCL and CDL data sets. Again, the difference in the two figures is the bulk oxygen concentration in the gas under the conditions of the experiment.

These data will be used to illustrate a correlation between the rate of coal devolatilization and loss of titanium from the coal. The curves in Figs. 7 through 9 represent overall mass and overall titanium release. The curves themselves are drawn to aid the eye and do not represent correlations or theory. All of the mass release data are on a dry, ash-free basis and lie very close to the line. The titanium data inherit the uncertainty in the mass loss data and that of several other chemical analyses (see Eq. 2). The increased scatter in the titanium data relative to the mass loss data reflect this variation. The solid curve representing overall titanium release reaches a plateau shortly after devolatilization stops. This plateau is the calculated average value of all data points after the end of devolatilization in each experiment.

The most obvious and important trends indicated by the data are: (1) a small fraction of the titanium leaves the coal during devolatilization and (2) the amount of titanium leaving the coal generally increases with increasing rate of devolatilization. The CDL data indicate that an average of five percent of the titanium is released during devolatilization. The data at intermediate rates of devolatilization, i.e., from the large particles in the CCL (Fig. 8), indicate an average of eight percent titanium leaving the particle. And the data at the most rapid rates of devolatilization in the CCL (Fig. 9) indicate an average of twelve percent titanium leaving the coal particle.

Figure 7. Illustration of titanium mass loss at moderate rates of devolatilization. Data are collected from the CDL with maximum gas temperatures of: (a) 1050 K and (b) 1250 K. All data are for 75-106 μm size fraction of an Illinois #6 coal (PSOC 1493D).

Figure 8. Illustration of titanium mass loss at intermediate rates of devolatilization compared to Figs. 7 and 8. Data are collected from the CCL in gas environments containing: (a) 6 mole percent and (b) 12 mole percent oxygen. All data are for the 106-125 μm size fraction of an Illinois #6 coal (PSOC 1493D).

Figure 9. Illustration of fractional titanium mass loss at rapid rates of devolatilization compared to Figs. 7 and 8. Data are collected from the CCL in gas environments containing: (a) 6 mole percent and (b) 12 mole percent oxygen. All data are for the 106-125 μm size fraction of an Illinois #6 coal (PSOC 1493D).

Release of titanium by vaporization can not satisfactorily explain this loss of titanium. The common forms of titanium in coal are less volatile than the common forms of either silicon or aluminum, yet the titanium is leaving the coal particles. Vaporization should be most rapid at peak particle temperatures. These occur after coal devolatilization, where the rate of titanium loss has become essentially zero. Also, the rate of vaporization from a given sample of coal should be determined primarily by the particle temperature history. These data indicate a more sensitive dependence on devolatilization rate than on temperature history. For example, compare the data in Figs. 8 and 9, all of which have virtually identical gas temperature histories but which represent two different devolatilization rates.

We propose convective transport by coal volatiles as a more satisfactory explanation for these data. Elucidation of the details of this mechanism will require additional careful experimentation. These data, however, provide direct support for the overall features of mineral matter release by coal devolatilization and a foundation from which hypotheses can be generated. Coal devolatilization is, on a particle scale, the most rapid reaction experienced by the particles during combustion. At conditions typical of commercial pulverized coal combustion, the rate of devolatilization exceeds that of the experiments illustrated by the data in Figs. 7 through 9. During this rapid reaction, organically associated material and possibly very fine particulate are locked into organic structures that are undergoing pyrolysis. This material is carried into the bulk gas stream with the volatiles, not because of its inherent volatility, but rather because of its intimate association with reacting coal matrix.

This mechanistic explanation explains the trend of increasing loss of material with increasing rate of devolatilization. This trend, with statistical confidence limits, is illustrated in Fig. 10(a). A detailed analysis of the confidence limits on a point-by-point basis using Eq. 2 indicates that only those data derived from experiments with many replicates and under conditions of rapid devolatilization or highest titanium mass loss can be demonstrated to be statistically significant, i.e., 95 % confidence limits for the mean that exclude zero mass loss. This results primarily from the limited number of effective replicate experiments under identical conditions at the same residence time. However, if the data collected before and after devolatilization are considered as two groups, we can demonstrate statistically that they have different titanium contents.

Figure 10(a) indicates the average and 95 percent confidence intervals for the fraction of titanium released from coal during devolatilization under each of the essentially equivalent conditions indicated in Figs. 7 through 9. In Fig. 10(a), the data from the CDL at each gas temperature condition and the data from the CCL for each different particle size are arranged in order of increasing rate of devolatilization. The first two points summarize data from the same size fraction of the same coal collected in the same reactor (CDL) at different gas temperatures. Therefore, the bulk gas temperature, or rate of devolatilization, is the dominant difference in the data. As indicated, the amount of titanium lost increased with increasing rate of devolatilization. The last two points summarize data collected from the CCL. In this case, the rate of devolatilization has been controlled by changing particle size. All of the data, including those collected at the most moderate rates of devolatilization, indicate a statistically significant loss of titanium during devolatilization, with the amount lost increasing with increasing rate of devolatilization.

Figure 10. Comparison of titanium mass before and after devolatilization for data collected from: (a) the CDL and CCL; and (b) the MFC. Data are plotted in order of: (a) increasing rate of devolatilization and (b) decreasing rank. Confidence intervals (95 %) are illustrated with both sets of data.

Similar data for a several additional coals tested in the MFC are presented Fig. 10(b) in rank order. The mass-average rate of devolatilization for the data from the MFC exceeds that of both the CCL and the CDL. However, because a utility grind coal was used in the MFC experiments, particle heating and devolatilization rates span a broad range in these results. The data indicate a complex rank dependence of titanium release. The Illinois #6 coal used in the CCL and CDL experiments ranks between the Kentucky #9 and Illinois #6 (2) coals indicated in Fig. 10(b).

As a practical consideration, the relevance of these results rests in their implication for materials that are bound in coal in a similar fashion as titanium but that play a more significant role in determining things such as ash deposit tenacity and strength in commercial combustion systems. Condensation of vapors during deposition is implicated in the formation of unmanageable, tenacious, strong deposits on boiler heat transfer surfaces. Inorganic materials likely to condense during combustion have their origin primarily as atomically dispersed species in the coal, with sodium being the most notable example and the remaining alkali and alkaline earth elements also implicated. The classical volatility of some of these species, most importantly sodium, precludes their use in these experiments to distinguish classical vaporization from convective transport during devolatilization. However, there is an obvious implication from the results of the nonvolatile titanium species for the remaining atomically dispersed material. Namely, if titanium is effectively transported by this mechanism, all other atomically dispersed species potentially could experience a similar fate.

Experiments conducted on the utility-grind samples of coal were conducted to evaluate the extent of alkali and alkaline earth metal release during coal devolatilization. Atomically dispersed alkali and alkaline earth material is of principal interest in these experiments since it is this material that would most likely be released by convective transport of the coal volatiles. The amount of atomically dispersed material was measured for selected coals from those tested in the MFC. Results of these measurements are illustrated in Figs. 11 through 14 for each of the major alkali or alkaline earth materials. More detailed data for all elements are presented in the appendix. In these figures, the atomically dispersed fraction of each element corresponds to the sum of the water soluble and ion exchangeable fractions.

There are clear rank and chemical element dependencies in the data. For example, the fractions of sodium, potassium and magnesium that are atomically dispersed are all greater for low-rank coals than for high-rank coals. The atomically dispersed fraction of calcium is, on average, slightly greater in high-rank coals than in low rank coals. The trend with rank for the calcium data is also less well behaved than with most of the other data. The fraction of atomically dispersed sodium is, in general, greater the fraction of atomically dispersed potassium by a factor of about 2.

Figure 15 illustrates the amount of sodium released from the coal as a function of rank with 95 % confidence intervals. There is a general correlation between sodium release and mode of occurrence, with the amount of release increasing with increasing atomically dispersed fraction of sodium. In addition to combustion conditions and mode of occurrence of the materials, interactions between inorganic fractions and recondensation or reactions of vapors with other fly ash impact the amount of sodium ultimately vaporized. These complexities, together with experimental and analytical uncertainties, contribute to the trends in the data. Note that the

confidence intervals are quite large for many of the samples. The size of the confidence interval depends on the precision of the data (often $\pm 10\%$ in the MFC) and the number of replicate samples. With less than seven replicate samples, the confidence intervals are larger the standard deviation. With one or two replicates, the confidence intervals are infinitely large and nine times larger than the standard deviation, respectively. The number of replicate samples used to compute the confidence intervals varies from two to eight among these coals. Results for coals from Table 2 that had fewer than two replicates are not shown. The size of the confidence intervals for these data are primarily a result of small numbers of replicate experiments for most of the coals.

Figure 11. Mode of occurrence of sodium as a function of coal rank for selected coals from Table 2. The atomically dispersed fraction, indicated by the sum of the ion exchangeable and water soluble fractions, approaches unity for low-rank coals and is and averages about 0.5 for high-rank coals. Contrast with potassium data in Fig. 12.

By contrast, the average potassium release is much less than sodium (Fig. 16). The first-order comparison of the potassium and sodium data leads to the expected result. Less potassium released because less potassium is available in atomically dispersed form. The details of the trend of potassium release with rank is not expected. The high-rank coals show greater release (albeit still small) than the low-rank coals. This aspect of the data will require further investigation before it can be explained.

Figure 12. Mode of occurrence of potassium as a function of coal rank for selected coals from Table 2. The atomically dispersed fraction, indicated by the sum of the ion exchangeable and water soluble fractions, averages about 0.5 for low-rank coals and 0.05 for high-rank coals. Contrast with sodium data in Fig. 11.

Atomically dispersed sodium and potassium are both reasonably volatile at combustion temperatures. The trends seen in Figs. 15 and 16 with respect to rank, as well as the comparison of sodium release with potassium release, would be expected for either release by convective transport or release by vaporization. It is difficult from these data to distinguish what fraction of the material may have been released by what mechanism. In comparison with sodium and potassium, calcium and magnesium are refractory. Release of these materials would be expected to

Figure 13. Mode of occurrence of calcium as a function of coal rank for selected coals from Table 2. The atomically dispersed fraction, indicated by the sum of the ion exchangeable and water soluble fractions, is greater than 0.5 for all coals and averages slightly higher for high-rank coals than for low-rank coals. The amount of calcium in the low-rank coals is much larger than in high-rank coals. Contrast with data for magnesium (Fig. 14).

be dominated by convective transport. Figures 17 and 18 illustrate results for these alkaline earth materials. The trend with rank is consistent with the expectation that release is more likely to occur as the fraction of atomically dispersed material increases. A comparison of the magnitude of the release of alkaline earth materials with that of alkali materials should indicate the extent to which convective transport of atomically dispersed material is influencing the results. The magnitude of release of the more refractory materials is less than that of sodium, but typically by only a small amount. This observation supports the hypothesis that convective transport influences the release of inorganic material during coal combustion.

Figure 14. Mode of occurrence of magnesium as a function of coal rank for selected coals from Table 2. The atomically dispersed fraction, indicated by the sum of the ion exchangeable and water soluble fractions, averages about 0.5 for high-rank coals and approaches unity for low-rank coals except the Texas lignite. Contrast with data for calcium (Fig. 13).

Figure 15. Fractional release of sodium as a function of coal rank. Generally, the fraction of released sodium increases with increased atomically dispersed sodium. Confidence intervals (95 %) are also indicated for the data. The number of replicated measurements in the primary contributor to the range of the 95 % confidence interval.

Figure 16.

Fractional release of potassium as a function of coal rank. The amount of released potassium is much less than sodium (comp. Fig. 15), consistent with their modes of occurrence in the coals. The rank dependence of the data is somewhat surprising. Confidence intervals (95 %) are also indicated for the data. The number of replicated measurements in the primary contributor to the range of the 95 % confidence interval.

Figure 17. Fractional release of calcium as a function of coal rank. The amount of released potassium is much less than sodium (comp. Fig. 15), consistent with their modes of occurrence in the coals. The rank dependence of the data is somewhat surprising. Confidence intervals (95 %) are also indicated for the data. The number of replicated measurements in the primary contributor to the range of the 95 % confidence interval.

Figure 18. Fractional release of magnesium as a function of coal rank. The amount of released potassium is much less than sodium (comp. Fig. 15), consistent with their modes of occurrence in the coals. The rank dependence of the data is somewhat surprising. Confidence intervals (95 %) are also indicated for the data. The number of replicated measurements in the primary contributor to the range of the 95 % confidence interval.

Comparisons with Literature Data

Figure 19. Rank and element resolved elemental release rates from small-scale combustors. Among the less volatile components, iron stands out as being extensively released.

One series of studies investigating inorganic release during combustion of coal from a wide range of coals reports both the fraction of material vaporized and the fraction of fume composed of several inorganic components [Quann, et al., 1982; Quann, et al., 1990; Quann and Sarofim, 1982]. The results of this study are shown in Fig. 19. The total amount of inorganics vaporized is seen to vary over the same range as is seen in our data, with generally the same trends. We

observe somewhat higher calcium release with some coals than is indicated in Fig. 19. The amount of the fume that is composed of iron generally increases with increasing rank in these results. Also shown in Fig. 24 are other elements that were observed to leave the particle. There is generally reasonable agreement between the two sets of data. The data in Fig. 19 are based on measured fume compositions whereas the data presented thus far in this report are based on composition of residual particles.

Conclusions

Coal devolatilization at rates typical of pulverized coal combustors induces a mineral matter release mechanism that is characterized by convective transport of organically-bound and possibly small-grained material away from the coal particle. This mechanism is experimentally demonstrated for titanium for a variety of devolatilization rates (heating rates) and a variety of coal types. The extent of loss of titanium varies from zero to over 16 percent of the original titanium mass. The extent of titanium loss depends most strongly on particle heating and devolatilization rate, organically associated oxygen, and extent of tar production. These tendencies support the proposed mechanism of titanium release as relating to the atomically dispersed inorganic material convectively carried out of the coal particle.

Data relating the amount of alkali and alkaline earth material released during coal combustion to its mode of occurrence and volatility are presented as a function of coal rank and inorganic element. These data illustrate that the amount of release is primarily dependent on the mode of occurrence of the inorganic material and secondarily dependent on its volatility. This observation is consistent with the proposed mechanism of release and suggests that it is significant for both volatile and nonvolatile inorganic constituents that are atomically dispersed.

These data indicate that the mechanism of convective transport during coal devolatilization contributes to the formation of inorganic vapors and fumes during coal combustion. This additional mechanism of mineral matter release should be considered when describing the chemical composition of fly ash particles and the amount of condensable material formed during combustion.

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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	
Fixed Carbon	77.00	76.53	dp>600µm		+28	0.00	
Volatile Matter	18.49	18.37	600µm>dp>300µm		28x48	0.70	
Moisture	0.62		300µm>dp>149µm		48x100	3.67	
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	14.37	
C	87.52	86.98	74µm>dp>44µm		200x325	15.47	
H	4.26	4.23	44µm>dp		-325	65.80	
O	1.55	1.54	Size Distribution (Malvern)*			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					
Hemispherical	2332	1278					
Fluid	2428	1331					
Oxidizing Conditions							
Initial Deformation	2366	1297					
Spherical	2395	1313					
Hemispherical	2439	1337					
Fluid	2487	1364					
			Dv.5	Volume Mean Diam.	25.00	Malvern	All Data
			Dv.9	90 % volume diameter	65.85		
			Dv.1	10 percentile volume diameter	5.02		
			D4,3		30.10		
			D3,2	Sauter Mean Diameter	11.63		
			Span		2.37		
			Specific Surface Area (m²/3/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		mass % in size bin	
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 (µm)	% in size bin	cum. vol. per.	Diameter (µm)
S	2.00	1.99				% in size bin
Cl	0.19	0.19				cum. vol. per.
Ash	21.30	21.13	188m	0.00	100.0	118.4m2
Ash Chemistry	% dry fuel	% ash	162m	0.00	100.0	102.1m2
SiO2	10.93	51.29	140m	0.00	100.0	88.1m2
Al2O3	5.16	24.23	121m	0.00	100.0	76m2
TiO2	0.20	0.92	104m	0.00	100.0	65.6m2
Fe2O3	2.85	13.40	89.9m	0.12	99.9	56.6m2
CaO	0.53	2.47	77.5m	0.22	99.7	48.8m2
MgO	0.28	1.30	66.9m	0.30	99.4	42.1m2
K2O	0.65	3.06	57.7m	0.93	98.4	38.3m2
Na2O	0.06	0.30	49.8m	3.43	95.0	31.3m2
SO3	0.52	2.42	42.9m	5.83	89.2	27m2
P2O5	0.03	0.14	37.1m	7.73	81.4	23.3m2
Cl			32m	8.32	73.1	20.1m2
Undetermined	0.13	0.59	27.6m	7.37	65.8	17.4m2
Total	21.33	100.1	23.8m	6.07	59.7	15m2
Forms of Sulfur (% dry fuel)			20.5m	5.38	54.3	12.9m2
Pyritic	1.49		17.7m	5.87	48.4	11.1m2
Organic	0.48		15.3m	6.38	42.1	9.6m2
Sulfatic	0.11		13.2m	6.03	36.0	8.3m2
Fraction Free Silica	0.29		11.4m	5.12	30.9	7.2m2
Fraction Pyritic Iron	0.65		9.8m	3.98	26.9	6.2m2
Heating Value (Btu/lb, dry)			8.5m	3.42	23.5	5.3m2
As Fired	11830	11732	7.3m	3.47	20.0	4.8m2
Dulong	11987	11888	6.3m	3.75	16.3	4m2
Acid Sol. Alkali (ppm)	Dry	As Rec'd	5.4m	3.60	12.7	3.4m2
Na	343	343	4.7m	2.97	9.7	3m2
Mg	1208	1208	4.1m	2.30	7.4	2.8m2
Ca	3767	3767	3.5m	1.68	5.7	2.2m2
K	2292	2292	3m	1.25	4.5	1.9m2
Fusion Temp.	°F	°C	2.6m	1.07	3.4	1.6m2
Reducing Conditions			2.2m	0.98	2.4	1.4m2
Initial Deformation	2177	1192	1.9m	1.83	0.6	1.2m2
Spherical	2317	1269	Size Statistics (Malvern Data Only)			
Hemispherical	2376	1302	Dv.5	Volume Mean Diam.	16.65	Malvern
Fluid	2437	1336	Dv.9	90 % volume diameter	39.58	All Data
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 (m²/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				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	cum. mass %
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
S	0.87	0.85					cum. vol. per.
Cl	0.15	0.15	188m	0.00	100.0	118.4m2	
Ash	9.34	9.21	162m	0.00	100.0	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	0.00	100.0	88.1m2	
SiO2	5.14	55.07	121m	0.00	100.0	76m2	
Al2O3	2.80	29.96	104m	0.00	100.0	65.6m2	
TiO2	0.13	1.41	89.9m	0.00	100.0	56.6m2	
Fe2O3	0.60	6.38	77.5m	0.08	99.9	48.8m2	
CaO	0.10	1.07	66.9m	1.13	98.8	42.1m2	
MgO	0.10	1.02	57.7m	3.25	95.6	38.3m2	
K2O	0.27	2.91	49.8m	5.65	89.9	31.3m2	
Na2O	0.05	0.49	42.9m	7.50	82.4	27m2	
SO3	0.11	1.22	37.1m	8.95	73.5	23.3m2	
P2O5	0.01	0.09	32m	8.60	64.9	20.1m2	
Cl			27.6m	6.95	57.9	17.4m2	
Undetermined	0.04	0.39	23.8m	5.83	52.1	15m2	
Total	9.34	100.0	20.5m	5.38	46.7	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	5.78	40.9	11.1m2	
Pyritic	0.23		15.3m	5.93	35.0	9.6m2	
Organic	0.64		13.2m	5.05	29.9	8.3m2	
Sulfatic	0.00		11.4m	4.10	25.8	7.2m2	
Fraction Free Silica	0.18		9.8m	3.23	22.6	6.2m2	
Fraction Pyritic Iron	0.48		8.5m	3.00	19.6	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	3.10	16.5	4.8m2	
As Fired	13805	13607	6.3m	3.25	13.3	4m2	
Dulong	14054	13852	5.4m	2.90	10.4	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	2.33	8.0	3m2	
Na			4.1m	1.80	6.2	2.8m2	
Mg			3.5m	1.30	4.9	2.2m2	
Ca			3m	1.05	3.9	1.9m2	
K			2.6m	0.98	2.9	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.85	2.1	1.4m2	
Reducing Conditions			1.9m	2.08	0.0	1.2m2	
Initial Deformation	1428	776	Size Statistics (Malvern Data Only)				
Spherical	1442	783	Dv.5	Volume Mean Diam.		Malvern	All Data
Hemispherical	1451	788	Dv.9	90 % volume diameter		19.38	
Fluid	1473	800	Dv.1	10 percentile volume diameter		43.00	
Oxidizing Conditions			D4,3			4.60	
Initial Deformation	1445	785	D3,2	Sauter Mean Diameter		21.03	
Spherical	1463	795	Span			10.00	
Hemispherical	1471	799	Specific Surface Area (m ² /cc)			2.00	
Fluid	1486	808				0.62	

*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						
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 % in		cum. vol.	Diameter	% in	cum. vol.	
S	3.52	3.48	(µm) size bin		per.	(µm) size bin	per.		
Cl	0.09	0.09	188m	0.31	99.7	118.4m2			
Ash	9.01	8.91	162m	0.83	98.9	102.1m2			
Ash Chemistry	% dry fuel	% ash	140m	1.24	97.6	88.1m2			
SiO2	3.53	39.16	121m	1.59	96.0	76m2			
Al2O3	1.74	19.31	104m	1.70	94.3	65.6m2			
TiO2	0.08	0.84	89.9m	1.91	92.4	56.6m2			
Fe2O3	2.48	27.53	77.5m	2.24	90.2	48.8m2			
CaO	0.41	4.56	66.9m	2.69	87.5	42.1m2			
MgO	0.08	0.84	57.7m	3.26	84.2	38.3m2			
K2O	0.11	1.18	49.8m	4.84	79.4	31.3m2			
Na2O	0.08	0.87	42.9m	6.24	73.2	27m2			
SO3	0.37	4.08	37.1m	7.04	66.1	23.3m2			
P2O5	0.03	0.34	32m	6.28	59.9	20.1m2			
Cl			27.6m	4.81	55.0	17.4m2			
Undetermined	0.11	1.25	23.8m	4.35	50.7	15m2			
Total	9.01	100.0	20.5m	4.58	46.1	12.9m2			
Forms of Sulfur (% dry fuel)			17.7m	4.74	41.4	11.1m2			
Pyritic	2.07		15.3m	4.61	36.8	9.6m2			
Organic	1.42		13.2m	4.15	32.6	8.3m2			
Sulfatic	0.03		11.4m	3.74	28.9	7.2m2			
Fraction Free Silica	0.26		9.8m	3.39	25.5	6.2m2			
Fraction Pyritic Iron	0.61		8.5m	3.16	22.3	5.3m2			
Heating Value (Btu/lb, dry)			7.3m	3.01	19.3	4.8m2			
As Fired	13728	13577	6.3m	2.99	16.3	4m2			
Dulong	13523	13374	5.4m	2.96	13.4	3.4m2			
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	2.73	10.6	3m2			
Na			4.1m	2.14	8.5	2.8m2			
Mg			3.5m	1.68	6.8	2.2m2			
Ca			3m	1.30	5.5	1.9m2			
K			2.6m	1.16	4.4	1.6m2			
Fusion Temp.	°F	°C	2.2m	1.11	3.3	1.4m2			
Reducing Conditions			1.9m	2.38	0.9	1.2m2			
Initial Deformation	1984	1085	Size Statistics (Malvern Data Only)						
Spherical	2020	1104					Malvern	All Data	
Hemispherical	2080	1138	Dv.5	Volume Mean Diam.		25.04			
Fluid	2245	1229	Dv.9	90 % volume diameter		63.86			
Oxidizing Conditions			Dv.1	10 percentile volume diameter		4.51			
Initial Deformation	2387	1308	D4,3			30.11			
Spherical	2448	1342	D3,2	Sauter Mean Diameter		10.70			
Hemispherical	2496	1369	Span			2.56			
Fluid	2542	1394	Specific Surface Area (m^3/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					cum. vol. per.
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	Dv.5	Volume Mean Diam.		Malvern	All Data
Hemispherical	1228	664	Dv.9	90 % volume diameter		24.13	
Fluid	1271	688	Dv.1	10 percentile volume diameter		49.83	
Oxidizing Conditions			D4,3			6.08	
Initial Deformation	1232	666	D3,2	Sauter Mean Diameter		27.03	
Spherical	1258	681	Span			13.40	
Hemispherical	1280	693				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.

Pittsburgh #8 (2)								
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 (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin	cum. vol. per.
S	1.57	1.54	188m	0.00	100.0	118.4m2	0.08	99.9
Cl	0.10	0.09	162m	0.00	100.0	102.1m2	0.15	99.9
Ash	6.63	6.51	140m	0.00	100.0	88.1m2	0.18	99.8
Ash Chemistry	% dry fuel	% ash	121m	0.00	100.0	76m2	0.13	99.9
SiO2	3.16	47.70	104m	0.00	100.0	65.6m2	1.33	98.7
Al2O3	1.60	24.08	89.9m	0.25	99.8	56.6m2	5.30	94.7
TiO2	0.07	1.05	77.5m	0.40	99.4	48.8m2	9.88	90.1
Fe2O3	1.11	16.81	66.9m	0.35	99.0	42.1m2	11.45	88.6
CaO	0.23	3.46	57.7m	1.05	98.0	38.3m2	10.03	90.0
MgO	0.06	0.84	49.8m	5.35	92.6	31.3m2	8.03	92.0
K2O	0.12	1.75	42.9m	9.45	83.2	27m2	8.00	92.0
Na2O	0.03	0.45	37.1m	12.60	70.6	23.3m2	8.88	91.1
SO3	0.20	2.99	32m	11.95	58.6	20.1m2	7.23	92.8
P2O5	0.04	0.62	27.6m	8.55	50.1	17.4m2	4.43	95.6
Cl			23.8m	6.60	43.5	15m2	3.70	96.3
Undetermined	0.01	0.23	20.5m	6.00	37.5	12.9m2	4.40	95.6
Total	6.62	100.0	17.7m	6.35	31.1	11.1m2	3.90	96.1
Forms of Sulfur (% dry fuel)			15.3m	6.40	24.7	9.6m2	2.88	97.1
Pyritic	0.69		13.2m	5.25	19.5	8.3m2	1.63	98.4
Organic	0.82		11.4m	4.05	15.4	7.2m2	1.45	98.6
Sulfatic	0.05		9.8m	2.85	12.6	6.2m2	1.50	98.5
Fraction Free Silica	0.24		8.5m	2.25	10.3	5.3m2	1.33	98.7
Fraction Pyritic Iron	0.74		7.3m	2.00	8.3	4.8m2	1.20	98.8
Heating Value (Btu/lb, dry)			6.3m	1.80	6.5	4m2	0.93	99.1
As Fired	13994	13761	5.4m	1.65	4.9	3.4m2	0.88	99.1
Dulong	14184	13947	4.7m	1.35	3.5	3m2	0.70	99.3
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	0.90	2.6	2.8m2	0.30	99.7
Na			3.5m	0.80	1.8	2.2m2	0.13	99.9
Mg			3m	0.50	1.3	1.9m2	0.00	100.0
Ca			2.6m	0.35	1.0	1.6m2	0.05	100.0
K			2.2m	0.25	0.7	1.4m2	0.00	100.0
Fusion Temp.	°F	°C	1.9m	0.55	0.2	1.2m2	0	100.0
Reducing Conditions			Size Statistics (Malvern Data Only)					
Initial Deformation	2109	1154					Malvern	All Data
Spherical	2268	1242	Dv.5	Volume Mean Diam.		24.78		
Hemispherical	2383	1306	Dv.9	90 % volume diameter		44.78		
Fluid	2481	1360	Dv.1	10 percentile volume diameter		18.55		
Oxidizing Conditions			D4,3			25.52		
Initial Deformation	2472	1356	D3,2	Sauter Mean Diameter		14.80		
Spherical	2519	1382	Span			1.48		
Hemispherical	2550	1399	Specific Surface Area (m^3/cc)				0.39	
Fluid	2604	1429						

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

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

Massey Sprouce							
Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	
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 % in		cum. vol.	Diameter	% in
S	1.05	1.03	(µm)	size bin	per.	(µm)	size bin
Cl			188m			118.4m2	
Ash	8.33	8.14	162m			102.1m2	
Ash Chemistry	% dry fuel	% ash	140m			88.1m2	
SiO2	4.61	55.35	121m			76m2	
Al2O3	2.18	26.22	104m			65.6m2	
TiO2	0.10	1.23	89.9m			56.6m2	
Fe2O3	0.97	11.62	77.5m			48.8m2	
CaO	0.12	1.42	66.9m			42.1m2	
MgO	0.07	0.86	57.7m			38.3m2	
K2O	0.19	2.28	49.8m			31.3m2	
Na2O	0.02	0.29	42.9m			27m2	
SO3	0.15	1.76	37.1m			23.3m2	
P2O5	0.01	0.08	32m			20.1m2	
Cl			27.6m			17.4m2	
Undetermined	-0.09	-1.11	23.8m			15m2	
Total	8.33	100.0	20.5m			12.9m2	
Forms of Sulfur (% dry fuel)			17.7m			11.1m2	
Pyritic	0.49		15.3m			9.6m2	
Organic	0.53		13.2m			8.3m2	
Sulfatic	0.03		11.4m			7.2m2	
Fraction Free Silica			9.8m			6.2m2	
Fraction Pyritic Iron			8.5m			5.3m2	
Heating Value (Btu/lb, dry)			7.3m			4.8m2	
As Fired	13768	13454	6.3m			4m2	
Dulong	14012	13692	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			Size Statistics (Malvern Data Only)				
Spherical			Malvern All Data				
Hemispherical			Dv.5	Volume Mean Diam.			
Fluid			Dv.9	90 % volume diameter			
Oxidizing Conditions			Dv.1	10 percentile volume diameter			
Initial Deformation			D4,3				
Spherical			D3,2	Sauter Mean Diameter			
Hemispherical			Span				
Fluid			Specific Surface Area (m^3/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
Fixed Carbon	53.00	52.28	dp>600µm	+28	0.00
Volatile Matter	36.87	36.37	600µm>dp>300µm	28x48	0.05
Moisture	1.36		300µm>dp>149µm	48x100	1.43
Ultimate	Dry	As Rec'd	149µm>dp>74µm	100x200	32.50
C	74.82	73.80	74µm>dp>44µm	200x325	30.15
H	4.97	4.90	44µm>dp	-325	35.88
O	7.57	7.47	Size Distribution (Malvern)*		Size Distribution (Malvern)*
N	1.46	1.44	Diameter (µm)	% in size bin	cum. vol. per.
S	0.97	0.96	188m	0.00	100.0
Cl	0.09	0.09	162m	0.05	100.0
Ash	10.15	10.02	140m	0.05	99.9
Ash Chemistry	% dry fuel	% ash	121m	0.05	99.9
SiO ₂	5.86	57.67	104m	0.05	99.8
Al ₂ O ₃	3.09	30.39	89.9m	0.18	99.6
TiO ₂	0.21	2.06	77.5m	0.63	99.0
Fe ₂ O ₃	0.49	4.83	66.9m	1.48	97.5
CaO	0.12	1.15	57.7m	2.98	94.6
MgO	0.04	0.41	49.8m	5.85	88.7
K ₂ O	0.10	0.99	42.9m	8.43	80.3
Na ₂ O	0.02	0.17	37.1m	9.73	70.6
SO ₃	0.13	1.28	32m	9.08	61.5
P ₂ O ₅	0.01	0.13	27.6m	7.48	54.0
Cl			23.8m	6.40	47.6
Undetermined	0.09	0.91	20.5m	5.73	41.9
Total	10.15	100.0	17.7m	5.35	36.5
Forms of Sulfur (% dry fuel)			15.3m	5.30	31.2
Pyritic	0.31		13.2m	4.95	26.3
Organic	0.66		11.4m	4.18	22.1
Sulfatic	0.00		9.8m	3.33	18.8
Fraction Free Silica	0.21		8.5m	2.75	16.0
Fraction Pyritic Iron	0.78		7.3m	2.50	13.5
Heating Value (Btu/lb, dry)			6.3m	2.48	11.1
As Fired	13226	13046	5.4m	2.43	8.6
Dulong	13418	13235	4.7m	2.13	6.5
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	1.65	4.9
Na			3.5m	1.35	3.5
Mg			3m	0.93	2.6
Ca			2.6m	0.65	1.9
K			2.2m	0.58	1.4
Fusion Temp.	°F	°C	1.9m	0.60	0.8
Reducing Conditions			Size Statistics (Malvern Data Only)		
Initial Deformation	2949	1620	Dv.5	Volume Mean Diam.	23.48
Spherical	2980	1638	Dv.9	90 % volume diameter	47.54
Hemispherical	2992	1644	Dv.1	10 percentile volume diameter	6.28
Fluid	3000	1649	D4,3		25.23
Oxidizing Conditions			D3,2	Sauter Mean Diameter	13.04
Initial Deformation	2960	1627	Span		1.75
Spherical	2996	1647	Specific Surface Area (m ² /cc)		0.45
Hemispherical	3000	1649			
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			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)	% in size bin	cum. vol. per.
S	4.78	4.73	188m			118.4m2		
Cl			162m			102.1m2		
Ash	10.68	10.57	140m			88.1m2		
Ash Chemistry	% dry fuel	% ash	121m			76m2		
SiO2	4.42	41.40	104m			65.6m2		
Al2O3	2.19	20.51	89.9m			56.6m2		
TiO2	0.10	0.89	77.5m			48.8m2		
Fe2O3	3.10	29.03	66.9m			42.1m2		
CaO	0.22	2.07	57.7m			38.3m2		
MgO	0.08	0.78	49.8m			31.3m2		
K2O	0.18	1.73	42.9m			27m2		
Na2O	0.04	0.40	37.1m			23.3m2		
SO3	0.25	2.33	32m			20.1m2		
P2O5	0.02	0.15	27.6m			17.4m2		
Cl			23.8m			15m2		
Undetermined	0.08	0.71	20.5m			12.9m2		
Total	10.68	100.0	17.7m			11.1m2		
Forms of Sulfur (% dry fuel)			15.3m			9.6m2		
Pyritic	1.81		13.2m			8.3m2		
Organic	2.82		11.4m			7.2m2		
Sulfatic	0.15		9.8m			6.2m2		
Fraction Free Silica			8.5m			5.3m2		
Fraction Pyritic Iron			7.3m			4.8m2		
Heating Value (Btu/lb, dry)			6.3m			4m2		
As Fired	13004	12871	5.4m			3.4m2		
Dulong	13190	13055	4.7m			3m2		
Acid Sol. Alkali (ppm)			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.			1.9m			1.2m2		
Reducing Conditions			Size Statistics (Malvern Data Only)					
Initial Deformation	1917	1047	Malvern All Data					
Spherical	1980	1082						
Hemispherical	2154	1179	Dv.5	Volume Mean Diam.				
Fluid	2232	1222	Dv.9	90 % volume diameter				
Oxidizing Conditions			Dv.1	10 percentile volume diameter				
Initial Deformation	2438	1337	D4,3					
Spherical	2502	1372	D3,2	Sauter Mean Diameter				
Hemispherical	2518	1381	Span					
Fluid	2532	1389	Specific Surface Area (m^3/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	
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
S	0.46	0.44					cum. vol. per.
Cl	0.04	0.04	188m	0.00	100.0	118.4m2	
Ash	10.51	10.17	162m	0.00	100.0	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	0.00	100.0	88.1m2	
SiO2	6.06	57.69	121m	0.00	100.0	76m2	
Al2O3	1.92	18.32	104m	0.00	100.0	65.6m2	
TiO2	0.10	0.96	89.9m	0.08	99.9	56.6m2	
Fe2O3	0.43	4.11	77.5m	0.28	99.7	48.8m2	
CaO	0.64	6.13	66.9m	0.63	99.0	42.1m2	
MgO	0.19	1.84	57.7m	1.35	97.7	38.3m2	
K2O	0.12	1.16	49.8m	3.68	94.0	31.3m2	
Na2O	0.45	4.32	42.9m	7.55	86.5	27m2	
SO3	0.48	4.57	37.1m	9.68	76.8	23.3m2	
P2O5	0.03	0.33	32m	9.13	67.7	20.1m2	
Cl			27.6m	7.45	60.2	17.4m2	
Undetermined	0.06	0.58	23.8m	6.28	53.9	15m2	
Total	10.51	100.0	20.5m	5.78	48.2	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	5.93	42.2	11.1m2	
Pyritic	0.08		15.3m	6.05	36.2	9.6m2	
Organic	0.37		13.2m	5.50	30.7	8.3m2	
Sulfatic	0.00		11.4m	4.60	26.1	7.2m2	
Fraction Free Silica	0.52		9.8m	3.68	22.4	6.2m2	
Fraction Pyritic Iron	0.24		8.5m	3.15	19.3	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	3.00	16.3	4.8m2	
As Fired	13108	12684	6.3m	2.95	13.3	4m2	
Dulong	13247	12819	5.4m	2.78	10.5	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	2.35	8.2	3m2	
Na			4.1m	1.70	6.5	2.8m2	
Mg			3.5m	1.45	5.0	2.2m2	
Ca			3m	1.05	4.0	1.9m2	
K			2.6m	0.88	3.1	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.83	2.3	1.4m2	
Reducing Conditions			1.9m	1.20	1.1	1.2m2	
Initial Deformation	2178	1192	Size Statistics (Malvern Data Only)				
Spherical	2246	1230			Malvern	All Data	
Hemispherical	2369	1298	Dv.5	Volume Mean Diam.	20.25		
Fluid	2641	1449	Dv.9	90 % volume diameter	42.45		
Oxidizing Conditions			Dv.1	10 percentile volume diameter	4.95		
Initial Deformation	2220	1216	D4,3		22.58		
Spherical	2265	1241	D3,2	Sauter Mean Diameter	10.88		
Hemispherical	2400	1316	Span		1.88		
Fluid	2675	1468	Specific Surface Area (m²/cc)		0.58		

*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				
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
S	4.78	4.60					
Cl	0.03	0.03					
Ash	22.15	21.28					
Ash Chemistry	% dry fuel	% ash					
SiO ₂	10.14	45.76	188m	0.00	100.0	118.4m ²	
Al ₂ O ₃	4.06	18.33	162m	0.00	100.0	102.1m ²	
TiO ₂	0.19	0.84	140m	0.00	100.0	88.1m ²	
Fe ₂ O ₃	4.70	21.23	121m	0.00	100.0	76m ²	
CaO	0.95	4.30	104m	0.00	100.0	65.6m ²	
MgO	0.24	1.11	89.9m	0.15	99.9	56.6m ²	
K ₂ O	0.48	2.17	77.5m	0.45	99.4	48.8m ²	
Na ₂ O	0.08	0.36	66.9m	0.80	98.6	42.1m ²	
SO ₃	1.02	4.61	57.7m	1.60	97.0	38.3m ²	
P ₂ O ₅	0.04	0.20	49.8m	3.85	93.2	31.3m ²	
Cl	0.02	0.09	42.9m	6.65	86.5	27m ²	
Undetermined	0.23	1.02	37.1m	9.55	77.0	23.3m ²	
Total	22.16	100.0	32m	9.90	67.1	20.1m ²	
Forms of Sulfur (% dry fuel)			27.6m	8.15	58.9	17.4m ²	
Pyritic	2.99		23.8m	6.85	52.1	15m ²	
Organic	1.59		20.5m	6.20	45.9	12.9m ²	
Sulfatic	0.20		17.7m	6.20	39.7	11.1m ²	
Fraction Free Silica	0.40		15.3m	6.35	33.3	9.6m ²	
Fraction Pyritic Iron	0.80		13.2m	5.70	27.6	8.3m ²	
Heating Value (Btu/lb, dry)			11.4m	4.75	22.8	7.2m ²	
As Fired	10524	10112	9.8m	3.50	19.3	6.2m ²	
Dulong	10909	10482	8.5m	2.90	16.5	5.3m ²	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	7.3m	2.80	13.6	4.8m ²	
Na	400	400	6.3m	2.75	10.9	4m ²	
Mg	1037	1037	5.4m	2.60	8.3	3.4m ²	
Ca	4981	4981	4.7m	2.20	6.1	3m ²	
K	3578	3578	4.1m	1.55	4.5	2.8m ²	
Fusion Temp.	°F	°C	3.5m	1.15	3.4	2.2m ²	
Reducing Conditions			3m	0.85	2.5	1.9m ²	
Initial Deformation	2238	1226	2.6m	0.70	1.8	1.6m ²	
Spherical	2270	1243	2.2m	0.55	1.3	1.4m ²	
Hemispherical	2310	1266	1.9m	1.25	0.0	1.2m ²	
Fluid	2352	1289	Size Statistics (Malvern Data Only)				
Oxidizing Conditions			Dv.5	Volume Mean Diam.		Malvern	All Data
Initial Deformation	2314	1268	Dv.9	90 % volume diameter		19.55	
Spherical	2354	1290	Dv.1	10 percentile volume diameter		39.75	
Hemispherical	2404	1318	D4,3			5.20	
Fluid	2446	1341	D3,2	Sauter Mean Diameter		21.75	
			Span			11.25	
			Specific Surface Area (m ² /cc)			1.80	
						0.55	

*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
Fixed Carbon	48.34	46.30	dp>600µm	+28	0.00
Volatile Matter	39.46	37.79	600µm>dp>300µm	28x48	0.00
Moisture	4.22		300µm>dp>149µm	48x100	1.78
Ultimate	Dry	As Rec'd	149µm>dp>74µm	100x200	25.20
C	68.12	65.24	74µm>dp>44µm	200x325	25.88
H	4.74	4.54	44µm>dp	-325	47.15
O	9.91	9.49	Size Distribution (Malvern)*		Size Distribution (Malvern)*
N	1.22	1.17	Diameter (µm)	% in size bin	cum. vol. per.
S	3.72	3.57			
Cl	0.08	0.08			
Ash	12.21	11.69			
Ash Chemistry	% dry fuel	% ash			
SiO ₂	5.94	48.66			
Al ₂ O ₃	2.20	18.00			
TiO ₂	0.11	0.87			
Fe ₂ O ₃	2.23	18.31			
CaO	0.58	4.78			
MgO	0.12	1.02			
K ₂ O	0.25	2.08			
Na ₂ O	0.12	1.02			
SO ₃	0.55	4.53			
P ₂ O ₅	0.03	0.21			
Cl					
Undetermined	0.12	0.94			
Total	12.26	100.4			
Forms of Sulfur (% dry fuel)					
Pyritic	1.06				
Organic	2.21				
Sulfatic	0.54				
Fraction Free Silica	0.45				
Fraction Pyritic Iron	0.44				
Heating Value (Btu/lb, dry)					
As Fired	12059	11550			
Dulong	12228	11712			
Acid Sol. Alkali (ppm)	Dry	As Rec'd			
Na					
Mg					
Ca					
K					
Fusion Temp.	°F	°C			
Reducing Conditions					
Initial Deformation	1996	1091			
Spherical	2054	1123			
Hemispherical	2177	1192			
Fluid	2367	1297			
Oxidizing Conditions					
Initial Deformation	2291	1255			
Spherical	2331	1277			
Hemispherical	2360	1293			
Fluid	2480	1360			
			Size Statistics (Malvern Data Only)		
			Dv.5	Volume Mean Diam.	25.65
			Dv.9	90 % volume diameter	50.57
			Dv.1	10 percentile volume diameter	6.52
			D4,3		27.65
			D3,2	Sauter Mean Diameter	13.97
			Span		1.73
			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
Volatile 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					cum. vol. per.
Cl	0.06	0.05	188m	0.00	100.0	118.4m2	
Ash	3.99	3.54	162m	0.00	100.0	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	0.00	100.0	88.1m2	
SiO2	1.25	31.44	121m	0.00	100.0	76m2	
Al2O3	0.66	16.66	104m	0.00	100.0	65.6m2	
TiO2	0.08	2.09	89.9m	0.00	100.0	56.6m2	
Fe2O3	1.52	38.03	77.5m	0.00	100.0	48.8m2	
CaO	0.11	2.72	66.9m	0.00	100.0	42.1m2	
MgO	0.04	1.06	57.7m	0.02	100.0	38.3m2	
K2O	0.07	1.86	49.8m	0.03	100.0	31.3m2	
Na2O	0.04	1.02	42.9m	0.10	99.9	27m2	
SO3	0.15	3.66	37.1m	0.53	99.3	23.3m2	
P2O5	0.01	0.14	32m	0.92	98.4	20.1m2	
Cl			27.6m	2.05	96.4	17.4m2	
Undetermined	0.05	1.26	23.8m	3.80	92.6	15m2	
Total	3.98	99.9	20.5m	5.17	87.4	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	6.22	81.2	11.1m2	
Pyritic	0.03		15.3m	7.15	74.0	9.6m2	
Organic	2.19		13.2m	7.83	66.2	8.3m2	
Sulfatic	0.85		11.4m	8.40	57.8	7.2m2	
Fraction Free Silica	0.20		9.8m	8.33	49.5	6.2m2	
Fraction Pyritic Iron	0.02		8.5m	7.73	41.7	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	6.95	34.8	4.8m2	
As Fired	13656	12139	6.3m	6.53	28.2	4m2	
Dulong	13289	11813	5.4m	6.18	22.1	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	5.53	16.5	3m2	
Na			4.1m	4.47	12.1	2.8m2	
Mg			3.5m	3.17	8.9	2.2m2	
Ca			3m	2.23	6.7	1.9m2	
K			2.6m	1.73	4.9	1.6m2	
Fusion Temp.	°F	°C	2.2m	1.43	3.5	1.4m2	
Reducing Conditions			1.9m	2.58	0.9	1.2m2	
Initial Deformation	2108	1153	Size Statistics (Malvern Data Only)				
Spherical	2257	1236				Malvern	All Data
Hemispherical	2344	1284	Dv.5	Volume Mean Diam.		8.98	
Fluid	2394	1312	Dv.9	90 % volume diameter		19.92	
Oxidizing Conditions			Dv.1	10 percentile volume diameter		3.40	
Initial Deformation	2442	1339	D4,3			10.42	
Spherical	2531	1388	D3,2	Sauter Mean Diameter		6.47	
Hemispherical	2569	1409	Span			1.85	
Fluid	2600	1426	Specific Surface Area (m²/cc)			0.83	

*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)
S	4.00	3.71				% in size bin
Cl	0.06	0.05				cum. vol. per.
Ash	15.64	14.49	188m	0.00	100.0	118.4m2
Ash Chemistry	% dry fuel	% ash	162m	0.00	100.0	102.1m2
SiO2	7.12	45.54	140m	0.02	100.0	88.1m2
Al2O3	3.08	19.71	121m	0.03	100.0	76m2
TiO2	0.15	0.98	104m	0.02	99.9	65.6m2
Fe2O3	3.61	23.09	89.9m	0.07	99.9	56.6m2
CaO	0.50	3.22	77.5m	0.33	99.5	48.8m2
MgO	0.16	1.05	66.9m	1.23	98.3	42.1m2
K2O	0.39	2.47	57.7m	2.92	95.4	38.3m2
Na2O	0.14	0.87	49.8m	5.38	90.0	31.3m2
SO3	0.57	3.62	42.9m	7.83	82.2	27m2
P2O5	0.02	0.14	37.1m	9.22	73.0	23.3m2
Cl	0.03	0.17	32m	9.33	63.6	20.1m2
Undetermined	-0.12	-0.77	27.6m	8.38	55.2	17.4m2
Total	15.65	100.1	23.8m	7.28	48.0	15m2
Forms of Sulfur (% dry fuel)			20.5m	6.35	41.6	12.9m2
Pyritic	1.70		17.7m	5.83	35.8	11.1m2
Organic	1.89		15.3m	5.72	30.1	9.6m2
Sulfatic	0.41		13.2m	5.37	24.7	8.3m2
Fraction Free Silica	0.34		11.4m	4.45	20.2	7.2m2
Fraction Pyritic Iron	0.59		9.8m	3.48	16.8	6.2m2
Heating Value (Btu/lb, dry)			8.5m	2.80	14.0	5.3m2
As Fired	11611	10759	7.3m	2.42	11.5	4.8m2
Dulong	15493	14356	6.3m	2.28	9.3	4m2
Acid Sol. Alkali (ppm)	Dry	As Rec'd	5.4m	2.13	7.1	3.4m2
Na	694	694	4.7m	1.85	5.3	3m2
Mg	830	830	4.1m	1.47	3.8	2.8m2
Ca	2835	2835	3.5m	1.15	2.7	2.2m2
K	2225	2225	3m	0.87	1.8	1.9m2
Fusion Temp.	°F	°C	2.6m	0.57	1.2	1.6m2
Reducing Conditions			2.2m	0.38	0.8	1.4m2
Initial Deformation	1979	1082	1.9m	0.37	0.5	1.2m2
Spherical	2041	1116	Size Statistics (Malvern Data Only)			
Hemispherical	2170	1188			Malvern	All Data
Fluid	2339	1282	Dv.5	Volume Mean Diam.	23.57	
Oxidizing Conditions			Dv.9	90 % volume diameter	47.35	
Initial Deformation	2323	1273	Dv.1	10 percentile volume diameter	6.53	
Spherical	2414	1323	D4,3		26.15	
Hemispherical	2469	1354	D3,2	Sauter Mean Diameter	13.80	
Fluid	2526	1385	Span		1.77	
			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)	% in size bin
S	0.65	0.58					cum. vol. per.
Cl	0.03	0.02	188m	0.00	100.0	118.4m2	
Ash	9.99	9.00	162m	0.05	100.0	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	0.10	99.9	88.1m2	
SiO2	3.63	36.34	121m	0.15	99.7	76m2	
Al2O3	1.49	14.94	104m	0.20	99.5	65.6m2	
TiO2	0.07	0.75	89.9m	0.15	99.4	56.6m2	
Fe2O3	0.82	8.21	77.5m	0.45	98.9	48.8m2	
CaO	2.20	22.01	66.9m	1.90	97.0	42.1m2	
MgO	0.33	3.26	57.7m	4.25	92.8	38.3m2	
K2O	0.08	0.82	49.8m	7.45	85.3	31.3m2	
Na2O	0.09	0.87	42.9m	10.35	75.0	27m2	
SO3	1.07	10.76	37.1m	10.80	64.2	23.3m2	
P2O5	0.07	0.66	32m	10.05	54.1	20.1m2	
Cl			27.6m	8.30	45.8	17.4m2	
Undetermined	0.10	1.01	23.8m	6.30	39.5	15m2	
Total	9.95	99.6	20.5m	5.40	34.1	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	5.15	29.0	11.1m2	
Pyritic	0.19		15.3m	5.05	23.9	9.6m2	
Organic	0.43		13.2m	4.60	19.3	8.3m2	
Sulfatic	0.03		11.4m	3.45	15.9	7.2m2	
Fraction Free Silica	0.38		9.8m	2.70	13.2	6.2m2	
Fraction Pyritic Iron	0.19		8.5m	2.15	11.0	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	1.90	9.1	4.8m2	
As Fired	11921	10734	6.3m	1.70	7.4	4m2	
Dulong	11517	10370	5.4m	1.60	5.8	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.40	4.4	3m2	
Na			4.1m	1.20	3.2	2.8m2	
Mg			3.5m	0.95	2.3	2.2m2	
Ca			3m	0.75	1.5	1.9m2	
K			2.6m	0.50	1.0	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.35	0.7	1.4m2	
Reducing Conditions			1.9m	0.25	0.4	1.2m2	
Initial Deformation	2186	1196	Size Statistics (Malvern Data Only)				
Spherical	2245	1229				Malvern	All Data
Hemispherical	2276	1246	Dv.5	Volume Mean Diam.		29.70	
Fluid	2338	1281	Dv.9	90 % volume diameter		54.20	
Oxidizing Conditions			Dv.1	10 percentile volume diameter		7.85	
Initial Deformation	2275	1246	D4,3			31.15	
Spherical	2316	1269	D3,2	Sauter Mean Diameter		16.15	
Hemispherical	2349	1287	Span			1.55	
Fluid	2452	1344	Specific Surface Area (m ² /cc)			0.38	

*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					
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 (m³/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)*			Size Distribution (Malvern)*		
N	0.91	0.82	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin	cum. vol. per.
S	0.40	0.36	188m	0.00	100.0	118.4m2		
Cl	0.03	0.03	162m	0.00	100.0	102.1m2		
Ash	6.16	5.53	140m	0.00	100.0	88.1m2		
Ash Chemistry	% dry fuel	% ash	121m	0.00	100.0	76m2		
SiO2	1.87	30.42	104m	0.00	100.0	65.6m2		
Al2O3	0.91	14.81	89.9m	0.03	100.0	56.6m2		
TiO2	0.07	1.12	77.5m	0.18	99.8	48.8m2		
Fe2O3	0.44	7.22	66.9m	1.00	98.8	42.1m2		
CaO	1.28	20.72	57.7m	2.50	96.3	38.3m2		
MgO	0.31	5.08	49.8m	4.75	91.6	31.3m2		
K2O	0.02	0.38	42.9m	7.30	84.3	27m2		
Na2O	0.12	1.95	37.1m	9.20	75.1	23.3m2		
SO3	1.00	16.16	32m	9.20	65.9	20.1m2		
P2O5	0.07	1.08	27.6m	7.28	58.6	17.4m2		
Cl			23.8m	5.60	53.0	15m2		
Undetermined	0.07	1.07	20.5m	5.05	47.9	12.9m2		
Total	6.16	100.0	17.7m	5.25	42.7	11.1m2		
Forms of Sulfur (% dry fuel)			15.3m	5.48	37.2	9.6m2		
Pyritic	0.07		13.2m	5.03	32.2	8.3m2		
Organic	0.27		11.4m	4.10	28.1	7.2m2		
Sulfatic	0.00		9.8m	3.38	24.7	6.2m2		
Fraction Free Silica	0.27		8.5m	3.10	21.6	5.3m2		
Fraction Pyritic Iron	0.13		7.3m	3.13	18.5	4.8m2		
Heating Value (Btu/lb, dry)			6.3m	3.18	15.3	4m2		
As Fired	11877	10655	5.4m	3.08	12.2	3.4m2		
Dulong	11762	10551	4.7m	2.73	9.5	3m2		
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	2.25	7.3	2.8m2		
Na			3.5m	1.73	5.5	2.2m2		
Mg			3m	1.25	4.3	1.9m2		
Ca			2.6m	1.03	3.3	1.6m2		
K			2.2m	0.83	2.4	1.4m2		
Fusion Temp.	°F	°C	1.9m	1.23	1.2	1.2m2		
Reducing Conditions			Size Statistics (Malvern Data Only)					
Initial Deformation	2066	1130				Malvern	All Data	
Spherical	2113	1156	Dv.5	Volume Mean Diam.		20.20		
Hemispherical	2131	1166	Dv.9	90 % volume diameter		44.78		
Fluid	2188	1198	Dv.1	10 percentile volume diameter		4.55		
Oxidizing Conditions			D4,3			22.93		
Initial Deformation	2132	1167	D3,2	Sauter Mean Diameter		10.40		
Spherical	2177	1191	Span			1.98		
Hemispherical	2202	1205	Specific Surface Area (m^3/cc)			0.61		
Fluid	2271	1244						

*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		mass % in size bin	
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
S	0.53	0.43	(µm)	size bin	(µm)	size bin
Cl	0.02	0.02		per.		per.
Ash	5.12	4.23	188m	0.36	99.6	118.4m2
Ash Chemistry	% dry fuel	% ash	162m	0.95	98.7	102.1m2
SiO2	1.32	25.78	140m	1.41	97.3	88.1m2
Al2O3	0.87	16.96	121m	1.78	95.5	76m2
TiO2	0.06	1.15	104m	1.89	93.6	65.6m2
Fe2O3	0.33	6.42	89.9m	1.96	91.7	56.6m2
CaO	0.74	14.51	77.5m	2.05	89.6	48.8m2
MgO	0.16	3.14	66.9m	2.48	87.1	42.1m2
K2O	0.02	0.47	57.7m	3.40	83.7	38.3m2
Na2O	0.41	7.99	49.8m	5.38	78.4	31.3m2
SO3	1.07	20.83	42.9m	7.54	70.8	27m2
P2O5	0.05	0.93	37.1m	9.31	61.5	23.3m2
Cl			32m	9.10	52.4	20.1m2
Undetermined	0.09	1.82	27.6m	7.10	45.3	17.4m2
Total	5.12	100.0	23.8m	5.41	39.9	15m2
Forms of Sulfur (% dry fuel)			20.5m	4.73	35.2	12.9m2
Pyritic	0.16		17.7m	4.95	30.2	11.1m2
Organic	0.33		15.3m	5.19	25.0	9.6m2
Sulfatic	0.04		13.2m	4.65	20.4	8.3m2
Fraction Free Silica	0.02		11.4m	3.71	16.7	7.2m2
Fraction Pyritic Iron	0.61		9.8m	2.75	13.9	6.2m2
Heating Value (Btu/lb, dry)			8.5m	2.33	11.6	5.3m2
As Fired	12424	10253	7.3m	2.28	9.3	4.8m2
Dulong	12315	10162	6.3m	2.23	7.1	4m2
Acid Sol. Alkali (ppm)	Dry	As Rec'd	5.4m	2.01	5.1	3.4m2
Na			4.7m	1.53	3.6	3m2
Mg			4.1m	1.01	2.5	2.8m2
Ca			3.5m	0.79	1.8	2.2m2
K			3m	0.54	1.2	1.9m2
Fusion Temp.	°F	°C	2.6m	0.31	0.9	1.6m2
Reducing Conditions			2.2m	0.31	0.6	1.4m2
Initial Deformation	2056	1124	1.9m	0.49	0.1	1.2m2
Spherical	2143	1173	Size Statistics (Malvern Data Only)			
Hemispherical	2161	1183			Malvern	All Data
Fluid	2194	1201	Dv.5	Volume Mean Diam.	31.06	
Oxidizing Conditions			Dv.9	90 % volume diameter	64.68	
Initial Deformation	2333	1278	Dv.1	10 percentile volume diameter	7.63	
Spherical	2457	1347	D4,3		34.15	
Hemispherical	2472	1356	D3,2	Sauter Mean Diameter	15.80	
Fluid	2495	1368	Span		1.76	
			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				
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
S	0.48	0.38					cum. vol. per.
Cl	0.08	0.06	188m	0.00	100.0	118.4m2	
Ash	6.46	5.08	162m	0.05	100.0	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	0.05	99.9	88.1m2	
SiO2	1.96	30.31	121m	0.05	99.9	76m2	
Al2O3	1.05	16.27	104m	0.05	99.8	65.6m2	
TiO2	0.08	1.27	89.9m	0.15	99.7	56.6m2	
Fe2O3	0.33	5.04	77.5m	1.10	98.6	48.8m2	
CaO	1.36	21.07	66.9m	3.05	95.5	42.1m2	
MgO	0.31	4.74	57.7m	5.85	89.7	38.3m2	
K2O	0.02	0.35	49.8m	8.55	81.1	31.3m2	
Na2O	0.09	1.41	42.9m	9.40	71.7	27m2	
SO3	1.13	17.46	37.1m	9.30	62.4	23.3m2	
P2O5	0.06	0.91	32m	7.85	54.6	20.1m2	
Cl			27.6m	6.05	48.5	17.4m2	
Undetermined	0.08	1.17	23.8m	5.35	43.2	15m2	
Total	6.46	100.0	20.5m	5.50	37.7	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	5.65	32.0	11.1m2	
Pyritic	0.08		15.3m	5.30	26.7	9.6m2	
Organic	0.40		13.2m	4.25	22.5	8.3m2	
Sulfatic	0.00		11.4m	3.45	19.0	7.2m2	
Fraction Free Silica	0.19		9.8m	2.95	16.1	6.2m2	
Fraction Pyritic Iron	0.31		8.5m	2.70	13.4	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	2.50	10.9	4.8m2	
As Fired	12815	10085	6.3m	2.30	8.6	4m2	
Dulong	11993	9438	5.4m	2.05	6.5	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.70	4.8	3m2	
Na			4.1m	1.20	3.6	2.8m2	
Mg			3.5m	1.05	2.6	2.2m2	
Ca			3m	0.70	1.9	1.9m2	
K			2.6m	0.50	1.4	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.40	1.0	1.4m2	
Reducing Conditions			1.9m	0.80	0.2	1.2m2	
Initial Deformation	2121	1161	Size Statistics (Malvern Data Only)				
Spherical	2152	1178	Dv.5	Volume Mean Diam.		Malvern	All Data
Hemispherical	2172	1189	Dv.9	90 % volume diameter		24.75	
Fluid	2210	1210	Dv.1	10 percentile volume diameter		50.10	
Oxidizing Conditions			D4,3			6.05	
Initial Deformation	2154	1179	D3,2	Sauter Mean Diameter		27.35	
Spherical	2192	1200	Span			13.50	
Hemispherical	2209	1209				1.75	
Fluid	2269	1243				0.46	
			Specific Surface Area (m ² /cc)				

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

*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 % in		cum. vol.	Diameter	% in	cum. vol.
S	0.56	0.45	(µm)	size bin	per.	(µm)	size bin	per.
Cl	0.04	0.03	188m	0.00	100.0	118.4m2	0.08	99.9
Ash	6.18	4.96	162m	0.05	100.0	102.1m2	0.13	99.9
Ash Chemistry	% dry fuel	% ash	140m	0.08	99.9	88.1m2	0.15	99.9
SiO2	1.61	26.06	121m	0.13	99.8	76m2	0.10	99.9
Al2O3	0.86	13.96	104m	0.13	99.6	65.6m2	0.38	99.6
TiO2	0.08	1.29	89.9m	0.13	99.5	56.6m2	3.45	96.6
Fe2O3	0.33	5.35	77.5m	0.45	99.1	48.8m2	7.43	92.6
CaO	1.51	24.40	66.9m	1.45	97.6	42.1m2	9.40	90.6
MgO	0.26	4.28	57.7m	3.18	94.4	38.3m2	9.35	90.7
K2O	0.01	0.19	49.8m	5.58	88.9	31.3m2	8.50	91.5
Na2O	0.05	0.86	42.9m	8.18	80.7	27m2	8.20	91.8
SO3	1.29	20.82	37.1m	9.88	70.8	23.3m2	8.10	91.9
P2O5	0.06	0.99	32m	9.75	61.1	20.1m2	6.75	93.3
Cl			27.6m	7.98	53.1	17.4m2	5.15	94.9
Undetermined	0.11	1.80	23.8m	6.18	46.9	15m2	4.90	95.1
Total	6.18	100.0	20.5m	5.30	41.6	12.9m2	5.35	94.7
Forms of Sulfur (% dry fuel)			17.7m	5.45	36.2	11.1m2	4.58	95.4
Pyritic	0.12		15.3m	5.68	30.5	9.6m2	3.70	96.3
Organic	0.40		13.2m	5.40	25.1	8.3m2	2.68	97.3
Sulfatic	0.04		11.4m	4.45	20.6	7.2m2	2.18	97.8
Fraction Free Silica	0.21		9.8m	3.45	17.2	6.2m2	2.13	97.9
Fraction Pyritic Iron	0.43		8.5m	2.88	14.3	5.3m2	1.90	98.1
Heating Value (Btu/lb, dry)			7.3m	2.58	11.7	4.8m2	1.53	98.5
As Fired	11927	9573	6.3m	2.43	9.3	4m2	1.28	98.7
Dulong	11881	9536	5.4m	2.20	7.1	3.4m2	1.13	98.9
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.90	5.2	3m2	0.88	99.1
Na			4.1m	1.15	4.1	2.8m2	0.45	99.6
Mg			3.5m	1.08	3.0	2.2m2	0.10	99.9
Ca			3m	0.83	2.2	1.9m2	0.00	100.0
K			2.6m	0.53	1.6	1.6m2	0.00	100.0
Fusion Temp.	°F	°C	2.2m	0.40	1.2	1.4m2	0.00	100.0
Reducing Conditions			1.9m	0.53	0.7	1.2m2	0.00	100.0
Initial Deformation	2161	1183	Size Statistics (Malvern Data Only)					
Spherical	2214	1212			Malvern		All Data	
Hemispherical	2236	1224	Dv.5	Volume Mean Diam.	23.10			
Fluid	2288	1253	Dv.9	90 % volume diameter	45.41			
Oxidizing Conditions			Dv.1	10 percentile volume diameter	6.29			
Initial Deformation	2154	1179	D4,3		25.04			
Spherical	2204	1207	D3,2	Sauter Mean Diameter	13.66			
Hemispherical	2231	1222	Span		1.71			
Fluid	2285	1252	Specific Surface Area (m²/3/cc)		0.44			

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

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

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

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

Beulah

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	cum. vol.
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	cum. mass %
Fixed Carbon	17.51	14.27	dp>600µm		+28	0.00	0.00
Volatile Matter	30.41	24.78	600µm>dp>300µm		28x48	2.40	2.40
Moisture	18.50		300µm>dp>149µm		48x100	9.83	12.23
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	18.28	30.50
C	29.43	23.99	74µm>dp>44µm		200x325	17.23	47.73
H	3.20	2.61	44µm>dp		-325	52.28	100.00
O	12.95	10.55	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	0.51	0.41	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	1.75	1.43					
Cl	0.08	0.06					
Ash	52.18	42.53					
Ash Chemistry	% dry fuel	% ash					
SiO2	34.36	65.85	188m	0.00	100.0	118.4m2	0.10
Al2O3	10.13	19.41	162m	0.00	100.0	102.1m2	0.35
TiO2	0.45	0.87	140m	0.00	100.0	88.1m2	0.40
Fe2O3	0.87	1.66	121m	0.00	100.0	76m2	0.35
CaO	1.56	2.99	104m	0.00	100.0	65.6m2	0.25
MgO	0.25	0.48	89.9m	0.08	99.9	56.6m2	1.80
K2O	0.98	1.88	77.5m	0.13	99.8	48.8m2	4.90
Na2O	1.35	2.60	66.9m	0.15	99.6	42.1m2	6.85
SO3	1.47	2.82	57.7m	0.22	99.4	38.3m2	7.55
P2O5	0.00	0.01	49.8m	1.02	98.4	31.3m2	7.50
Cl	0.01	0.02	42.9m	2.78	95.6	27m2	7.30
Undetermined	0.74	1.42	37.1m	4.85	90.8	23.3m2	6.75
Total	52.17	100.0	32m	6.48	84.3	20.1m2	6.05
Forms of Sulfur (% dry fuel)			27.6m	6.97	77.3	17.4m2	5.60
Pyritic	0.29		23.8m	6.90	70.4	15m2	5.60
Organic	1.35		20.5m	6.68	63.7	12.9m2	5.55
Sulfatic	0.10		17.7m	6.70	57.0	11.1m2	4.80
Fraction Free Silica	0.56		15.3m	6.73	50.3	9.6m2	4.30
Fraction Pyritic Iron	0.41		13.2m	6.45	43.8	8.3m2	3.90
Heating Value (Btu/lb, dry)			11.4m	5.95	37.9	7.2m2	3.55
As Fired	5076	4137	9.8m	5.12	32.8	6.2m2	3.30
Dulong	5334	4347	8.5m	4.45	28.3	5.3m2	2.85
Acid Sol. Alkali (ppm)	Dry	As Rec'd	7.3m	4.05	24.3	4.8m2	2.40
Na	8788	8788	6.3m	3.95	20.3	4m2	2.20
Mg	1156	1156	5.4m	3.78	16.5	3.4m2	2.10
Ca	7628	7628	4.7m	3.42	13.1	3m2	1.75
K	5862	5862	4.1m	2.88	10.2	2.8m2	0.80
Fusion Temp.	°F	°C	3.5m	2.13	8.1	2.2m2	0.60
Reducing Conditions			3m	1.58	6.5	1.9m2	0.30
Initial Deformation	2349	1287	2.6m	1.37	5.2	1.6m2	0.00
Spherical	2458	1348	2.2m	1.30	3.9	1.4m2	0.10
Hemispherical	2580	1416	1.9m	2.33	1.5	1.2m2	0.10
Fluid	2759	1515	Size Statistics (Malvern Data Only)				
Oxidizing Conditions					Malvern	All Data	
Initial Deformation	2338	1281	Dv.5	Volume Mean Diam.	14.76		
Spherical	2433	1334	Dv.9	90 % volume diameter	34.26		
Hemispherical	2576	1413	Dv.1	10 percentile volume diameter	3.89		
Fluid	2762	1517	D4,3		17.45		
			D3,2	Sauter Mean Diameter	8.39		
			Span		2.06		
			Specific Surface Area (m ² /cc)		0.76		

*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
Fixed Carbon	61.06	60.62	dp>600µm	+28	0.00
Volatile Matter	30.27	30.05	600µm>dp>300µm	28x48	0.00
Moisture	0.72		300µm>dp>149µm	48x100	1.30
Ultimate	Dry	As Rec'd	149µm>dp>74µm	100x200	26.30
C	77.95	77.39	74µm>dp>44µm	200x325	26.30
H	4.79	4.76	44µm>dp	-325	46.10
O	5.51	5.47	Size Distribution (Malvern)*		Size Distribution (Malvern)*
N	1.43	1.42	Diameter (µm)	% in size bin	cum. vol. per.
S	1.65	1.64			
Cl					
Ash	8.67	8.61			
Ash Chemistry	% dry fuel	% ash			
SiO ₂	4.25	49.03			
Al ₂ O ₃	2.13	24.53			
TiO ₂	0.09	1.00			
Fe ₂ O ₃	1.48	17.03			
CaO	0.20	2.31			
MgO	0.07	0.86			
K ₂ O	0.17	1.99			
Na ₂ O	0.03	0.36			
SO ₃	0.17	1.92			
P ₂ O ₅	0.03	0.37			
Cl					
Undetermined	0.05	0.60			
Total	8.67	100.0			
Forms of Sulfur (% dry fuel)					
Pyritic	0.89				
Organic	0.75				
Sulfatic	0.01				
Fraction Free Silica	0.25				
Fraction Pyritic Iron	0.75				
Heating Value (Btu/lb, dry)					
As Fired	13933	13833			
Dulong					
Acid Sol. Alkali (ppm)	Dry	As Rec'd			
Na					
Mg					
Ca					
K					
Fusion Temp.	°F	°C			
Reducing Conditions					
Initial Deformation	2133	1167			
Spherical	2429	1332			
Hemispherical	2449	1343			
Fluid	2500	1371			
Oxidizing Conditions					
Initial Deformation	2497	1369			
Spherical	2574	1412			
Hemispherical	2602	1428			
Fluid	2632	1444			
			Size Statistics (Malvern Data Only)		
				Malvern	All Data
			Dv.5	Volume Mean Diam.	
			Dv.9	90 % volume diameter	
			Dv.1	10 percentile volume diameter	
			D4,3		
			D3,2	Sauter Mean Diameter	
			Span		
			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					cum. vol. per.
Cl	0.07	0.06	188m	1.83	98.2	118.4m2	
Ash	6.26	5.84	162m	4.39	93.8	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	5.51	88.3	88.1m2	
SiO2	2.42	38.68	121m	5.36	82.9	76m2	
Al2O3	1.29	20.56	104m	3.92	79.0	65.6m2	
TiO2	0.06	1.03	89.9m	2.77	76.2	56.6m2	
Fe2O3	0.73	11.71	77.5m	3.74	72.5	48.8m2	
CaO	0.48	7.67	66.9m	4.46	68.1	42.1m2	
MgO	0.11	1.68	57.7m	4.80	63.3	38.3m2	
K2O	0.07	1.18	49.8m	5.54	57.7	31.3m2	
Na2O	0.21	3.38	42.9m	6.08	51.6	27m2	
SO3	0.65	10.39	37.1m	7.15	44.5	23.3m2	
P2O5	0.04	0.70	32m	6.53	38.0	20.1m2	
Cl			27.6m	5.22	32.7	17.4m2	
Undetermined	0.04	0.62	23.8m	4.18	28.6	15m2	
Total	6.11	97.6	20.5m	3.63	24.9	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	3.50	21.4	11.1m2	
Pyritic	0.41		15.3m	3.51	17.9	9.6m2	
Organic	0.61		13.2m	3.24	14.7	8.3m2	
Sulfatic	0.08		11.4m	2.72	12.0	7.2m2	
Fraction Free Silica	0.20		9.8m	2.09	9.9	6.2m2	
Fraction Pyritic Iron	0.68		8.5m	1.65	8.3	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	1.46	6.8	4.8m2	
As Fired	13357	12448	6.3m	1.40	5.4	4m2	
Dulong	12948	12066	5.4m	1.34	4.1	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.21	2.9	3m2	
Na			4.1m	0.86	2.0	2.8m2	
Mg			3.5m	0.67	1.3	2.2m2	
Ca			3m	0.69	0.6	1.9m2	
K			2.6m	0.34	0.3	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.29	0.0	1.4m2	
Reducing Conditions			1.9m	0.54	-0.5	1.2m2	
Initial Deformation	2139	1171	Size Statistics (Malvern Data Only)				
Spherical	2201	1205			Malvern	All Data	
Hemispherical	2243	1228	Dv.5	Volume Mean Diam.	53.26		
Fluid	2342	1283	Dv.9	90 % volume diameter	80.51		
Oxidizing Conditions			Dv.1	10 percentile volume diameter	24.72		
Initial Deformation	2319	1271	D4,3		51.78		
Spherical	2338	1281	D3,2	Sauter Mean Diameter	24.84		
Hemispherical	2388	1309	Span		1.31		
Fluid	2443	1339	Specific Surface Area (m ² /cc)		0.33		

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

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

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

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

*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	cum. vol.
S	1.56	1.46	(µm)	size bin	per.	(µm)	size bin	per.
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^3/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)*			Size Distribution (Malvern)*	
N	1.11	0.89	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	1.74	1.39					cum. vol. per.
Cl	0.00	0.00	188m	0.00	100.0	118.4m2	
Ash	8.91	7.11	162m	0.00	100.0	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	0.05	100.0	88.1m2	
SiO2	2.63	29.55	121m	0.05	99.9	76m2	
Al2O3	1.29	14.44	104m	0.05	99.9	65.6m2	
TiO2	0.09	1.01	89.9m	0.05	99.8	56.6m2	
Fe2O3	1.21	13.57	77.5m	0.15	99.7	48.8m2	
CaO	1.31	14.70	66.9m	1.15	98.5	42.1m2	
MgO	0.32	3.54	57.7m	3.10	95.4	38.3m2	
K2O	0.10	1.12	49.8m	6.10	89.3	31.3m2	
Na2O	0.11	1.27	42.9m	8.80	80.5	27m2	
SO3	1.84	20.67	37.1m	9.25	71.3	23.3m2	
P2O5	0.02	0.28	32m	8.60	62.7	20.1m2	
Cl			27.6m	7.15	55.5	17.4m2	
Undetermined	0.01	0.08	23.8m	5.70	49.8	15m2	
Total	8.93	100.2	20.5m	5.50	44.3	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	5.85	38.5	11.1m2	
Pyritic	0.55		15.3m	5.70	32.8	9.6m2	
Organic	0.88		13.2m	5.20	27.6	8.3m2	
Sulfatic	0.31		11.4m	4.25	23.3	7.2m2	
Fraction Free Silica	0.26		9.8m	3.60	19.7	6.2m2	
Fraction Pyritic Iron	0.49		8.5m	3.25	16.5	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	2.95	13.5	4.8m2	
As Fired	11876	9473	6.3m	2.70	10.8	4m2	
Dulong	11835	9441	5.4m	2.40	8.4	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	2.10	6.3	3m2	
Na			4.1m	1.90	4.4	2.8m2	
Mg			3.5m	1.30	3.1	2.2m2	
Ca			3m	1.10	2.0	1.9m2	
K			2.6m	0.70	1.3	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.45	0.9	1.4m2	
Reducing Conditions			1.9m	0.30	0.6	1.2m2	
Initial Deformation	1999	1093	Size Statistics (Malvern Data Only)				
Spherical	2106	1152	Dv.5	Volume Mean Diam.		Malvern	All Data
Hemispherical	2142	1172	Dv.9	90 % volume diameter		23.90	
Fluid	2233	1223	Dv.1	10 percentile volume diameter		50.60	
Oxidizing Conditions			D4,3			6.00	
Initial Deformation	2188	1198	D3,2	Sauter Mean Diameter		27.15	
Spherical	2212	1211	Span			13.45	
Hemispherical	2239	1226				1.85	
Fluid	2320	1271					
			Specific Surface Area (m ² /cc)				0.45

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

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