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The Release of Iron During Coal Combustion

Milestone Report

L.L. Baxter

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THE RELEASE OF IRON DURING COAL COMBUSTION

Milestone Report

Larry L. Baxter
Combustion Research Facility
Sandia National Laboratories
Livermore, CA 94551-0969

Abstract

A series of investigations of iron release during combustion is reported for a suite of coals ranging in rank from lignite to low-volatile (lv) bituminous coal under combustion conditions ranging from oxidizing to inert. Experimental measurements are described in which, under selected conditions, major fractions of the iron in the coal are released within a 25 ms period immediately following coal devolatilization. Mechanistic interpretation of the data suggest that the iron is released as a consequence of oxygen attack on porous pyrrhotite particles. Experimental testing of the proposed mechanism reveals that the release is dependent on the presence of both pyrite in the raw coal and oxygen in the gas phase, that slow preoxidation (weathering) of the pyrite significantly inhibits the iron release, and that iron loss increases as oxygen penetration of the particle increases. Each observation is consistent with the postulated mechanism.

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Introduction

Iron plays an important role in the formation of both fly ash and deposits in many pulverized-coal-fired boilers. Several authors indicate that iron content is a significant indicator of the slagging propensity of a majority of U.S. bituminous coals, in particular eastern bituminous coals [Bryers, 1976; Raask, 1985]. The pyritic iron content of these coals is shown to be a particularly relevant consideration.

The decomposition of pyrite in combustion environments has been discussed by many authors [Cole, et al., 1987; Groves, et al., 1987; Huffman, et al., 1989; Raask, 1985; Srinivasachar and Boni, 1989; Srinivasachar, et al., 1990; Taneja and Jones, 1984]. These authors describe how pyrite decomposes to form pyrrhotite in inert environments at temperatures of 720-820 K. Pyrrhotite often has no definite crystalline structure and its approximate chemical composition is Fe_7S_8 . Under conditions of even modest heating rates and upon exposure to oxygen, pyrite decomposition products can be highly porous materials [Dunn, et al., 1989]. The decomposition of pyrite to pyrrhotite effects an increase in porosity and some channeling and fragmentation [Baxter, 1990]. Pyrrhotite melts in an inert environment at temperatures between 800 and 1450 K, depending on its mode of preparation. At higher temperatures, pyrrhotite can further decompose to form metallic iron. Both pyrite and pyrrhotite are reactive to oxygen. Pyrites combined with carbon also combust differently, usually more slowly, than pure pyrites. Therefore, the transformations of pyrite inclusions in coal particles during combustion are potentially complex but qualitatively understood.

Our work focuses on the release of iron-containing material from coal during combustion. The mode of occurrence of iron in the coals studied varies from primarily (> 95 %) pyrite to dominantly nonpyritic (sulfates, oxides, and carbonates). Experimental evidence for the release of iron-containing material from coal/char particles leads to a chemical/physical mechanistic interpretation directly related to pyrite decomposition and reaction. Further experiments test the critical aspects of this proposed mechanism and contrast it to vaporization, the more common explanation for this type of data. Finally, reported observations by other investigators are discussed, together with their possible explanation by the same mechanism.

Coal Characterization and Experimental Conditions

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 Iv 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 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 1 - 5. 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 (N₂) 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/cm² 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].

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).

Loss of a selected element from the coal and char particles can be determined from elemental analyses of their inorganic material and a knowledge of the overall particle mass loss by the following equation:

$$f_i(t) = \frac{x_i(t)}{x_i(0)} \frac{m(t)}{m(0)} \quad (1)$$

The variable f represents the total mass of any constituent of the particle (in this case iron), normalized by its original mass. The variable x represents the mass fraction of that constituent in the particle at residence time t . The variable m represents the total particle mass. The subscript i is an index for the various inorganic elements. Time-dependent values and initial values are indicated by t and 0 as independent variables, respectively.

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	lv Bituminous
Lower Kittanning	1516-D	81.4	18.6	15488	10.3	lv 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.

Elemental analyses of the unreacted sample and the sample of the raw material provide the information required to compute the first fraction in Equation 1. Both "tracer" and, where possible, mass balance techniques allow estimations of the second fraction, i.e., the residual particle mass. Only the CCL provides a capability to determine overall mass loss by an experimentally determined mass balance. Residual mass of the particles in this reactor is determined both by calculating the ratio of mass of coal fed to mass of char collected and by a tracer technique. Agreement between the two techniques is excellent so long as appropriate tracers are chosen.

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

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

† Ash is on a dry basis.

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

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

Figure 1. 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 2. 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 $1\text{ }\mu\text{m}$ in diameter.

Figure 3. 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.

Figure 4. 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 5. Schematic diagram of the Sandia Multifuel Combustor. A sampling system similar to that illustrated in Figure 2 is used with the MFC.

Any element that does not leave the particles during reaction may be used as a tracer. The residual mass is determined from a tracer as follows:

$$\frac{m(t)}{m(0)} = \frac{x_j(0)}{x_j(t)} \quad (2)$$

where subscript j identifies a tracer. Note that the precision of the measure of residual particle mass depends on the precision of the tracer measurement in the raw coal. Promising candidates for tracers include silicon, aluminum and, in some cases, titanium [Baxter, et al., 1993]. The independent analysis of all three of these quantities provides a cross check of the data and allows determination of statistical confidence intervals. A mass balance technique, i.e., the ratio of mass collected to mass fed in the reactor, allows a fourth independent measure of overall mass loss.

The overall mass loss ($1-m/m_O$) estimated by a tracer using Equation 2 will be low if a portion of the tracer is lost from the sample during the experiment. Two provisions prevent data from bias of this type in these experiments. First, the tracers selected for these experiments occur in significantly different modes and as different size grains in the coal. The silicon and aluminum occur in the form of silica or silicate grains in the coal matrix. The size distributions of these grains have been measured as a function of burnout, with mineral grain sizes in the raw coal on the order of 5-10 μm [Baxter, 1990]. The titanium, on the other hand, is more homogeneously dispersed through the coal and typically occurs in smaller size grains. Some of the titanium is also atomically dispersed. It is unlikely that mineral species, with such differences in size and mode of occurrence in the coal, are sensitive to the same types of evolution processes.

The second provision against systematic bias of the data involves the comparison between the results of the mass balance and tracer techniques. Inorganic species used as tracers may be lost from the coal or char particle during combustion but cannot systematically be added to the coal. Therefore, the tracer techniques will bias the estimate of m/m_O to higher values, if at all. On the other hand, a value of m/m_O determined from a mass balance on the reactor may be too low, due to sample lost from the collection system. However, the mass balance technique cannot systematically overestimate the overall mass loss. Therefore, the two techniques will be biased in opposite directions, if at all. Agreement between the results from the two techniques provides a reasonably rigorous test of both the precision and accuracy of the m/m_O values.

Results and Discussion

Fuel Characterization

The fuel on which the initial experiments focus is a hva bituminous, Illinois #6 coal (PSOC-1493d). Size- and aerodynamically-classified samples of this coal in two size ranges (75-105 μm and 106-125 μm) are involved in the experiments. The elemental mass fractions of the inorganic constituents of these two size fractions of the coal appear in Table 3 as oxide percents. The values in the table represent averages and coefficients of variation from two to eight replicate measurements for each size class. Total ash content was also measured independently of the elemental ash composition. This measured result is presented together with the sum of the oxides in the table. The total ash content is typically higher than the sum of the elemental components, with the difference representing unmeasured species. Sulfur is the largest contributor to these unmeasured species.

Elemental compositions of the ash of the two size fractions differ in the amount of magnesium, calcium, sodium, potassium, iron, aluminium, silicon, and titanium, in that order. The differences in the mineral compositions are sufficiently large that the two size fractions are treated separately in the analysis of the data.

The variation in measured iron content is large compared with other major components of the ash. This large variation must be recognized when interpreting the results of experiments. Analysis of the sulfur forms in this coal indicates that essentially all (> 95 %) of the iron is originally bound

as pyrite. Silicon, aluminum and titanium are the most precisely determined ash species in these experiments, as indicated by the coefficient of variations. Four replicated samples were used in determining all of the compositions for the 75-106 μm size fraction. At least six replicates were used in determining the silicon, aluminium, titanium and iron compositions of the 106-125 μm coal particles. Four replicated measurements were performed for the remaining elements except magnesium, for which two measurements were obtained. All of these measurements were performed in the same laboratory by the same technique. Additional measurements were obtained at other laboratories with these samples and by other investigators using very similar samples of the same coal. These additional data are not used in analyzing the results of our experiments due to relatively high laboratory-to-laboratory variations in the results.

Accuracy and consistency of the CDL- and CCL-derived chemical analyses are monitored by periodic analysis of NIST standard coals. Results for the 22 analyses of the NIST standard coals completed during the course of this project are summarized in Table 4 for the eight major elements common to coal ashes. Both the accuracy and precision of the measurements are relevant to our results. The precision is arguably more significant than the accuracy and is indicated by the standard deviation and the coefficient of variation (standard deviation divided by the mean). The four elements relevant to this study are Si, Ti, Fe, and Al. As is indicated in the table, the standard deviation is less than 6 % of the mean for these components. The accuracy is indicated by the ratio

Table 3
Elemental analysis of the inorganic constituents of size-classified samples of Illinois #6 coal.

Oxide	75-106 mm Fraction		106-125 mm Fraction	
	Mean (mass %)	Coefficient of Variation (-)	Mean (mass %)	Coefficient of Variation (-)
SiO ₂	3.61	0.061	4.23	0.140
TiO ₂	0.088	0.042	0.092	0.102
Fe ₂ O ₃	4.2	0.137	3.55	0.162
Al ₂ O ₃	1.43	0.049	1.68	0.123
CaO	0.70	0.206	0.56	0.382
MgO	0.011	2.00	0.110	0.334
Na ₂ O	0.096	0.208	0.039	0.336
K ₂ O	0.18	0.310	0.14	0.640
Ash				
(sum)	10.31	—	10.40	—
(measured)	11.83	0.112	11.85	0.174

of the average measured value to the certified value in the standard. The average measured values of the components most relevant to this investigation (Si, Al, Ti, and Fe) are all within 5 % of the certified value. These data provide a traceable path between our measurements and certified NIST standards. Measurements are both less accurate and less precise for the alkali and alkaline earth elements, due in part to their low overall concentrations in the fuel.

The chemical analysis laboratories of CONSOL Inc. analyzed all samples derived from the MFC. These analyses benefit from the coal-specific optimized procedures used by CONSOL. All samples were done in duplicate, with the average of the two measurements reported. Every third sample is a NIST-traceable standard and is used as the basis for calibration of the instrument. The accuracy and precision of the elemental compositions so analyzed are approximately ± 3 % of the measured values.

Based on these results and statistical analysis of the data, trends in data from both the small scale reactors (CDL and CCL) and the MFC are shown to significantly exceed measurement uncertainty with respect to chemical analysis. Uncertainty introduced by experimental techniques is also quantified and shown to be small compared to trends observed in the data. These results also indicate that the variations in measured initial concentrations of the samples, as indicated in Table 3, are usually dominated by true sample-to-sample variation rather than chemical analysis error.

Table 4

Experimentally determined composition of the inorganic constituents of a NIST standard coal (NBS 1632b) compared with the certified values.

Oxide	Laboratory Results		NIST Certified Values	
	Mean (mass %)	Coefficient of Variation (-)	Mean (mass %)	Ratio of Lab to Standard (-)
SiO ₂	2.95	0.042	3.00*	0.98
TiO ₂	0.0724	0.055	0.076	0.95
Fe ₂ O ₃	1.05	0.048	1.09	0.96
Al ₂ O ₃	1.62	0.036	1.615	1.00
CaO	0.282	0.154	0.26	1.08
MgO	0.0627	0.198	0.064	0.98
Na ₂ O	0.0656	0.326	0.069	0.95
K ₂ O	0.0755	0.470	0.09	0.84

* The value for silicon is reported by NIST but not certified.

Overall Mass Loss

Figure 6 illustrates typical (m/m_O) data obtained during these experiments. The data are tightly grouped, with no large and consistent differences between the results of the various analyses. A detailed examination indicates that the titanium results are consistently different from the others for reasons discussed in detail elsewhere [Baxter, et al., 1993]. For our purposes, however, the results are in sufficient agreement. Similar data were obtained for each particle size range and each gas environment.¹ Table 5 summarizes all of the m/m_O data for this coal and reports mean values (μ), standard deviations (σ), and confidence intervals for the mean values. In general, the value of m/m_O is determined within 5-10 absolute percent at a 95 percent confidence level. Note that the confidence intervals are for *the mean value of m/m_O* , not an indication of the range of variation among the m/m_O values.

Iron Loss

These data and the elemental analysis of iron in the char particles provide the information required in Equation 1 to estimate the amount of iron released from the coal. Figure 7 shows the results of such an analysis for particles from the 106-125 μm size fraction in the 6 percent oxygen environment (top) and the 12 percent oxygen environment (bottom). These data indicate a large and rapid depletion of iron in the char immediately after coal devolatilization, but before significant char oxidation. Approximately 45 percent of the total original iron in the coal particle leaves over this 25 ms time period. The statistical analysis of all of the experiments performed with the large particles is reported in Table 6. The small particle data are discussed later.

The data in Table 3 show the magnitude of variations in measured iron content of the raw coal. The nonzero confidence intervals shown at a residence time of 0 ms in Figure 7 reflect this variation. Both imprecision in the measurement and actual sample-to-sample variation in the iron content contribute to this variation. The detection limit for iron by this analysis technique is 0.001 weight percent, which is equal to or lower than the detection limits for the species being used as tracers. In addition, data for each single sample are closely grouped. Therefore, the variability in measured iron content shown in Table 3 and at 0 ms in Figure 7 are apparently due to actual sample-to-sample variation rather than to imprecise experimental technique. This sample-to-sample variation in iron content is also the likely cause for the indicated increase in average iron content indicated in Table 6 in the 12 % oxygen environment at a particle residence time of 47 ms.

¹Systematic errors in the mass balance technique were observed for two data points (47 and 72 ms) in the 6 % oxygen environment for the 75-106 μm particles. Therefore, these data were not used in the overall data analysis. Elimination of these data has no impact on the qualitative results and only a minimal impact on the quantitative results.

Figure 6. Typical mass loss data obtained during experiments in the CCL. These data are for the 106-125 μm particles in the 6 mole percent oxygen environment. In general, overall mass loss (m/m_o) is determined within about 4 percent.

These sample-to-sample variations in the iron content of the particles persist despite our efforts to homogenize the fuel through size and aerodynamic classification. A comparison of the trends illustrated in Figure 7 with the uncertainty in the measurement (due to all sources, including sample-to-sample variations) is somewhat complicated since the various means of calculating the iron loss (f_i) are not entirely independent. All depend on the same measure of iron in the coal sample. The variance in the value of f can be estimated as a function of residence time by standard techniques using the measured coefficients of variation from Table 3. The variance of f is approximated by the variance of each of its components as follows [Papoulis, 1984]:

$$\sigma_{f_i}^2 = \sigma_{m_i/m_o}^2 \left(\frac{\partial f_i}{\partial m_i/m_o} \right)^2 + \sigma_{x_i}^2 \left(\frac{\partial f_i}{\partial x_i} \right)^2 + \sigma_{x_o}^2 \left(\frac{\partial f_i}{\partial x_o} \right)^2 \quad (3)$$

Table 5
Overall mass loss data and confidence intervals as a function of residence time for
both particle size ranges and both gas environments.

τ^a	μ	σ	95 % Confidence	99 % Confidence
(ms)	(-)	(-)	Interval (+/-) (-)	Interval (+/-) (-)
75-106 μm size Fraction				
6 % Overall Oxygen Concentration				
0.0	1.0	0.0	0.0	0.0
47.0	0.35	0.007	0.061	0.307
72.0	0.31	0.002	0.022	0.109
95.0	0.28	0.006	0.052	0.260
117.0	0.26	0.002	0.002	0.005
12 % Overall Oxygen Concentration				
0.0	1.0	0.0	0.0	0.0
47.0	0.39	0.012	0.015	0.025
72.0	0.31	0.032	0.080	0.185
95.0	0.22	0.005	0.013	0.030
117.0	0.15	0.010	0.026	0.059
106-125 μm size Fraction				
6 % Overall Oxygen Concentration				
0.0	1.0	0.0	0.0	0.0
47.0	0.47	0.021	0.053	0.122
72.0	0.43	0.025	0.061	0.142
95.0	0.40	0.054	0.133	0.307
117.0	0.36	0.029	0.072	0.166
12 % Overall Oxygen Concentration				
0.0	1.0	0.0	0.0	0.0
47.0	0.48	0.022	0.055	0.126
72.0	0.34	0.034	0.084	0.193
95.0	0.25	0.028	0.029	0.045
117.0	0.20	0.022	0.056	0.129

^a Based on measured velocities of a 100 μm particle.

The three right-hand terms represent the contributions from uncertainty in: (1) the overall mass loss, (2) the amount of element i (in this case iron) in the sample, and (3) the amount of element i in the raw coal, respectively. The indicated variances (σ^2) in the equation are taken from Table 2.3 directly for the last and first terms, respectively. The variance in the second term is calculated from the coefficient of variation in Table 3, accounting for the change in the overall iron content of the sample.

If the measured standard deviations in iron measurements are smaller than the 95 % confidence intervals of the chemical measurement technique itself, the latter, more conservative number, is used in its place. The indicated derivatives are evaluated at the mean values of the variables x_i , x_o , and m_i/m_o . Equation 3 becomes

$$\sigma_{f_i}^2 = \sigma_{m_i/m_o}^2 \left(\frac{\langle x_i \rangle}{\langle x_o \rangle} \right)^2 + \sigma_{x_i}^2 \left(\left\langle \frac{m_i}{m_o} \right\rangle \frac{1}{\langle x_o \rangle} \right)^2 + \sigma_{x_o}^2 \left(\left\langle \frac{m_i}{m_o} \right\rangle \frac{\langle x_i \rangle}{\langle x_o \rangle^2} \right)^2 \quad (4)$$

where σ_m represents the variance of measurement m , angle brackets represent mean values, and the remaining terms have been previously defined. Calculation of the variance allows computation of the confidence intervals. The resulting confidence intervals for the data in Figure 7 are shown in Table 6.

Use has been made of the physical bounds on the function f ($0 \leq f(t) \leq 1.0$) in compiling Table 6. Table 6 confirms that the observed trends shown in Figure 7 are larger than the uncertainty in the data. Clearly, a significant fraction of the iron in the coal is released from the coal particles during the 25 ms immediately after devolatilization. The iron is apparently released either as a volatile compound or in the form of a fine particulate fume that is small enough to pass, uncollected, through the filter in the sampling line. As will be shown below, there is compelling evidence that, in fact, the released iron is one component of a fine particulate fume.

Iron dominates the total amount of mineral evolved from this coal in these experiments. Figure 8 illustrates the composition of the original coal minerals on an elemental basis and the fraction of each which evolves from the particle in a typical experiment. Sulfur is excluded from this plot due to the complexity of characterizing the interactions of organic and inorganic sulfur during combustion. Over 80 mass percent (on an elemental basis) of the evolved mineral consisted of iron. These results are from a single experiment. There are random variations in the data that are indicated as small amounts of loss of other inorganic constituents. The small amount of aluminium mass loss indicated in the figure is an example of one such result. In general, there is no indication of any loss of aluminium or silicon during these experiments.

Additional iron-release data for this coal, i.e., those for the 75-106 μm particles, are presented in Fig. 9 and Table 7. The same basic trend is seen in these data, with a large release of iron immediately after coal devolatilization, during the incipient stages of combustion. A more detailed discussion of these data is included after the presentation of a proposed mechanism for this iron release and in the context of testing the predictions of that mechanism.

Figure 7. Iron loss data for the 106-125 μm diameter particles. Data from both the 6 mole % oxygen (a) and 12 mole % oxygen (b) environments in the CCL are shown. The large decrease in iron seen at about 50 ms residence time in both environments corresponds to the incipient stages of oxidation, when the coal particles are first exposed to oxygen.

Table 6
Iron evolution data, with confidence intervals, for the 106-125 μm size fraction
of the Illinois #6 coal in both gas environments.

τ^a	μ	σ	95 % Confidence	99 % Confidence
(ms)	(-)	(-)	Interval (-)	Interval (-)
106—125 μm size Fraction				
6 % Overall Oxygen Concentration				
0.0	1.0	0.0	1.0—1.0	1.0—1.0
47.0	0.91	0.160	1.0—0.77	1.0—0.70
72.0	0.57	0.101	0.66—0.48	0.70—0.43
95.0	0.48	0.102	0.58—0.37	0.64—0.31
117.0	0.54	0.086	0.63—0.46	0.68—0.41
12 % Overall Oxygen Concentration				
0.0	1.0	0.0	1.0—1.0	1.0—1.0
47.0	1.10	0.175	1.0—0.93	1.0—0.84
72.0	0.48	0.196	0.57—0.39	0.63—0.34
95.0	0.56	0.202	0.66—0.46	0.60—0.29
117.0	0.59	0.175	0.70—0.48	0.76—0.42

^a Based on measured velocities of a 100 μm particle.

Mechanistic Interpretation

The release of most inorganic species from coal particles traditionally is explained as a process of local reduction followed by vaporization [Neville, et al., 1980; Quann, et al., 1982; Quann and Sarofim, 1982; Senior and Flagan, 1984; Wibberley and Wall, 1986], although some authors specifically reject this idea for iron-containing species [Raask, 1985]. The suitability of the vaporization mechanism as an explanation for the data obtained in our work is investigated as follows. If we assume a constant diameter sphere undergoing pseudo-steady vaporization and reaction in a quiescent medium, the total rate of iron vaporization from the sphere should be given by

$$N_f = h_f \theta A (x_s - x_b) + x_s \sum_{i=1}^n N_i \quad (5)$$

where N_f is the molar transfer rate of iron from the particle, h_f is the mass transfer coefficient, θ is the blowing factor, A is the particle surface area and x is the mole fraction of iron at the surface (subscript s) and in the bulk phase (subscript b). This expression can be evaluated for the vaporization of elemental iron under the most favorable conditions for this vaporization as follows.

Figure 8. Typical elemental compositions of the residual and evolved coal minerals. Data are for particles at 117 ms residence time in an environment with 6 mole percent bulk oxygen concentration in the CCL.

The mass transfer coefficient can be derived from a Sherwood number correlation and the diffusion coefficient of iron in the gas phase. The mole fraction of iron at the surface can be approximated as a function of temperature from a vapor pressure curve and the mole fraction in the bulk phase will be considered negligible.

The following observations and approximations allow quantitative evaluation of N_f . The peak measured particle temperatures during the iron release were about 1710 K (average particle temperature is 1688 K) in the 6 % oxygen environment. Assuming a 100 μm sphere at the peak temperature, the mass transfer coefficient is about 0.40 mol/cm²-s, the vapor pressure of iron is about 6.1×10^{-6} atm, and the sum of the molar fluxes (from the data in Table 5) is 7.87×10^{-8} mol/s. These values assume metallic iron is the vaporizing species and the remainder of the mass lost from the coal particle is carbon. The predicted total molar transfer rate is 2.5×10^{-11} mol/s. A

Table 7
Iron evolution data, with confidence intervals, for the 75—106 μm size fraction
of the Illinois #6 coal in both gas environments.

τ^a	μ	σ	95 % Confidence	99 % Confidence
(ms)	(-)	(-)	Interval	Interval
			(-)	(-)
75—106 μm size Fraction				
6 % Overall Oxygen Concentration				
0.0	1.0	0.0	1.0—1.0	1.0—1.0
47.0	0.61	0.090	0.80—0.42	1.00—0.16
72.0	0.53	0.077	0.69—0.36	0.91—0.14
95.0	0.44	0.064	0.58—0.30	0.76—0.12
117.0	0.41	0.059	0.51—0.32	0.58—0.24
12 % Overall Oxygen Concentration				
0.0	1.0	0.0	1.0—1.0	1.0—1.0
47.0	0.65	0.098	0.81—0.50	0.94—0.37
72.0	0.59	0.106	0.82—0.35	1.00—0.04
95.0	0.45	0.066	0.59—0.30	0.78—0.12
117.0	0.49	0.060	0.62—0.36	0.80—0.18

^a Based on measured velocities of a 100 μm particle.

reasonable upper bound on the rate of vaporization corresponds to the entire particle surface being covered with iron, in which case the transfer rate is about 7.8×10^{-10} mol/s. The observed transfer rate is much higher, i.e., over 7.1×10^{-9} mol/s.

There are several simplifying assumptions in the above discussion that merit more careful examination. Coal particles are not spherically symmetric (see Fig. 10 below), nor are the mineral grains homogeneously distributed throughout the coal. A theoretical discussion of vaporization from isolated mineral grains in coal particles is available in the literature [Quann and Sarofim, 1982] and can be used to indicate the consequences of explicitly considering the granular nature of the mineral grains. This study shows that, for inorganic material that occurs as discrete mineral grains, such as pyrite and its decomposition products, “internal diffusion resistance [to mass transfer] will dominate and that the partial pressure...at the surface will be orders of magnitude less than the equilibrium value at the inclusions.” The study shows that the rate of vaporization indicated above corresponds to the maximum possible rate and is likely to be orders of magnitude higher than the actual rate for discrete mineral grains.

Figure 9. Iron loss data obtained for the 75-105 μm diameter particles. Data from both the 6 mole % oxygen (a) and 12 mole % oxygen (b) environments in the CCL are shown.

There remain significant assumptions about spherical symmetry, chemical reactions by the vapors, etc. To consider the implications of these assumptions is a complicated theoretical task. We turn rather to the experimental observation that the iron release occurs at rates far in excess of more volatile and more plentiful components such as silica. According to standard references [Perry, et al., 1984], the vapor pressure of metallic iron is lower than that of silicon or any of its oxide derivatives. The fact that essentially no silicon was observed to leave the particles, even though they experience the same experimental conditions as the iron, is an indication of the inadequacy of vaporization as an explanation for these data, independent of any theoretical considerations. However, the silicon vapor pressure data in standard reference texts [Perry, et al., 1984; Weast, 1976] is in significant disagreement with similar data from other reliable sources [Chase, et al., 1985; Lankford, et al., 1985]. Until these discrepant data are resolved, it is not clear whether silicon loss could be expected to be greater or less than iron loss by vaporization.

There are several iron-containing species more volatile than metallic iron which should be considered. Iron carbonyls are among the most well-known of these. However, iron pentacarbonyl, the most stable iron carbonyl, decomposes at low temperatures (300-500 K) and is difficult to form from stable iron-containing compounds. Ferrous and ferric chloride are both quite volatile. But, there is insufficient chlorine in this coal to account for the loss of iron by the formation and vaporization of these compounds. There are a few organo-metallic compounds which have also been considered. These are not necessarily more volatile than metallic iron and are unstable at high temperatures. Furthermore, the decomposition of pyrite at high temperatures is reasonably well understood and involves no volatile intermediate species. On the basis of these analyses and observations, we conclude that the iron is not being released through a mechanism of vaporization under these combustion conditions.

We postulate an alternative mechanism for this iron release from the coal. This is illustrated conceptually in Figure 10. In this figure, a pyrite grain is shown imbedded in a coal particle. The pyrite is nearly as reactive to oxygen as is coal or coal char. However, during the early combustion history of the particle the coal volatiles evolve and consume the local oxygen. Sulfur is emitted simultaneously from the pyrite as it decomposes to pyrrhotite. At the end of coal devolatilization, the pyrite particles have been converted to pyrrhotite, which is also very reactive to oxygen. As the oxygen-depleted volatile cloud separates from the coal particle, the pyrrhotite grains are exposed to oxygen. It is at this point that the large decrease in iron is observed (see Figure 7, for example). This suggests that the chemical reactivity of pyrrhotite to oxygen is related to the evolution of iron. We postulate that an iron fume is formed as a consequence of this chemical reactivity and that some portion of the fume is convected away from the particles during the early stages of char oxidation.

Verification of Mechanism

Several further experiments were conducted to verify and add detail to this postulated mechanism. Scanning electron micrographs of the coal particles were obtained at each stage of burning. These micrographs, shown in Fig. 11, show that the pyrrhotite grains are very porous prior to the loss

Figure 10. Conceptual diagram of the mechanism of iron evolution postulated on the basis of our experiments. The iron is released as a particulate fume as the porous pyrrhotite grains react with oxygen and disintegrate.

of iron. Fig. 11a is taken from the 106-125 μm particles collected at 47 ms residence time in the 6 percent oxygen environment. A closer examination of the same particles (Fig. 11b) reveals the porous nature of the particles, being composed of small nodules, 0.1 μm or less in diameter, loosely bound together to form the larger pyrrhotite grain. After the loss of iron, the original grains appear to have disintegrated (Fig. 12). The micrograph illustrated in Fig. 12 is taken from the 106-125 μm particles collected at 72 ms residence time in the 6 percent oxygen environment. The top portion of the mineral grain in this micrograph is composed primarily of silicon and aluminium and shows no indication of disintegration. The bottom half is iron-rich and appears to have fragmented. The very small particles littering the surface of the char are also iron-rich and are examples of fume particles generated by the disintegration of the larger mineral grain. Both convection by the products of heterogeneous char combustion and thermophoretic forces on the fume particles in the thermal boundary layer will tend to transport much of this fume away from the particle. These submicron fume particles are sufficiently small so that they pass through the nominal 1 μm openings in the filter without being collected in the sampling system.

Data illustrating the transformations from pyrite, to pyrrhotite, to oxides during these experiments are shown in Figure 12 for both particle sizes. The transformations occur as expected on the basis of the previously cited studies of high temperature pyrite chemistry. The data were obtained with an automated scanning electron microscope technique, the precision of which is discussed elsewhere [Baxter, 1990; Yang and Baxter, 1991].

The data from experiments with smaller particles also show that this postulated mechanism correctly predicts trends in iron release rates that are opposite to those predicted by a vaporization mechanism. The postulated mechanism depends on the presence of an oxidizing environment in the vicinity of the pyrite/pyrrhotite grain whereas vaporization depends on the existence of a locally reducing environment. A larger fraction of the volume of a small particle is exposed to oxygen than for a large particle under similar conditions of temperature and oxygen concentration. Therefore, repeating the experiments with smaller particles should produce trends in the data that distinguish a vaporization process from a heterogeneous reaction process. Figure 9 shows the results of an experiment in which smaller (75—106 μm diameter) coal particles were entrained in the same environments. The *extent* of iron loss is expected to increase if the mechanism proceeds through a chemical reaction with oxygen whereas it should decrease if it proceeds through vaporization. However, the small particles have a greater total exterior surface area than the large particles. Therefore, the *rate* of iron loss is expected to increase by both mechanisms as particle size decreases.

Oxygen penetration in the particles can be approximated using the Thiele modulus description of intrinsic reaction [Satterfield, 1970]. In this case, the global reaction rate coefficients and oxygen dependence were inferred from the particle temperature and solid sample data. Particle apparent density, void fraction, and N_2 BET surface area were measured at 0.32 g/cc, 0.810, and 55 m^2/g , respectively. Under the conditions of these experiments, the ratio of the effectiveness factor of the small particles (90 μm) to that of the large particles (115 μm) varies from 1.4 to 1.5, depending on the assumed value of the tortuosity factor.

Figure 11. Scanning electron micrographs of (a) a char particle with included pyrrhotite grains immediately before iron evolution, and (b) the detailed structure of the pyrrhotite grain. By contrast, Fig. 12 illustrates the structure of the iron-containing grains shortly before iron loss occurs.

Figure 12. Scanning electron micrographs of the residual iron nodule after partial oxidation of the pyrrhotite grain. The large number of small iron-containing granules littering the surface are believed to be indicative of the iron loss. By comparison, Figure 11 illustrates the structure of the iron-containing grains shortly before the loss of iron is observed.

Figure 13. Forms of iron-containing mineral species in the coal samples as a function of residence time in (a) the 6 mole % oxygen environment and (b) the 12 mole % oxygen environment in the CCL experiments.

Therefore, changing the particle size fraction in the reactor could be expected to increase the effect of oxygen on the rate of intrinsic reactions by a factor of 40 to 50 percent. This increased oxygen penetration should produce a measurable change in the iron loss data.

The results of these experiments, shown in Figure 9, illustrate that the extent of iron loss increases as coal particle size decreases, consistent with the mechanism of chemical reaction as an explanation for the loss of iron. Table 7 lists the means, standard deviations and confidence intervals for the data shown in Figure 9. The 95 % confidence intervals of these data exclude those of the data for the larger particles at the latest residence times in both gas environments. Time required to heat and devolatilize the particles also decreases due to smaller particle mass. The overall mass loss for these data are reported together with the larger particles in Table 5.

These data support the proposed mechanism of iron release through chemical reaction and provide additional details of the process. The porous pyrrhotite grains appear to disintegrate as they react with oxygen, freeing the small nodules of the grain. Many of these small nodules adhere to the coal particle, while others are carried away from the coal particle with the products of heterogeneous combustion of the coal char or by thermophoresis. Those which are carried into the bulk gas stream become the iron oxide/sulfide fume which passes through the filter. However, they do not become vapors during the process. They are emitted as small (up to 0.8 μm) solid particles.

The sampling system used in the CDL was used in the CCL to allow the fine particulate to be collected. Micrographs of the collected material are illustrated in Figures 14-16, together with energy dispersive spectra of the particles (coated with gold to enhance the signal) and the filter. Note that sodium and iron are the only two species in appreciable concentration in the particulate that are not present in the filter. The presence of sodium is attributed to either vaporization or release during devolatilization. The latter mechanism is discussed elsewhere [Baxter, et al., 1993]. Sulfur is also present, but it is masked by the signal from the gold coating. There is no iron signal from the filter itself. Closer examination of the particles indicates that they are approximately 0.5 μm in diameter and appear to have significant porosity. Sulfur is also a major constituent of the particles on the filter, but its peak is masked by the gold in these spectra.

The remaining coals indicated in Tables 1 and 2 were examined to determine the extent of iron loss during combustion. Representative results for the coals tested in both the CCL and CDL are presented in Fig. 17. The coals illustrated range from lv bituminous to lignite and are arranged in rank order. The iron loss correlates reasonably well with the amount of pyritic iron in the coal.

The pyritic iron contents are determined by performing a mass balance on measured pyritic sulfur contents and are measured both before and after the experiments. Note that, even under nitrogen storage, the pyrite oxidizes somewhat in essentially all coals. All data shown in Figure 17 are from the CCL and represent the average of several runs under conditions of different particle size (45 to 125 μm) and oxygen concentration (6 to 12 %). Many of the same coals were used in additional experiments in the CDL. In the inert environment of the CDL, no iron release was observed for any coal. The CDL operates at a significantly lower temperature than the CCL (maximum T_g is 1250 K in the CDL, 1700 K in the CCL), in addition to being an inert flow facility.

Sensitivity of Results to the Extent of Weathering

The presence of iron in submicron particulate has been observed by several investigators. A reasonably comprehensive study of this type was conducted by Quann and Sarofim [Quann and Sarofim, 1982], in which iron enrichment was observed in much the same pattern. Enrichment of iron in the submicron fume compared to the bulk coal greatly exceeds that of other reasonably refractory materials such as, for example, silicon. Similar results are reported by other investigators for a narrower range of coals (discussed later). Most of the other species observed in the fume could be described as products of ash vaporization. The iron results were presented without further discussion. We believe the results can satisfactorily be described in terms of the above mechanism.

However, these investigators and others typically see lower absolute amounts of iron in the fume than have been observed in this study, even though the enrichment factors are high. A possible explanation for the differences in the amount of iron released as a fume between these several investigations is the role of weathering on the release of an iron fume.

Experiments have been conducted in two parts to indicate the extent of coal weathering on iron fume formation. First, the extent by which exposure of coal to room air at room temperature might oxidize the pyrite was investigated. Three utility grind coals originally containing 100 percent pyritic iron [Boni, et al., 1990] were reanalyzed after short exposure to room temperature air. Figure 18 illustrates the fraction of pyritic iron in the coals before (raw) and after (weathered) exposure to air. Pyritic iron content of all three coals decreased to approximately 60 percent.

Further similar exposure of the coals to air produced an additional 4 to 5 percent decrease. Thus the initial oxidation of pyrite proceeds much more rapidly than the later oxidation. Our hypothesis is that the surface of the pyrite grains is rapidly oxidizing and producing a sulfated layer. This sulfate layer inhibits the further oxidation of the remaining pyritic iron.

The sulfate layer formed on pyrite grains during exposure to air likely impedes the formation of the iron fume under combustion conditions. Combustion tests in the MFC were conducted to evaluate this hypothesis. The first objective was to determine the extent of fume formation from the weathered coal and compare this to the fume formed from the raw coal. The utility grind Illinois #6 coal on which the data in Fig. 18 are based is reasonably similar to the size-classified Illinois #6 coal (PSOC-1493d) with the important exception of overall iron content. The former was selected as the test fuel for these experiments. The ash compositions of these two coals are indicated in Tables 8 and 9. In these experiments, no formation of the iron fume was detected, in contrast to experiments previously reported which used the unweathered coal. These results are illustrated in Fig. 19.

In a second set of weathering experiments an attempt was made to resolve the rate of pyrite oxidation with time under laboratory conditions. Two samples of the 106-125 μm size fraction of PSOC 1493 coal were placed in a Petri dish and exposed to a laboratory environment for three days and one week, respectively. The samples were placed back in a nitrogen purged container and submitted for analysis.

Figure 14. SEM photographs of iron fume particles captured in the gases from size-classified (106-125 μm) Illinois #6 coal particles. The micron-sized fume particles are composed principally of potassium, sodium, and iron.

Figure 15. EDS spectra of sampled fume (see Fig. 14) illustrating the presence of iron. Silicon, lead (unlabeled peak at ≈ 2.58 keV), and potassium are present in approximately the same ratios in the filter as is seen in this spectrum (see Fig. 16). Performing this background correction, particle composition is observed to be dominated by iron, with some sodium. Gold peak, which arises from the coating used to improve SEM imaging, is off scale on this plot.

Figure 16. EDS spectrum of carbonate filters. The primary components of the filter are carbon and oxygen, neither of which can be seen by the detector used in this system. The primary trace component is silicon, with minor amounts of potassium, very little if any sodium, and no detectable iron. Gold and lead are used to coat the surface to improve the image quality. Compared with EDS spectrum of fume particles dispersed on this filter, the principal difference is iron concentration (Fig. 15).

Figure 17. Summary of iron release as a function of coal rank and of pyritic iron content.

Table 8

Elemental Ash Composition (Expressed as Oxides) in the Illinois #6 Coal as Fired in the Multifuel Combustor

Illinois #6 Coal Utility-grind Sample (ASTM Ash = 10.1 %)			
Oxide	Mass % of Coal	Oxide	Mass % of Coal
SiO ₂	4.64	CaO	0.53
Al ₂ O ₃	1.74	Na ₂ O	0.071
TiO ₂	0.092	K ₂ O	0.205
Fe ₂ O ₃	2.042	MgO	0.129

Table 9

Elemental Ash Composition (Expressed as Oxides) in the Illinois #6 Coal
Used in Previous Experiments in the Char Combustion Laboratory

Illinois #6 Coal (PSOC-1493d)			
106-125 μm			
(ASTM Ash = 11.5 %)			
Oxide	Mass % of Coal	Oxide	Mass % of Coal
SiO ₂	4.23	CaO	0.458
Al ₂ O ₃	1.68	Na ₂ O	0.041
TiO ₂	0.092	K ₂ O	0.116
Fe ₂ O ₃	3.55	MgO	0.084

Figure 18. Decrease in pyritic iron content with exposure of pulverized coal to air at room temperature for approximately one week for three coals.

Figure 20 illustrates the resulting fractions of pyritic iron in the pristine (raw) coal, the coal exposed for three days, and the coal exposed for one week. The amount of pyritic iron decreases rapidly at first and then more slowly, consistent with the results from the utility-grind sample indicated in Fig. 18.

Results from the MFC are consistent with those from the smaller-scale facilities. Coals that contain significant fractions of pyritic iron (typically pristine eastern coals) experience some iron loss during the early stages of combustion, whereas those with little or no pyritic iron (typically western and weathered eastern coals) experience none. These trends are illustrated in Figures 21 through 23 for high-rank (bituminous), low-rank (subbituminous and lignites) blended coals, respectively. Within each plot, coals are arranged by rank. Confidence intervals (95%) are indicated for all data where sufficient data are available to calculate them. Confidence intervals are determined based on measured standard deviations in replicated data and not on the approximated values using Eqs. 4 and 5. Several coals exhibit mean iron releases that differ from zero, but the error bars on the data nonetheless include zero. For these coals, one cannot say with 95 % or more confidence that there was any iron release. In these cases, the relatively small number of samples (typically four or less) on which the statistics are based is the underlying reason for the large confidence intervals. (One sample yields confidence infinitely wide. Two independent samples yield 95 % confidence intervals ≈ 9 times larger than the standard deviation. Seven samples are required before the confidence intervals become smaller than the standard deviation in the data.) Coals indicated in Table 2 for which insufficient independent data are available to calculate any confidence interval are not included in Figures 21-23.

Data in figures 21-23 are all plotted on the same scale to allow more direct comparison of the results. Our work with coal blends is fairly recent and we have not yet generated sufficient replicated data to produce reasonably small error bands. The error bands indicated are off-scale for two of the blends. They typically span a range of approximately ± 0.5 . The standard deviations of the data for these two blends are less than 0.15.

Figures 21 through 23 illustrate the trends in the MFC data. Coals with high initial pyritic iron fractions, which tend to be eastern, high-rank coals (Fig. 21), exhibit significant iron evolution during combustion. Coals with low initial pyritic iron concentrations, which tend to be western, low-rank coals (Fig. 22), exhibit little if any iron evolution. The coals in Fig. 21 that indicate no loss of iron include two western, high-rank coals (Utah Blind Canyon and Hanna Basin), and two coals with very large confidence intervals (Eastern Kentucky and Mingo Logan) indicating few sets of data. Blends of coals tend to exhibit behavior commensurate with the blend ratio, although there are fewer data for these coals and the error bars are considerably larger. The confidence intervals are compared in the figure to the magnitude of the release. Thus, the release of iron from the Upper Freeport coal is about 0.15 ± 0.05 , indicating with greater than 95% confidence that the release is greater than 0. The magnitude of the confidence intervals depends on both the consistency of the data and the number of data points available. The number of independently collected data points used to compute the results illustrated in Figure 21 varies from eight to two. Coals with one data point (or fewer) are not illustrated because no confidence interval can be established for these data. The primary contributor to the size of the confidence interval is the number of points, with the consistency among the data being secondary. One independently

Figure 19. Comparison of the fractional release of iron as a fume from a raw coal (see Table 9) and a weathered sample of similar coal (see Table 8). Data for the raw coal are from the Char Combustion Laboratory. Data for the weathered coal are from the Multifuel Combustor.

measured data point in this context means that the raw coal is characterized, the coal is used in a MFC combustion test during which a fly ash sample is obtained, and the fly ash sample is analyzed. Overall mass loss is determined from tracer analysis, aluminium and titanium being the most commonly used tracers. (Silicon loss is observed in some MFC tests, unlike the CCL and CDL tests. The difference in behavior in the facilities is presumed to be caused by the longer residence times in the MFC.)

The statistical analysis of these data indicates that iron loss occurs to a somewhat lesser extent in these coals than in the pristine coal samples used in the CCL and CDL. The data also show a strong correlation between pyritic iron content and the overall iron loss. Even among the low-rank coals, those with large fractions of pyritic iron (Decker, for example) indicate significant loss of iron whereas those with less pyritic iron indicate no iron loss. Complete analyses of all of the utility grind coals, including pyritic iron content, are included in the appendix.

Figure 20. Declining pyritic iron content with exposure time to laboratory (air) environment in the samples of 106-125 μm coal used in these experiments.

Comparisons with Literature Data

Several observations from previously reported data can also be satisfactorily explained by the mechanism of iron release discussed in this paper. Raask reports studies [Raask, 1984; Raask, 1985] in which he observes the formation of an iron fume. In these studies, pure pyrite particles were rapidly heated in both oxidizing and reducing environments. Those introduced into an oxidizing environment produced an iron fume containing 0.1—0.5 μm particles. Raask attributed this to fragmentation of the pyrite particle during sulfur emission and subsequent decomposition to pyrrhotite.

Figure 21. MFC iron release results for high-rank coals (low-volatile bituminous through high-volatile bituminous C) with 95 % confidence intervals. The principal reason for the differences in size of the confidence intervals is the number of independent samples available for analysis. Hanna Basin and Utah Blind Canyon are western coals that rank as bituminous coals.

Figure 22. MFC iron release results for low-rank coals (subbituminous A through lignites) with 95 % confidence intervals. The overall amount of iron release is lower for these coals than the high-rank coals (see Fig. 21), with confidence intervals that rarely exclude 0. These data are plotted on the same scale as those for the other coals (Figs. 21 and 23).

Figure 23. MFC iron release results for blended coals with 95 % confidence intervals. None of these coals has more than three independent samples on which to base the statistics. This is the major contributor to the larger error bars. These data are plotted on the same scale as those for the other coals (Figs. 21 and 22).

Investigations of changes in mineral grain size distributions, including those of pyrite and its decomposition products, during the early stages of coal combustion have been reported on the same Illinois #6 coal used in our experiments [Baxter, 1990]. The results indicate that pyrite does fragment during decomposition to pyrrhotite, but the extent of fragmentation is insufficient to generate the fume. Furthermore, the mineral grain fragmentation which occurs during pyrite decomposition to pyrrhotite occurs a few milliseconds earlier than the fume formation illustrated in Figure 10. Fume formation is noted immediately after this decomposition by the mechanism described above. The oxidative decomposition of porous pyrrhotite grains is, we believe, an alternative explanation for the data of Raask.

Reported experimental data on size and composition of submicron particles formed during coal combustion compare favorably with these results [Flagan and Taylor, 1980; Taylor and Flagan, 1981; Taylor and Flagan, 1982]. In these studies, a subbituminous coal was combusted at both near-stoichiometric ($\phi = 0.96$) and fuel-lean conditions ($\phi = 0.57$). An enrichment of iron in the small particle sizes is observed at the near-stoichiometric condition and is much *more* prevalent at the fuel-lean conditions. In both cases, iron enrichment is more substantial than is silica enrichment in the small particle sizes. Specific data on the type of coal used and the forms of the mineral components in the raw coal are not given in the studies cited. Nevertheless, these results are consistent with the mechanism described above and would explain why iron was enriched in the small sizes as overall oxygen content increases. The data also indicate a peak in the iron particle size distribution of the fume at an aerodynamic diameter of 1 μm . If one assumes that these particles have specific gravities in the neighborhood of iron oxides (≈ 5), the actual particle diameters would be between 0.3 and 0.9 μm , consistent with the experimental results reported above, but much too large to be the consequence of a vaporization/recondensation process.

One series of studies investigating iron release during combustion of coal from a wide range of coals reports both the fraction of iron vaporized and the fraction of fume composed of iron [Quann, et al., 1982; Quann, et al., 1990; Quann and Sarofim, 1982]. The results of this study are shown in Fig. 24. The total amount of iron vaporized is seen to vary from about 0.5 to 14 %, slightly less than we observed with pulverized samples but of the same order of magnitude. 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. Although much of the data can be explained by vaporization, the iron data stands out among the more refractory components as having an unusually high extent of release.

Recent data on the partitioning of alkali metals [Gallagher, 1992] and iron [Bool III, 1993] indicate less extensive loss of iron during combustion than is reported here, but a similar trend in terms of the fraction of iron in the fume increasing with increasing rank. Cascade impactors rather than polycarbonate filters were used to separate particles by size in the sampling stream. All data were collected under fuel-lean conditions. However, the fraction of iron found in the fume is not readily available from these data for all coals. These results are in agreement with those reported in this document and with those from MIT with the exception of the fraction of the iron released. The differences in the extent of iron loss could be partially explained by the sensitivity to preoxidation or weathering. Little attempt was made in the data of either Gallagher or Bool to prevent the coals

Figure 24. Rank and element resolved elemental release rates from small-scale combustors. Among the less volatile components, iron stands out as being extensively released.

from being exposed to oxygen prior to testing. Further work will be required to resolve this issue definitively.

Conclusions

Experiments focused on the release of iron during coal combustion are reported. Experimental conditions of gas and particle temperature and gas composition were selected to represent those commonly found in pulverized-coal combustors during char oxidation. Carefully characterized, size- and gravity-classified coal particles containing iron in the form of pyrite were used in the experiments.

A rapid and extensive loss of iron from the coal particles during their early combustion history is observed. The iron loss is consistently observed immediately following coal devolatilization, during the incipient stages of heterogeneous char reaction. Approximately half of the iron in the coal is lost during this 25 ms period. This accounts for over 80 percent of the mineral lost from these coal particles in this experiment.

The data are not satisfactorily described by a reduction/vaporization process. The loss of iron is more rapid than can be explained by traditional models of vaporization rates. Furthermore, other, more volatile mineral components of the coal particles do not vaporize during these experiments.

A mechanism for the loss of iron is postulated based on these experimental data. The mechanism attributes the iron loss to the formation of an iron fume (particles $< 1\ \mu\text{m}$) by chemical reaction of porous pyrrhotite grains with oxygen. These grains disintegrate when exposed to oxygen, releasing the iron fume. Part of the fume adheres to the char particle surface and the remainder is carried with the combustion products of char oxidation into the surrounding gas.

The mechanism is supported by all of the observations. Scanning electron micrographs reveal the porous pyrrhotite particles before the release of iron and the iron fume on the surface of the particles after the iron release. Disintegrated remains of pyrrhotite grains are also observed in the particles immediately after the loss of iron. The iron release is rapid and limited to the earliest stage of char combustion. No iron release is observed during the latter stages of char combustion. Transformations of pyrite to pyrrhotite occur before the release of iron, whereas transformations from pyrrhotite to oxides of iron occur as the fume is generated. Finally, the extent of iron loss increases as the penetration depth of oxygen in the particle increases, a trend opposite that predicted by vaporization mechanisms. Vaporization of iron-containing species does not satisfactorily explain these data.

Practical Implications

In a general sense, this investigation suggests that chemical reactions of mineral grains should be included as a source of mass in comprehensive descriptions of mineral release from coal or char particles. Iron fume is commonly observed in boiler fly ash at both pilot and commercial scale. The proportion of iron in the submicron particle size is too great to reasonably ascribe its formation to classical vaporization and recondensation processes. This investigation documents the formation of such material and its sensitivity: (a) to the form of iron in coal, (b) oxygen concentration, and coal weathering. We also postulate a formation mechanism consistent with all of our observations. While (c) will most likely decrease the amount of the iron fume formation in

existing and planned (e.s. Combustion 2000) coal utilization equipment compared with the pristine, unoxidized samples discussed here, significant iron fume nevertheless will form under many conditions. This significant change in partitioning of iron throughout the fly ash size distribution will affect ash deposition rates, deposit properties, precipitator performance.

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

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

† Ash is on a dry basis.

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

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

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

Pocahantas #3

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

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

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

Upper Freeport							
Analyses			Analyses				
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin	
Fixed Carbon	54.40	53.95	dp>600µm		+28	0.00	
Volatile Matter	24.17	23.97	600µm>dp>300µm		28x48	2.63	
Moisture	0.83		300µm>dp>149µm		48x100	7.33	
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	20.90	
C	66.46	65.91	74µm>dp>44µm		200x325	19.53	
H	4.16	4.12	44µm>dp		-325	49.60	
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)	% in size bin
S	2.00	1.99					
Cl	0.19	0.19					
Ash	21.30	21.13					
Ash Chemistry	% dry fuel	% ash					
SiO2	10.93	51.29					
Al2O3	5.16	24.23					
TiO2	0.20	0.92					
Fe2O3	2.85	13.40					
CaO	0.53	2.47					
MgO	0.28	1.30					
K2O	0.65	3.06					
Na2O	0.06	0.30					
SO3	0.52	2.42					
P2O5	0.03	0.14					
Cl							
Undetermined	0.13	0.59					
Total	21.33	100.1					
Forms of Sulfur (% dry fuel)							
Pyritic	1.49						
Organic	0.48						
Sulfatic	0.11						
Fraction Free Silica							
Fraction Pyritic Iron	0.65						
Heating Value (Btu/lb, dry)							
As Fired	11830	11732					
Dulong	11987	11888					
Acid Sol. Alkali (ppm)	Dry	As Rec'd					
Na	343	343					
Mg	1208	1208					
Ca	3767	3767					
K	2292	2292					
Fusion Temp.	°F	°C					
Reducing Conditions							
Initial Deformation	2177	1192	Size Statistics (Malvern Data Only)				
Spherical	2317	1269	Malvern All Data				
Hemispherical	2376	1302	Dv.5	Volume Mean Diam.	16.65		
Fluid	2437	1336	Dv.9	90 % volume diameter	39.58		
Oxidizing Conditions			Dv.1	10 percentile volume diameter	4.38		
Initial Deformation	2443	1339	D4,3		19.93		
Spherical	2513	1378	D3,2	Sauter Mean Diameter	9.52		
Hemispherical	2548	1398	Span		2.12		
Fluid	2604	1429	Specific Surface Area (m²/cc)				0.57

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	cum. vol. per.	
S	0.87	0.85	188m	0.00	100.0	118.4m2			
Cl	0.15	0.15	162m	0.00	100.0	102.1m2			
Ash	9.34	9.21	140m	0.00	100.0	88.1m2			
Ash Chemistry	% dry fuel	% ash	121m	0.00	100.0	76m2			
SiO2	5.14	55.07	104m	0.00	100.0	65.6m2			
Al2O3	2.80	29.96	89.9m	0.00	100.0	56.6m2			
TiO2	0.13	1.41	77.5m	0.08	99.9	48.8m2			
Fe2O3	0.60	6.38	66.9m	1.13	98.8	42.1m2			
CaO	0.10	1.07	57.7m	3.25	95.6	38.3m2			
MgO	0.10	1.02	49.8m	5.65	89.9	31.3m2			
K2O	0.27	2.91	42.9m	7.50	82.4	27m2			
Na2O	0.05	0.49	37.1m	8.95	73.5	23.3m2			
SO3	0.11	1.22	32m	8.60	64.9	20.1m2			
P2O5	0.01	0.09	27.6m	6.95	57.9	17.4m2			
Cl			23.8m	5.83	52.1	15m2			
Undetermined	0.04	0.39	20.5m	5.38	46.7	12.9m2			
Total	9.34	100.0	17.7m	5.78	40.9	11.1m2			
Forms of Sulfur (% dry fuel)			15.3m	5.93	35.0	9.6m2			
Pyritic	0.23		13.2m	5.05	29.9	8.3m2			
Organic	0.64		11.4m	4.10	25.8	7.2m2			
Sulfatic	0.00		9.8m	3.23	22.6	6.2m2			
Fraction Free Silica	0.18		8.5m	3.00	19.6	5.3m2			
Fraction Pyritic Iron	0.48		7.3m	3.10	16.5	4.8m2			
Heating Value (Btu/lb, dry)			6.3m	3.25	13.3	4m2			
As Fired	13805	13607	5.4m	2.90	10.4	3.4m2			
Dulong	14054	13852	4.7m	2.33	8.0	3m2			
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	1.80	6.2	2.8m2			
Na			3.5m	1.30	4.9	2.2m2			
Mg			3m	1.05	3.9	1.9m2			
Ca			2.6m	0.98	2.9	1.6m2			
K			2.2m	0.85	2.1	1.4m2			
Fusion Temp.	°F	°C	1.9m	2.08	0.0	1.2m2			
Reducing Conditions			Size Statistics (Malvern Data Only)						
Initial Deformation	1428	776	Dv.5 Volume Mean Diam.				19.38	Malvern	All Data
Spherical	1442	783	Dv.9 90 % volume diameter				43.00		
Hemispherical	1451	788	Dv.1 10 percentile volume diameter				4.60		
Fluid	1473	800	D4,3				21.03		
Oxidizing Conditions			D3,2 Sauter Mean Diameter				10.00		
Initial Deformation	1445	785	Span				2.00		
Spherical	1463	795							
Hemispherical	1471	799							
Fluid	1486	808	Specific Surface Area (m^3/cc)				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 (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin	cum. vol. per.
S	3.52	3.48	188m	0.31	99.7	118.4m2		
Cl	0.09	0.09	162m	0.83	98.9	102.1m2		
Ash	9.01	8.91	140m	1.24	97.6	88.1m2		
Ash Chemistry	% dry fuel	% ash	121m	1.59	96.0	76m2		
SiO2	3.53	39.16	104m	1.70	94.3	65.6m2		
Al2O3	1.74	19.31	89.9m	1.91	92.4	56.6m2		
TiO2	0.08	0.84	77.5m	2.24	90.2	48.8m2		
Fe2O3	2.48	27.53	66.9m	2.69	87.5	42.1m2		
CaO	0.41	4.56	57.7m	3.26	84.2	38.3m2		
MgO	0.08	0.84	49.8m	4.84	79.4	31.3m2		
K2O	0.11	1.18	42.9m	6.24	73.2	27m2		
Na2O	0.08	0.87	37.1m	7.04	66.1	23.3m2		
SO3	0.37	4.08	32m	6.28	59.9	20.1m2		
P2O5	0.03	0.34	27.6m	4.81	55.0	17.4m2		
Cl			23.8m	4.35	50.7	15m2		
Undetermined	0.11	1.25	20.5m	4.58	46.1	12.9m2		
Total	9.01	100.0	17.7m	4.74	41.4	11.1m2		
Forms of Sulfur (% dry fuel)			15.3m	4.61	36.8	9.6m2		
Pyritic	2.07		13.2m	4.15	32.6	8.3m2		
Organic	1.42		11.4m	3.74	28.9	7.2m2		
Sulfatic	0.03		9.8m	3.39	25.5	6.2m2		
Fraction Free Silica	0.26		8.5m	3.16	22.3	5.3m2		
Fraction Pyritic Iron	0.61		7.3m	3.01	19.3	4.8m2		
Heating Value (Btu/lb, dry)			6.3m	2.99	16.3	4m2		
As Fired	13728	13577	5.4m	2.96	13.4	3.4m2		
Dulong	13523	13374	4.7m	2.73	10.6	3m2		
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	2.14	8.5	2.8m2		
Na			3.5m	1.68	6.8	2.2m2		
Mg			3m	1.30	5.5	1.9m2		
Ca			2.6m	1.16	4.4	1.6m2		
K			2.2m	1.11	3.3	1.4m2		
Fusion Temp.	°F	°C	1.9m	2.38	0.9	1.2m2		
Reducing Conditions			Size Statistics (Malvern Data Only)					
Initial Deformation	1984	1085				Malvern	All Data	
Spherical	2020	1104	Dv.5	Volume Mean Diam.		25.04		
Hemispherical	2080	1138	Dv.9	90 % volume diameter		63.86		
Fluid	2245	1229	Dv.1	10 percentile volume diameter		4.51		
Oxidizing Conditions			D4,3			30.11		
Initial Deformation	2387	1308	D3,2	Sauter Mean Diameter		10.70		
Spherical	2448	1342	Span			2.56		
Hemispherical	2496	1369	Specific Surface Area (m^3/cc)			0.66		
Fluid	2542	1394						

*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
Fixed Carbon	58.15	56.51	dp>600µm		+28	0.00
Volatile Matter	36.24	35.22	600µm>dp>300µm		28x48	0.15
Moisture	2.81		300µm>dp>149µm		48x100	2.50
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	14.10
C	78.18	75.98	74µm>dp>44µm		200x325	19.75
H	5.02	4.87	44µm>dp		-325	63.50
O	8.25	8.02	Size Distribution (Malvern)*		Size Distribution (Malvern)*	
N	1.62	1.57	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm) % in size bin
S	0.95	0.92				
Cl	0.38	0.37				
Ash	5.62	5.46				
Ash Chemistry	% dry fuel	% ash				
SiO ₂	2.98	53.00	188m	0.00	100.0	118.4m ²
Al ₂ O ₃	1.36	24.18	162m	0.08	99.9	102.1m ²
TiO ₂	0.07	1.28	140m	0.10	99.8	88.1m ²
Fe ₂ O ₃	0.64	11.44	121m	0.10	99.7	76m ²
CaO	0.12	2.19	104m	0.10	99.6	65.6m ²
MgO	0.06	1.03	89.9m	0.23	99.4	56.6m ²
K ₂ O	0.13	2.39	77.5m	1.20	98.2	48.8m ²
Na ₂ O	0.14	2.41	66.9m	2.95	95.3	42.1m ²
SO ₃	0.11	2.00	57.7m	5.40	89.9	38.3m ²
P ₂ O ₅	0.01	0.24	49.8m	7.88	82.0	31.3m ²
Cl			42.9m	8.90	73.1	27m ²
Undetermined	-0.01	-0.17	37.1m	9.13	64.0	23.3m ²
Total	5.62	100.0	32m	8.13	55.8	20.1m ²
Forms of Sulfur (% dry fuel)			27.6m	6.55	49.3	17.4m ²
Pyritic	0.36		23.8m	5.85	43.4	15m ²
Organic	0.57		20.5m	5.70	37.7	12.9m ²
Sulfatic	0.02		17.7m	5.73	32.0	11.1m ²
Fraction Free Silica	0.32		15.3m	5.38	26.6	9.6m ²
Fraction Pyritic Iron	0.70		13.2m	4.33	22.3	8.3m ²
Heating Value (Btu/lb, dry)			11.4m	3.58	18.7	7.2m ²
As Fired	14516	14108	9.8m	2.98	15.8	6.2m ²
Dulong	13879	13489	8.5m	2.70	13.1	5.3m ²
Acid Sol. Alkali (ppm)	Dry	As Rec'd	7.3m	2.53	10.5	4.8m ²
Na			6.3m	2.30	8.2	4m ²
Mg			5.4m	2.03	6.2	3.4m ²
Ca			4.7m	1.78	4.4	3m ²
K			4.1m	1.23	3.2	2.8m ²
Fusion Temp.	°F	°C	3.5m	1.08	2.1	2.2m ²
Reducing Conditions			3m	0.70	1.4	1.9m ²
Initial Deformation	1081	583	2.6m	0.48	1.0	1.6m ²
Spherical	1183	639	2.2m	0.35	0.6	1.4m ²
Hemispherical	1228	664	1.9m	0.73	-0.1	1.2m ²
Fluid	1271	688	Size Statistics (Malvern Data Only)			
Oxidizing Conditions					Malvern	All Data
Initial Deformation	1232	666	Dv.5	Volume Mean Diam.	24.13	
Spherical	1258	681	Dv.9	90 % volume diameter	49.83	
Hemispherical	1280	693	Dv.1	10 percentile volume diameter	6.08	
Fluid	1308	709	D4,3		27.03	
			D3,2	Sauter Mean Diameter	13.40	
			Spån		1.80	
			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 % in		cum. vol.	Diameter	% in
S	1.57	1.54	(µm)	size bin	per.	(µm)	size bin
Cl	0.10	0.09					cum. vol.
Ash	6.63	6.51					per.
Ash Chemistry	% dry fuel	% ash	188m	0.00	100.0	118.4m2	0.08
SiO2	3.16	47.70	162m	0.00	100.0	102.1m2	0.15
Al2O3	1.60	24.08	140m	0.00	100.0	88.1m2	0.18
TiO2	0.07	1.05	121m	0.00	100.0	76m2	0.13
Fe2O3	1.11	16.81	104m	0.00	100.0	65.6m2	1.33
CaO	0.23	3.46	89.9m	0.25	99.8	56.6m2	5.30
MgO	0.06	0.84	77.5m	0.40	99.4	48.8m2	9.88
K2O	0.12	1.75	66.9m	0.35	99.0	42.1m2	11.45
Na2O	0.03	0.45	57.7m	1.05	98.0	38.3m2	10.03
SO3	0.20	2.99	49.8m	5.35	92.6	31.3m2	8.03
P2O5	0.04	0.62	42.9m	9.45	83.2	27m2	8.00
Cl			37.1m	12.60	70.6	23.3m2	8.88
Undetermined	0.01	0.23	32m	11.95	58.6	20.1m2	7.23
Total	6.62	100.0	27.6m	8.55	50.1	17.4m2	4.43
Forms of Sulfur (% dry fuel)			23.8m	6.60	43.5	15m2	3.70
Pyritic	0.69		20.5m	6.00	37.5	12.9m2	4.40
Organic	0.82		17.7m	6.35	31.1	11.1m2	3.90
Sulfatic	0.05		15.3m	6.40	24.7	9.6m2	2.88
Fraction Free Silica	0.24		13.2m	5.25	19.5	8.3m2	1.63
Fraction Pyritic Iron	0.74		11.4m	4.05	15.4	7.2m2	1.45
Heating Value (Btu/lb, dry)			9.8m	2.85	12.6	6.2m2	1.50
As Fired	13994	13761	8.5m	2.25	10.3	5.3m2	1.33
Dulong	14184	13947	7.3m	2.00	8.3	4.8m2	1.20
Acid Sol. Alkali (ppm)	Dry	As Rec'd	6.3m	1.80	6.5	4m2	0.93
Na			5.4m	1.65	4.9	3.4m2	0.88
Mg			4.7m	1.35	3.5	3m2	0.70
Ca			4.1m	0.90	2.6	2.8m2	0.30
K			3.5m	0.80	1.8	2.2m2	0.13
Fusion Temp.	°F	°C	3m	0.50	1.3	1.9m2	0.00
Reducing Conditions			2.6m	0.35	1.0	1.6m2	0.05
Initial Deformation	2109	1154	2.2m	0.25	0.7	1.4m2	0.00
Spherical	2268	1242	1.9m	0.55	0.2	1.2m2	0.00
Hemispherical	2383	1306	Size Statistics (Malvern Data Only)				
Fluid	2481	1360			Malvern		All Data
Oxidizing Conditions			Dv.5	Volume Mean Diam.		24.78	
Initial Deformation	2472	1356	Dv.9	90 % volume diameter		44.78	
Spherical	2519	1382	Dv.1	10 percentile volume diameter		18.55	
Hemispherical	2550	1399	D4,3			25.52	
Fluid	2604	1429	D3,2	Sauter Mean Diameter		14.80	
			Span			1.48	
			Specific Surface Area (m ² /cc)			0.39	

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

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

Massey Sprouce

Analyses			Analyses					
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin		cum. mass %
Fixed Carbon	56.99	55.69	dp>600µm		+28			
Volatile Matter	34.68	33.89	600µm>dp>300µm		28x48			
Moisture	2.28		300µm>dp>149µm		48x100			
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200			
C	77.89	76.11	74µm>dp>44µm		200x325			
H	5.04	4.93	44µm>dp		-325			
O	6.26	6.12	Size Distribution (Malvern)*			Size Distribution (Malvern)*		
N	1.43	1.40	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin	cum. vol. per.
S	1.05	1.03						
Cl								
Ash	8.33	8.14	188m			118.4m2		
Ash Chemistry	% dry fuel	% ash	162m			102.1m2		
SiO2	4.61	55.35	140m			88.1m2		
Al2O3	2.18	26.22	121m			76m2		
TiO2	0.10	1.23	104m			65.6m2		
Fe2O3	0.97	11.62	89.9m			56.6m2		
CaO	0.12	1.42	77.5m			48.8m2		
MgO	0.07	0.86	66.9m			42.1m2		
K2O	0.19	2.28	57.7m			38.3m2		
Na2O	0.02	0.29	49.8m			31.3m2		
SO3	0.15	1.76	42.9m			27m2		
P2O5	0.01	0.08	37.1m			23.3m2		
Cl			32m			20.1m2		
Undetermined	-0.09	-1.11	27.6m			17.4m2		
Total	8.33	100.0	23.8m			15m2		
Forms of Sulfur (% dry fuel)			20.5m			12.9m2		
Pyritic	0.49		17.7m			11.1m2		
Organic	0.53		15.3m			9.6m2		
Sulfatic	0.03		13.2m			8.3m2		
Fraction Free Silica	0.29		11.4m			7.2m2		
Fraction Pyritic Iron	0.63		9.8m			6.2m2		
Heating Value (Btu/lb, dry)			8.5m			5.3m2		
As Fired	13768	13454	7.3m			4.8m2		
Dulong	14012	13692	6.3m			4m2		
Acid Sol. Alkali (ppm)	Dry	As Rec'd	5.4m			3.4m2		
Na			4.7m			3m2		
Mg			4.1m			2.8m2		
Ca			3.5m			2.2m2		
K			3m			1.9m2		
Fusion Temp.	°F	°C	2.6m			1.6m2		
Reducing Conditions			2.2m			1.4m2		
Initial Deformation			1.9m			1.2m2		
Spherical			Size Statistics (Malvern Data Only)					
Hemispherical			Malvern All Data					
Fluid			Dv.5	Volume Mean Diam.				
Oxidizing Conditions			Dv.9	90 % volume diameter				
Initial Deformation			Dv.1	10 percentile volume diameter				
Spherical			D4,3					
Hemispherical			D3,2	Sauter Mean Diameter				
Fluid			Span					
Specific Surface Area (m^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		cum. mass %
Fixed Carbon	53.00	52.28	dp>600µm		+28	0.00		0.00
Volatile Matter	36.87	36.37	600µm>dp>300µm		28x48	0.05		0.05
Moisture	1.36		300µm>dp>149µm		48x100	1.43		1.48
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	32.50		33.98
C	74.82	73.80	74µm>dp>44µm		200x325	30.15		64.13
H	4.97	4.90	44µm>dp		-325	35.88		100.00
O	7.57	7.47	Size Distribution (Malvern)*			Size Distribution (Malvern)*		
N	1.46	1.44	Diameter % in		cum. vol.	Diameter	% in	cum. vol.
S	0.97	0.96	(µm)	size bin	per.	(µm)	size bin	per.
Cl	0.09	0.09	188m	0.00	100.0	118.4m2	0.05	100.0
Ash	10.15	10.02	162m	0.05	100.0	102.1m2	0.13	99.9
Ash Chemistry	% dry fuel	% ash	140m	0.05	99.9	88.1m2	0.15	99.9
SiO2	5.86	57.67	121m	0.05	99.9	76m2	0.23	99.8
Al2O3	3.09	30.39	104m	0.05	99.8	65.6m2	1.98	98.0
TiO2	0.21	2.06	89.9m	0.18	99.6	56.6m2	5.58	94.4
Fe2O3	0.49	4.83	77.5m	0.63	99.0	48.8m2	9.70	90.3
CaO	0.12	1.15	66.9m	1.48	97.5	42.1m2	10.70	89.3
MgO	0.04	0.41	57.7m	2.98	94.6	38.3m2	8.63	91.4
K2O	0.10	0.99	49.8m	5.85	88.7	31.3m2	6.40	93.6
Na2O	0.02	0.17	42.9m	8.43	80.3	27m2	6.98	93.0
SO3	0.13	1.28	37.1m	9.73	70.6	23.3m2	8.98	91.0
P2O5	0.01	0.13	32m	9.08	61.5	20.1m2	7.55	92.5
Cl			27.6m	7.48	54.0	17.4m2	4.28	95.7
Undetermined	0.09	0.91	23.8m	6.40	47.6	15m2	3.30	96.7
Total	10.15	100.0	20.5m	5.73	41.9	12.9m2	4.13	95.9
Forms of Sulfur (% dry fuel)			17.7m	5.35	36.5	11.1m2	4.35	95.7
Pyritic	0.31		15.3m	5.30	31.2	9.6m2	3.90	96.1
Organic	0.66		13.2m	4.95	26.3	8.3m2	2.40	97.6
Sulfatic	0.00		11.4m	4.18	22.1	7.2m2	1.63	98.4
Fraction Free Silica	0.21		9.8m	3.33	18.8	6.2m2	1.68	98.3
Fraction Pyritic Iron	0.78		8.5m	2.75	16.0	5.3m2	1.78	98.2
Heating Value (Btu/lb, dry)			7.3m	2.50	13.5	4.8m2	1.60	98.4
As Fired	13226	13046	6.3m	2.48	11.1	4m2	1.40	98.6
Dulong	13418	13235	5.4m	2.43	8.6	3.4m2	1.15	98.9
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	2.13	6.5	3m2	0.93	99.1
Na			4.1m	1.65	4.9	2.8m2	0.45	99.6
Mg			3.5m	1.35	3.5	2.2m2	0.15	99.9
Ca			3m	0.93	2.6	1.9m2	0.00	100.0
K			2.6m	0.65	1.9	1.6m2	0.00	100.0
Fusion Temp.	°F	°C	2.2m	0.58	1.4	1.4m2	0.00	100.0
Reducing Conditions			1.9m	0.60	0.8	1.2m2	0.00	100.0
Initial Deformation	2949	1620	Size Statistics (Malvern Data Only)					
Spherical	2980	1638				Malvern	All Data	
Hemispherical	2992	1644	Dv.5	Volume Mean Diam.		23.48		
Fluid	3000	1649	Dv.9	90 % volume diameter		47.54		
Oxidizing Conditions			Dv.1	10 percentile volume diameter		6.28		
Initial Deformation	2960	1627	D4,3			25.23		
Spherical	2996	1647	D3,2	Sauter Mean Diameter		13.04		
Hemispherical	3000	1649	Span			1.75		
Fluid	3000	1649	Specific Surface Area (m^3/cc)				0.45	

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

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

Pittsburgh #8 (1)

Analyses			Analyses					
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin		cum. mass %
Fixed Carbon	49.16	48.66	dp>600µm		+28	0.00		0.00
Volatile Matter	40.16	39.75	600µm>dp>300µm		28x48	0.20		0.20
Moisture	1.02		300µm>dp>149µm		48x100	0.80		1.00
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	22.10		23.10
C	71.51	70.78	74µm>dp>44µm		200x325	34.80		57.90
H	5.03	4.98	44µm>dp		-325	42.10		100.00
O	6.76	6.69	Size Distribution (Malvern)*			Size Distribution (Malvern)*		
N	1.24	1.23	Diameter % in		cum. vol.	Diameter	% in	cum. vol.
S	4.78	4.73	(µm)	size bin	per.	(µm)	size bin	per.
Cl			188m			118.4m2		
Ash	10.68	10.57	162m			102.1m2		
Ash Chemistry	% dry fuel	% ash	140m			88.1m2		
SiO2	4.42	41.40	121m			76m2		
Al2O3	2.19	20.51	104m			65.6m2		
TiO2	0.10	0.89	89.9m			56.6m2		
Fe2O3	3.10	29.03	77.5m			48.8m2		
CaO	0.22	2.07	66.9m			42.1m2		
MgO	0.08	0.78	57.7m			38.3m2		
K2O	0.18	1.73	49.8m			31.3m2		
Na2O	0.04	0.40	42.9m			27m2		
SO3	0.25	2.33	37.1m			23.3m2		
P2O5	0.02	0.15	32m			20.1m2		
Cl			27.6m			17.4m2		
Undetermined	0.08	0.71	23.8m			15m2		
Total	10.68	100.0	20.5m			12.9m2		
Forms of Sulfur (% dry fuel)			17.7m			11.1m2		
Pyritic	1.81		15.3m			9.6m2		
Organic	2.82		13.2m			8.3m2		
Sulfatic	0.15		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	13004	12871	6.3m			4m2		
Dulong	13190	13055	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	1917	1047	Size Statistics (Malvern Data Only)					
Spherical	1980	1082	Malvern All Data					
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	% in	cum. vol.	Diameter	% in
S	0.46	0.44	(µm)	size bin	per.	(µm)	size bin
Cl	0.04	0.04					cum. vol.
Ash	10.51	10.17					per.
Ash Chemistry	% dry fuel	% ash	188m	0.00	100.0	118.4m2	
SiO2	6.06	57.69	162m	0.00	100.0	102.1m2	
Al2O3	1.92	18.32	140m	0.00	100.0	88.1m2	
TiO2	0.10	0.96	121m	0.00	100.0	76m2	
Fe2O3	0.43	4.11	104m	0.00	100.0	65.6m2	
CaO	0.64	6.13	89.9m	0.08	99.9	56.6m2	
MgO	0.19	1.84	77.5m	0.28	99.7	48.8m2	
K2O	0.12	1.16	66.9m	0.63	99.0	42.1m2	
Na2O	0.45	4.32	57.7m	1.35	97.7	38.3m2	
SO3	0.48	4.57	49.8m	3.68	94.0	31.3m2	
P2O5	0.03	0.33	42.9m	7.55	86.5	27m2	
Cl			37.1m	9.68	76.8	23.3m2	
Undetermined	0.06	0.58	32m	9.13	67.7	20.1m2	
Total	10.51	100.0	27.6m	7.45	60.2	17.4m2	
Forms of Sulfur (% dry fuel)			23.8m	6.28	53.9	15m2	
Pyritic	0.08		20.5m	5.78	48.2	12.9m2	
Organic	0.37		17.7m	5.93	42.2	11.1m2	
Sulfatic	0.00		15.3m	6.05	36.2	9.6m2	
Fraction Free Silica	0.52		13.2m	5.50	30.7	8.3m2	
Fraction Pyritic Iron	0.24		11.4m	4.60	26.1	7.2m2	
Heating Value (Btu/lb, dry)			9.8m	3.68	22.4	6.2m2	
As Fired	13108	12684	8.5m	3.15	19.3	5.3m2	
Dulong	13247	12819	7.3m	3.00	16.3	4.8m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	6.3m	2.95	13.3	4m2	
Na			5.4m	2.78	10.5	3.4m2	
Mg			4.7m	2.35	8.2	3m2	
Ca			4.1m	1.70	6.5	2.8m2	
K			3.5m	1.45	5.0	2.2m2	
Fusion Temp.	°F	°C	3m	1.05	4.0	1.9m2	
Reducing Conditions			2.6m	0.88	3.1	1.6m2	
Initial Deformation	2178	1192	2.2m	0.83	2.3	1.4m2	
Spherical	2246	1230	1.9m	1.20	1.1	1.2m2	
Hemispherical	2369	1298	Size Statistics (Malvern Data Only)				
Fluid	2641	1449	Dv.5	Volume Mean Diam.	20.25	Malvern	All Data
Oxidizing Conditions			Dv.9	90 % volume diameter	42.45		
Initial Deformation	2220	1216	Dv.1	10 percentile volume diameter	4.95		
Spherical	2265	1241	D4,3		22.58		
Hemispherical	2400	1316	D3,2	Sauter Mean Diameter	10.88		
Fluid	2675	1468	Span		1.88		
			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			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 % in		cum. vol.	Diameter	% in	cum. vol.
S	4.78	4.60	(µm)	size bin	per.	(µm)	size bin	per.
Cl	0.03	0.03	188m	0.00	100.0	118.4m2		
Ash	22.15	21.28	162m	0.00	100.0	102.1m2		
Ash Chemistry	% dry fuel	% ash	140m	0.00	100.0	88.1m2		
SiO2	10.14	45.76	121m	0.00	100.0	76m2		
Al2O3	4.06	18.33	104m	0.00	100.0	65.6m2		
TiO2	0.19	0.84	89.9m	0.15	99.9	56.6m2		
Fe2O3	4.70	21.23	77.5m	0.45	99.4	48.8m2		
CaO	0.95	4.30	66.9m	0.80	98.6	42.1m2		
MgO	0.24	1.11	57.7m	1.60	97.0	38.3m2		
K2O	0.48	2.17	49.8m	3.85	93.2	31.3m2		
Na2O	0.08	0.36	42.9m	6.65	86.5	27m2		
SO3	1.02	4.61	37.1m	9.55	77.0	23.3m2		
P2O5	0.04	0.20	32m	9.90	67.1	20.1m2		
Cl	0.02	0.09	27.6m	8.15	58.9	17.4m2		
Undetermined	0.23	1.02	23.8m	6.85	52.1	15m2		
Total	22.16	100.0	20.5m	6.20	45.9	12.9m2		
Forms of Sulfur (% dry fuel)			17.7m	6.20	39.7	11.1m2		
Pyritic	2.99		15.3m	6.35	33.3	9.6m2		
Organic	1.59		13.2m	5.70	27.6	8.3m2		
Sulfatic	0.20		11.4m	4.75	22.8	7.2m2		
Fraction Free Silica	0.40		9.8m	3.50	19.3	6.2m2		
Fraction Pyritic Iron	0.80		8.5m	2.90	16.5	5.3m2		
Heating Value (Btu/lb, dry)			7.3m	2.80	13.6	4.8m2		
As Fired	10524	10112	6.3m	2.75	10.9	4m2		
Dulong	10909	10482	5.4m	2.60	8.3	3.4m2		
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	2.20	6.1	3m2		
Na	400	400	4.1m	1.55	4.5	2.8m2		
Mg	1037	1037	3.5m	1.15	3.4	2.2m2		
Ca	4981	4981	3m	0.85	2.5	1.9m2		
K	3578	3578	2.6m	0.70	1.8	1.6m2		
Fusion Temp.	°F	°C	2.2m	0.55	1.3	1.4m2		
Reducing Conditions			1.9m	1.25	0.0	1.2m2		
Initial Deformation	2238	1226	Size Statistics (Malvern Data Only)					
Spherical	2270	1243			Malvern		All Data	
Hemispherical	2310	1266	Dv.5	Volume Mean Diam.	19.55			
Fluid	2352	1289	Dv.9	90 % volume diameter	39.75			
Oxidizing Conditions			Dv.1	10 percentile volume diameter	5.20			
Initial Deformation	2314	1268	D4,3		21.75			
Spherical	2354	1290	D3,2	Sauter Mean Diameter	11.25			
Hemispherical	2404	1318	Span		1.80			
Fluid	2446	1341	Specific Surface Area (m ² /cc)		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	188m	0.00	100.0
Cl	0.08	0.08	162m	0.02	100.0
Ash	12.21	11.69	140m	0.07	99.9
Ash Chemistry	% dry fuel	% ash	121m	0.08	99.8
SiO2	5.94	48.66	104m	0.08	99.8
Al2O3	2.20	18.00	89.9m	0.08	99.7
TiO2	0.11	0.87	77.5m	0.42	99.3
Fe2O3	2.23	18.31	66.9m	1.72	97.5
CaO	0.58	4.78	57.7m	3.88	93.7
MgO	0.12	1.02	49.8m	6.70	87.0
K2O	0.25	2.08	42.9m	9.10	77.9
Na2O	0.12	1.02	37.1m	9.83	68.0
SO3	0.55	4.53	32m	9.15	58.9
P2O5	0.03	0.21	27.6m	7.75	51.1
Cl			23.8m	6.55	44.6
Undetermined	0.12	0.94	20.5m	5.88	38.7
Total	12.26	100.4	17.7m	5.65	33.0
Forms of Sulfur (% dry fuel)			15.3m	5.38	27.7
Pyritic	1.06		13.2m	4.70	23.0
Organic	2.21		11.4m	3.73	19.2
Sulfatic	0.54		9.8m	2.95	16.3
Fraction Free Silica	0.45		8.5m	2.52	13.8
Fraction Pyritic Iron	0.44		7.3m	2.32	11.4
Heating Value (Btu/lb, dry)			6.3m	2.18	9.3
As Fired	12059	11550	5.4m	2.07	7.2
Dulong	12228	11712	4.7m	1.75	5.4
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	1.38	4.1
Na			3.5m	1.07	3.0
Mg			3m	0.85	2.1
Ca			2.6m	0.58	1.6
K			2.2m	0.42	1.1
Fusion Temp.	°F	°C	1.9m	0.50	0.6
Reducing Conditions			Size Statistics (Malvern Data Only)		
Initial Deformation	1996	1091			Malvern
Spherical	2054	1123			All Data
Hemispherical	2177	1192	Dv.5	Volume Mean Diam.	25.65
Fluid	2367	1297	Dv.9	90 % volume diameter	50.57
Oxidizing Conditions			Dv.1	10 percentile volume diameter	6.52
Initial Deformation	2291	1255	D4,3		27.65
Spherical	2331	1277	D3,2	Sauter Mean Diameter	13.97
Hemispherical	2360	1293	Span		1.73
Fluid	2480	1360	Specific Surface Area (m ² /cc)		0.44

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

Table A.14 Summary of Properties of the SOAP.

Spherical Oil Agglomerate						
Analyses			Analyses			
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin
Fixed Carbon	53.04	47.15	dp>600µm		+28	0.27
Volatile Matter	42.98	38.20	600µm>dp>300µm		28x48	23.40
Moisture	11.10		300µm>dp>149µm		48x100	6.57
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	3.77
C	74.63	66.34	74µm>dp>44µm		200x325	1.80
H	5.21	4.63	44µm>dp		-325	64.20
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)
S	3.07	2.73				% in size bin
Cl	0.06	0.05				cum. vol. per.
Ash	3.99	3.54	188m	0.00	100.0	118.4m2
Ash Chemistry	% dry fuel	% ash	162m	0.00	100.0	102.1m2
SiO2	1.25	31.44	140m	0.00	100.0	88.1m2
Al2O3	0.66	16.66	121m	0.00	100.0	76m2
TiO2	0.08	2.09	104m	0.00	100.0	65.6m2
Fe2O3	1.52	38.03	89.9m	0.00	100.0	56.6m2
CaO	0.11	2.72	77.5m	0.00	100.0	48.8m2
MgO	0.04	1.06	66.9m	0.00	100.0	42.1m2
K2O	0.07	1.86	57.7m	0.02	100.0	38.3m2
Na2O	0.04	1.02	49.8m	0.03	100.0	31.3m2
SO3	0.15	3.66	42.9m	0.10	99.9	27m2
P2O5	0.01	0.14	37.1m	0.53	99.3	23.3m2
Cl			32m	0.92	98.4	20.1m2
Undetermined	0.05	1.26	27.6m	2.05	96.4	17.4m2
Total	3.98	99.9	23.8m	3.80	92.6	15m2
Forms of Sulfur (% dry fuel)			20.5m	5.17	87.4	12.9m2
Pyritic	0.03		17.7m	6.22	81.2	11.1m2
Organic	2.19		15.3m	7.15	74.0	9.6m2
Sulfatic	0.85		13.2m	7.83	66.2	8.3m2
Fraction Free Silica	0.20		11.4m	8.40	57.8	7.2m2
Fraction Pyritic Iron	0.02		9.8m	8.33	49.5	6.2m2
Heating Value (Btu/lb, dry)			8.5m	7.73	41.7	5.3m2
As Fired	13656	12139	7.3m	6.95	34.8	4.8m2
Dulong	13289	11813	6.3m	6.53	28.2	4m2
Acid Sol. Alkali (ppm)	Dry	As Rec'd	5.4m	6.18	22.1	3.4m2
Na			4.7m	5.53	16.5	3m2
Mg			4.1m	4.47	12.1	2.8m2
Ca			3.5m	3.17	8.9	2.2m2
K			3m	2.23	6.7	1.9m2
Fusion Temp.	°F	°C	2.6m	1.73	4.9	1.6m2
Reducing Conditions			2.2m	1.43	3.5	1.4m2
Initial Deformation	2108	1153	1.9m	2.58	0.9	1.2m2
Spherical	2257	1236	Size Statistics (Malvern Data Only)			
Hemispherical	2344	1284	Dv.5	Volume Mean Diam.	8.98	Malvern
Fluid	2394	1312	Dv.9	90 % volume diameter	19.92	All Data
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 (m ² /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 % in		cum. vol.	Diameter	% in	cum. vol.	
S	4.00	3.71	(µm)	size bin	per.	(µm)	size bin	per.	
Cl	0.06	0.05	188m	0.00	100.0	118.4m2			
Ash	15.64	14.49	162m	0.00	100.0	102.1m2			
Ash Chemistry	% dry fuel	% ash	140m	0.02	100.0	88.1m2			
SiO2	7.12	45.54	121m	0.03	100.0	76m2			
Al2O3	3.08	19.71	104m	0.02	99.9	65.6m2			
TiO2	0.15	0.98	89.9m	0.07	99.9	56.6m2			
Fe2O3	3.61	23.09	77.5m	0.33	99.5	48.8m2			
CaO	0.50	3.22	66.9m	1.23	98.3	42.1m2			
MgO	0.16	1.05	57.7m	2.92	95.4	38.3m2			
K2O	0.39	2.47	49.8m	5.38	90.0	31.3m2			
Na2O	0.14	0.87	42.9m	7.83	82.2	27m2			
SO3	0.57	3.62	37.1m	9.22	73.0	23.3m2			
P2O5	0.02	0.14	32m	9.33	63.6	20.1m2			
Cl	0.03	0.17	27.6m	8.38	55.2	17.4m2			
Undetermined	-0.12	-0.77	23.8m	7.28	48.0	15m2			
Total	15.65	100.1	20.5m	6.35	41.6	12.9m2			
Forms of Sulfur (% dry fuel)			17.7m	5.83	35.8	11.1m2			
Pyritic	1.70		15.3m	5.72	30.1	9.6m2			
Organic	1.89		13.2m	5.37	24.7	8.3m2			
Sulfatic	0.41		11.4m	4.45	20.2	7.2m2			
Fraction Free Silica	0.34		9.8m	3.48	16.8	6.2m2			
Fraction Pyritic Iron	0.59		8.5m	2.80	14.0	5.3m2			
Heating Value (Btu/lb, dry)			7.3m	2.42	11.5	4.8m2			
As Fired	11611	10759	6.3m	2.28	9.3	4m2			
Dulong	15493	14356	5.4m	2.13	7.1	3.4m2			
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.85	5.3	3m2			
Na	694	694	4.1m	1.47	3.8	2.8m2			
Mg	830	830	3.5m	1.15	2.7	2.2m2			
Ca	2835	2835	3m	0.87	1.8	1.9m2			
K	2225	2225	2.6m	0.57	1.2	1.6m2			
Fusion Temp.	°F	°C	2.2m	0.38	0.8	1.4m2			
Reducing Conditions			1.9m	0.37	0.5	1.2m2			
Initial Deformation	1979	1082	Size Statistics (Malvern Data Only)						
Spherical	2041	1116					Malvern	All Data	
Hemispherical	2170	1188	Dv.5	Volume Mean Diam.			23.57		
Fluid	2339	1282	Dv.9	90 % volume diameter			47.35		
Oxidizing Conditions			Dv.1	10 percentile volume diameter			6.53		
Initial Deformation	2323	1273	D4,3				26.15		
Spherical	2414	1323	D3,2	Sauter Mean Diameter			13.80		
Hemispherical	2469	1354	Span				1.77		
Fluid	2526	1385	Specific Surface Area (m^3/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					
Cl	0.03	0.02					
Ash	9.99	9.00					
Ash Chemistry	% dry fuel	% ash					
SiO ₂	3.63	36.34	188m	0.00	100.0	118.4m ²	
Al ₂ O ₃	1.49	14.94	162m	0.05	100.0	102.1m ²	
TiO ₂	0.07	0.75	140m	0.10	99.9	88.1m ²	
Fe ₂ O ₃	0.82	8.21	121m	0.15	99.7	76m ²	
CaO	2.20	22.01	104m	0.20	99.5	65.6m ²	
MgO	0.33	3.26	89.9m	0.15	99.4	56.6m ²	
K ₂ O	0.08	0.82	77.5m	0.45	98.9	48.8m ²	
Na ₂ O	0.09	0.87	66.9m	1.90	97.0	42.1m ²	
SO ₃	1.07	10.76	57.7m	4.25	92.8	38.3m ²	
P ₂ O ₅	0.07	0.66	49.8m	7.45	85.3	31.3m ²	
Cl			42.9m	10.35	75.0	27m ²	
Undetermined	0.10	1.01	37.1m	10.80	64.2	23.3m ²	
Total	9.95	99.6	32m	10.05	54.1	20.1m ²	
Forms of Sulfur (% dry fuel)			27.6m	8.30	45.8	17.4m ²	
Pyritic	0.19		23.8m	6.30	39.5	15m ²	
Organic	0.43		20.5m	5.40	34.1	12.9m ²	
Sulfatic	0.03		17.7m	5.15	29.0	11.1m ²	
Fraction Free Silica	0.38		15.3m	5.05	23.9	9.6m ²	
Fraction Pyritic Iron	0.19		13.2m	4.60	19.3	8.3m ²	
Heating Value (Btu/lb, dry)			11.4m	3.45	15.9	7.2m ²	
As Fired	11921	10734	9.8m	2.70	13.2	6.2m ²	
Dulong	11517	10370	8.5m	2.15	11.0	5.3m ²	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	7.3m	1.90	9.1	4.8m ²	
Na			6.3m	1.70	7.4	4m ²	
Mg			5.4m	1.60	5.8	3.4m ²	
Ca			4.7m	1.40	4.4	3m ²	
K			4.1m	1.20	3.2	2.8m ²	
Fusion Temp.	°F	°C	3.5m	0.95	2.3	2.2m ²	
Reducing Conditions			3m	0.75	1.5	1.9m ²	
Initial Deformation	2186	1196	2.6m	0.50	1.0	1.6m ²	
Spherical	2245	1229	2.2m	0.35	0.7	1.4m ²	
Hemispherical	2276	1246	1.9m	0.25	0.4	1.2m ²	
Fluid	2338	1281	Size Statistics (Malvern Data Only)				
Oxidizing Conditions							
Initial Deformation	2275	1246					
Spherical	2316	1269					
Hemispherical	2349	1287					
Fluid	2452	1344					

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

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

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

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

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

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

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

Belle Ayr

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

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

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

Wyodak

Analyses			Analyses					
Proximate	Dry	As Rec'd	Size Distribution		Sieves	mass % in size bin		cum. mass %
Fixed Carbon	48.27	38.74	dp>600µm		+28	0.00		0.00
Volatile Matter	45.50	36.52	600µm>dp>300µm		28x48	0.00		0.00
Moisture	19.74		300µm>dp>149µm		48x100	4.08		4.08
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	19.53		23.60
C	69.76	55.99	74µm>dp>44µm		200x325	20.38		43.98
H	4.95	3.97	44µm>dp		-325	56.03		100.00
O	17.49	14.04	Size Distribution (Malvern)*			Size Distribution (Malvern)*		
N	0.97	0.77	Diameter % 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/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	cum. vol. per.
S	0.42	0.32	188m		118.4m2
Cl	0.03	0.02	162m		102.1m2
Ash	5.51	4.25	140m		88.1m2
Ash Chemistry	% dry fuel	% ash	121m		76m2
SiO2	1.38	25.03	104m		65.6m2
Al2O3	0.63	11.36	89.9m		56.6m2
TiO2	0.04	0.66	77.5m		48.8m2
Fe2O3	0.45	8.18	66.9m		42.1m2
CaO	1.59	28.88	57.7m		38.3m2
MgO	0.31	5.60	49.8m		31.3m2
K2O	0.01	0.25	42.9m		27m2
Na2O	0.09	1.57	37.1m		23.3m2
SO3	0.97	17.65	32m		20.1m2
P2O5	0.04	0.81	27.6m		17.4m2
Cl			23.8m		15m2
Undetermined	0.00	0.01	20.5m		12.9m2
Total	5.51	100.0	17.7m		11.1m2
Forms of Sulfur (% dry fuel)			15.3m		9.6m2
Pyritic	0.02		13.2m		8.3m2
Organic	0.40		11.4m		7.2m2
Sulfatic	0.00		9.8m		6.2m2
Fraction Free Silica			8.5m		5.3m2
	0.32		7.3m		4.8m2
Fraction Pyritic Iron			6.3m		4m2
	0.06		5.4m		3.4m2
Heating Value (Btu/lb, dry)			4.7m		3m2
As Fired	12271	9461	4.1m		2.8m2
Dulong	11465	8840	3.5m		2.2m2
Acid Sol. Alkali (ppm)	Dry	As Rec'd	3m		1.9m2
Na			2.6m		1.6m2
Mg			2.2m		1.4m2
Ca			1.9m		1.2m2
K					
Fusion Temp.	°F	°C	Size Statistics (Malvern Data Only)		
Reducing Conditions					
Initial Deformation	2323	1273	Dv.5	Volume Mean Diam.	Malvern All Data
Spherical	2355	1291	Dv.9	90 % volume diameter	
Hemispherical	2381	1305	Dv.1	10 percentile volume diameter	
Fluid	2411	1322	D4,3		
Oxidizing Conditions			D3,2	Sauter Mean Diameter	
Initial Deformation	2349	1287	Span		
Spherical	2369	1298			
Hemispherical	2383	1306			
Fluid	2402	1317			
			Specific Surface Area (m²/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	cum. mass %
Fixed Carbon	47.95	37.26	dp>600µm		+28	0.00	0.00
Volatile Matter	45.67	35.48	600µm>dp>300µm		28x48	0.27	0.27
Moisture	22.30		300µm>dp>149µm		48x100	2.70	2.97
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	17.50	20.47
C	66.89	51.97	74µm>dp>44µm		200x325	22.60	43.07
H	4.89	3.80	44µm>dp		-325	56.93	100.00
O	20.20	15.70	Size Distribution (Malvern)*			Size Distribution (Malvern)*	
N	1.17	0.91	Diameter (µm)	% in size bin	cum. vol. per.	Diameter (µm)	% in size bin
S	0.47	0.37					cum. vol. per.
Cl	0.03	0.02	188m	0.00	100.0	118.4m2	
Ash	6.37	4.95	162m	0.00	100.0	102.1m2	
Ash Chemistry	% dry fuel	% ash	140m	0.02	100.0	88.1m2	
SiO2	1.78	28.00	121m	0.03	100.0	76m2	
Al2O3	0.90	14.16	104m	0.03	99.9	65.6m2	
TiO2	0.05	0.83	89.9m	0.08	99.8	56.6m2	
Fe2O3	0.39	6.09	77.5m	0.27	99.6	48.8m2	
CaO	1.60	25.09	66.9m	0.88	98.7	42.1m2	
MgO	0.38	5.95	57.7m	1.87	96.8	38.3m2	
K2O	0.02	0.26	49.8m	3.78	93.0	31.3m2	
Na2O	0.12	1.84	42.9m	6.80	86.2	27m2	
SO3	1.04	16.38	37.1m	9.47	76.8	23.3m2	
P2O5	0.04	0.67	32m	10.13	66.6	20.1m2	
Cl			27.6m	8.87	57.8	17.4m2	
Undetermined	0.05	0.73	23.8m	7.38	50.4	15m2	
Total	6.37	100.0	20.5m	6.47	43.9	12.9m2	
Forms of Sulfur (% dry fuel)			17.7m	6.32	37.6	11.1m2	
Pyritic	0.06		15.3m	6.32	31.3	9.6m2	
Organic	0.40		13.2m	5.75	25.5	8.3m2	
Sulfatic	0.01		11.4m	4.82	20.7	7.2m2	
Fraction Free Silica	0.24		9.8m	3.75	17.0	6.2m2	
Fraction Pyritic Iron	0.19		8.5m	3.03	13.9	5.3m2	
Heating Value (Btu/lb, dry)			7.3m	2.68	11.3	4.8m2	
As Fired	11516	8947	6.3m	2.48	8.8	4m2	
Dulong	11211	8711	5.4m	2.25	6.5	3.4m2	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	1.88	4.6	3m2	
Na	822	822	4.1m	1.30	3.3	2.8m2	
Mg	1891	1891	3.5m	1.00	2.3	2.2m2	
Ca	7250	7250	3m	0.70	1.6	1.9m2	
K	75	75	2.6m	0.48	1.2	1.6m2	
Fusion Temp.	°F	°C	2.2m	0.32	0.8	1.4m2	
Reducing Conditions			1.9m	0.27	0.6	1.2m2	
Initial Deformation	2223	1217	Size Statistics (Malvern Data Only)				
Spherical	2254	1234				Malvern	All Data
Hemispherical	2261	1239	Dv.5	Volume Mean Diam.		21.37	
Fluid	2273	1245	Dv.9	90 % volume diameter		42.02	
Oxidizing Conditions			Dv.1	10 percentile volume diameter		6.20	
Initial Deformation	2184	1196	D4,3			23.20	
Spherical	2214	1212	D3,2	Sauter Mean Diameter		12.98	
Hemispherical	2229	1221	Span			1.68	
Fluid	2249	1231	Specific Surface Area (m ² /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
Fixed Carbon	43.44	32.96	dp>600µm	+28	0.06
Volatile Matter	42.95	32.59	600µm>dp>300µm	28x48	2.88
Moisture	24.13		300µm>dp>149µm	48x100	12.81
Ultimate	Dry	As Rec'd	149µm>dp>74µm	100x200	22.60
C	60.97	46.26	74µm>dp>44µm	200x325	17.20
H	4.07	3.09	44µm>dp	-325	45.29
O	18.50	14.04	Size Distribution (Malvern)*		Size Distribution (Malvern)*
N	1.02	0.77	Diameter (µm)	% in size bin	cum. vol. per.
S	1.81	1.38	188m	0.18	99.8
Cl	0.04	0.03	162m	0.49	99.3
Ash	13.69	10.39	140m	0.72	98.6
Ash Chemistry	% dry fuel	% ash	121m	0.92	97.7
SiO ₂	2.87	20.93	104m	0.98	96.7
Al ₂ O ₃	1.89	13.78	89.9m	1.20	95.5
TiO ₂	0.06	0.41	77.5m	1.53	94.0
Fe ₂ O ₃	1.65	12.08	66.9m	1.92	92.1
CaO	2.21	16.13	57.7m	2.69	89.4
MgO	0.60	4.40	49.8m	4.01	85.4
K ₂ O	0.03	0.22	42.9m	5.41	79.9
Na ₂ O	0.88	6.41	37.1m	6.32	73.6
SO ₃	3.32	24.27	32m	6.37	67.3
P ₂ O ₅	0.00	0.00	27.6m	5.98	61.3
Cl			23.8m	5.70	55.6
Undetermined	0.19	1.38	20.5m	5.48	50.1
Total	13.69	100.0	17.7m	5.33	44.8
Forms of Sulfur (% dry fuel)			15.3m	5.29	39.5
Pyritic	0.47		13.2m	4.99	34.5
Organic	1.18		11.4m	4.64	29.8
Sulfatic	0.16		9.8m	4.12	25.7
Fraction Free Silica	0.10		8.5m	3.67	22.1
Fraction Pyritic Iron	0.37		7.3m	3.38	18.7
Heating Value (Btu/lb, dry)			6.3m	3.31	15.4
As Fired	10040	7617	5.4m	3.18	12.2
Dulong	10003	7590	4.7m	2.90	9.3
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.1m	2.47	6.8
Na	7357	7357	3.5m	1.82	5.0
Mg	3321	3321	3m	1.33	3.7
Ca	14036	14036	2.6m	1.11	2.6
K	152	152	2.2m	0.91	1.6
Fusion Temp.	°F	°C	1.9m	1.79	-0.1
Reducing Conditions			Size Statistics (Malvern Data Only)		
Initial Deformation	2026	1108			Malvern
Spherical	2149	1176			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 (m ² /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 % in		cum. vol.	Diameter	% in	cum. vol.	
S	1.75	1.43	(µm)	size bin	per.	(µm)	size bin	per.	
Cl	0.08	0.06	188m	0.00	100.0	118.4m2	0.10	99.9	
Ash	52.18	42.53	162m	0.00	100.0	102.1m2	0.35	99.7	
Ash Chemistry	% dry fuel	% ash	140m	0.00	100.0	88.1m2	0.40	99.6	
SiO2	34.36	65.85	121m	0.00	100.0	76m2	0.35	99.7	
Al2O3	10.13	19.41	104m	0.00	100.0	65.6m2	0.25	99.8	
TiO2	0.45	0.87	89.9m	0.08	99.9	56.6m2	1.80	98.2	
Fe2O3	0.87	1.66	77.5m	0.13	99.8	48.8m2	4.90	95.1	
CaO	1.56	2.99	66.9m	0.15	99.6	42.1m2	6.85	93.2	
MgO	0.25	0.48	57.7m	0.22	99.4	38.3m2	7.55	92.5	
K2O	0.98	1.88	49.8m	1.02	98.4	31.3m2	7.50	92.5	
Na2O	1.35	2.60	42.9m	2.78	95.6	27m2	7.30	92.7	
SO3	1.47	2.82	37.1m	4.85	90.8	23.3m2	6.75	93.3	
P2O5	0.00	0.01	32m	6.48	84.3	20.1m2	6.05	94.0	
Cl	0.01	0.02	27.6m	6.97	77.3	17.4m2	5.60	94.4	
Undetermined	0.74	1.42	23.8m	6.90	70.4	15m2	5.60	94.4	
Total	52.17	100.0	20.5m	6.68	63.7	12.9m2	5.55	94.5	
Forms of Sulfur (% dry fuel)			17.7m	6.70	57.0	11.1m2	4.80	95.2	
Pyritic	0.29		15.3m	6.73	50.3	9.6m2	4.30	95.7	
Organic	1.35		13.2m	6.45	43.8	8.3m2	3.90	96.1	
Sulfatic	0.10		11.4m	5.95	37.9	7.2m2	3.55	96.5	
Fraction Free Silica	0.56		9.8m	5.12	32.8	6.2m2	3.30	96.7	
Fraction Pyritic Iron	0.41		8.5m	4.45	28.3	5.3m2	2.85	97.2	
Heating Value (Btu/lb, dry)			7.3m	4.05	24.3	4.8m2	2.40	97.6	
As Fired	5076	4137	6.3m	3.95	20.3	4m2	2.20	97.8	
Dulong	5334	4347	5.4m	3.78	16.5	3.4m2	2.10	97.9	
Acid Sol. Alkali (ppm)	Dry	As Rec'd	4.7m	3.42	13.1	3m2	1.75	98.3	
Na	8788	8788	4.1m	2.88	10.2	2.8m2	0.80	99.2	
Mg	1156	1156	3.5m	2.13	8.1	2.2m2	0.60	99.4	
Ca	7628	7628	3m	1.58	6.5	1.9m2	0.30	99.7	
K	5862	5862	2.6m	1.37	5.2	1.6m2	0.00	100.0	
Fusion Temp.	°F	°C	2.2m	1.30	3.9	1.4m2	0.10	99.9	
Reducing Conditions			1.9m	2.33	1.5	1.2m2	0.10	99.9	
Initial Deformation	2349	1287	Size Statistics (Malvern Data Only)						
Spherical	2458	1348						Malvern	All Data
Hemispherical	2580	1416	Dv.5	Volume Mean Diam.		14.76			
Fluid	2759	1515	Dv.9	90 % volume diameter		34.26			
Oxidizing Conditions			Dv.1	10 percentile volume diameter		3.89			
Initial Deformation	2338	1281	D4,3			17.45			
Spherical	2433	1334	D3,2	Sauter Mean Diameter		8.39			
Hemispherical	2576	1413	Span			2.06			
Fluid	2762	1517	Specific Surface Area (m²/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		cum. mass %	
Fixed Carbon	61.06	60.62	dp>600µm		+28	0.00		0.00	
Volatile Matter	30.27	30.05	600µm>dp>300µm		28x48	0.00		0.00	
Moisture	0.72		300µm>dp>149µm		48x100	1.30		1.30	
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	26.30		27.60	
C	77.95	77.39	74µm>dp>44µm		200x325	26.30		53.90	
H	4.79	4.76	44µm>dp		-325	46.10		100.00	
O	5.51	5.47	Size Distribution (Malvern)*			Size Distribution (Malvern)*			
N	1.43	1.42	Diameter (µm)		% in size bin	cum. vol. per.	Diameter (µm)	% in size bin	cum. vol. per.
S	1.65	1.64	188m				118.4m2		
Cl			162m				102.1m2		
Ash	8.67	8.61	140m				88.1m2		
Ash Chemistry	% dry fuel	% ash	121m				76m2		
SiO2	4.25	49.03	104m				65.6m2		
Al2O3	2.13	24.53	89.9m				56.6m2		
TiO2	0.09	1.00	77.5m				48.8m2		
Fe2O3	1.48	17.03	66.9m				42.1m2		
CaO	0.20	2.31	57.7m				38.3m2		
MgO	0.07	0.86	49.8m				31.3m2		
K2O	0.17	1.99	42.9m				27m2		
Na2O	0.03	0.36	37.1m				23.3m2		
SO3	0.17	1.92	32m				20.1m2		
P2O5	0.03	0.37	27.6m				17.4m2		
Cl			23.8m				15m2		
Undetermined	0.05	0.60	20.5m				12.9m2		
Total	8.67	100.0	17.7m				11.1m2		
Forms of Sulfur (% dry fuel)			15.3m				9.6m2		
Pyritic		0.89	13.2m				8.3m2		
Organic		0.75	11.4m				7.2m2		
Sulfatic		0.01	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		13933	5.4m				3.4m2		
Dulong			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		2133	1167		Malvern All Data				
Spherical		2429	1332						
Hemispherical		2449	1343						
Fluid		2500	1371						
Oxidizing Conditions									
Initial Deformation		2497	1369						
Spherical		2574	1412						
Hemispherical		2602	1428						
Fluid		2632	1444						
			Specific Surface Area (m^3/cc)						

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

Pittsburgh #8-Decker Blend

Analyses			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 % in		cum. vol.	Diameter	% in	cum. vol.
S	1.04	0.97	(µm)	size bin	per.	(µm)	size bin	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			Malvern All Data
Spherical	1549	843	Dv.5	Volume Mean Diam.	143.33
Hemispherical	1610	877	Dv.9	90 % volume diameter	84.47
Fluid	1673	912	Dv.1	10 percentile volume diameter	21.74
Oxidizing Conditions			D4,3		54.68
Initial Deformation	1554	846	D3,2	Sauter Mean Diameter	26.56
Spherical	1579	860	Span		1.30
Hemispherical	1629	887	Specific Surface Area (m ² /cc)		0.30
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	
Fixed Carbon	49.69	42.64	dp>600µm		+28	0.00	
Volatile Matter	42.61	36.57	600µm>dp>300µm		28x48	0.35	
Moisture	14.17		300µm>dp>149µm		48x100	7.65	
Ultimate	Dry	As Rec'd	149µm>dp>74µm		100x200	21.90	
C	73.93	63.45	74µm>dp>44µm		200x325	19.85	
H	4.96	4.25	44µm>dp		-325	50.25	
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)	% in size bin
S	0.59	0.51					
Cl	0.08	0.06					
Ash	7.71	6.61					
Ash Chemistry	% dry fuel	% ash					
SiO2	2.99	38.84					
Al2O3	1.63	21.22					
TiO2	0.10	1.27					
Fe2O3	0.40	5.17					
CaO	0.93	12.13					
MgO	0.19	2.53					
K2O	0.10	1.35					
Na2O	0.07	0.96					
SO3	1.15	14.91					
P2O5	0.06	0.76					
Cl							
Undetermined	0.07	0.87					
Total	7.71	100.0					
Forms of Sulfur (% dry fuel)							
Pyritic	0.07						
Organic	0.53						
Sulfatic	0.00						
Fraction Free Silica							
Fraction Pyritic Iron							
Heating Value (Btu/lb, dry)							
As Fired	13821	11863					
Dulong	12942	11108					
Acid Sol. Alkali (ppm)							
Na							
Mg							
Ca							
K							
Fusion Temp.							
Reducing Conditions							
Initial Deformation	1147	619	Size Statistics (Malvern Data Only)				
Spherical	1174	634	Malvern All Data				
Hemispherical	1207	653	Dv.5	Volume Mean Diam.	21.45		
Fluid	1241	672	Dv.9	90 % volume diameter	47.13		
Oxidizing Conditions			Dv.1	10 percentile volume diameter	5.05		
Initial Deformation	1180	638	D4,3		24.28		
Spherical	1194	645	D3,2	Sauter Mean Diameter	11.30		
Hemispherical	1225	663	Span		1.95		
Fluid	1257	680	Specific Surface Area (m^2/cc)			0.56	

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

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	
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				Malvern	All Data
Hemispherical	2142	1172	Dv.5	Volume Mean Diam.		23.90	
Fluid	2233	1223	Dv.9	90 % volume diameter		50.60	
Oxidizing Conditions			Dv.1	10 percentile volume diameter		6.00	
Initial Deformation	2188	1198	D4,3			27.15	
Spherical	2212	1211	D3,2	Sauter Mean Diameter		13.45	
Hemispherical	2239	1226	Span			1.85	
Fluid	2320	1271	Specific Surface Area (m ² /cc)			0.45	

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

INITIAL DISTRIBUTION

Dr. Ralph Carabetta
Project Management
U.S. DOE/PETC
P.O. Box 10940
Pittsburgh, PA 15236-0940

Ms. Kay Downey
MS 58-M217
U.S. DOE/PETC
P.O. Box 10940
Pittsburgh, PA 15236-0940

Mr. James M. Ekmann
Director, Coal Combustion Division
U.S. DOE/PETC
P.O. Box 10940, MS 84-307
Pittsburgh, PA 15241

Dr. David Beecy, Director
Office of Advanced Research
Fossil Energy, FE-72
U.S. DOE/GTN
19901 Germantown Road
Germantown, MD 20585

Mr. Robert Wright
Office of Advanced Research
Fossil Energy, FE-72
U.S. DOE/GTN
19901 Germantown Road
Germantown, MD 20585

Mr. Philip M. Goldberg
Coal Utilization Division
U.S. DOE/PETC, 922-H
P.O. Box 10940
Pittsburgh, PA 15236-0940

Mr. James Hickerson
Coal Utilization Division
U.S. DOE/PETC, 922-H
P.O. Box 10940
Pittsburgh, PA 15236-0940

Dr. Larry Ruth
Coal Utilization Division
U.S. DOE/PETC
P.O. Box 10940
Pittsburgh, PA 15236-0940

Mr. Cliff Smith
Coal Utilization Division
U.S. DOE/PETC, 922-H
P.O. Box 10940
Pittsburgh, PA 15236-0940

Mr. James Jovanovich
PM-01, MS922-206
U.S. DOE/PETC, 922-H
P.O. Box 10940
Pittsburgh, PA 15236-0940

Mr. Laurance L. Oden
Albany Research Facility, Bureau of Mines
U.S. Department of the Interior
Albany, OR 97321

Professor János Beér
Massachusetts Institute of Tech.
Department of Chemical Engineering
66-552
Cambridge, MA 02139

Professor Robert Essenhugh
Mechanical Engineering Department
Ohio State University
206 West 18th Avenue
Columbus, OH 43210

Professor Thomas H. Fletcher
Chemical Engineering Department
Brigham Young University
350 CB
Provo, UT 84602

Professor Robert Hurt
Division of Engineering, Box D
Brown University
Providence, RI 02912

Professor Bryan M. Jenkins
University of California, Davis
Biological and Ag. Eng. Dpt.
Davis, CA 95616-5294

Dr. Michael L. Jones
Energy and Mineral Research Center
University of North Dakota
Box 8213, University Station
Grand Forks, ND 58202
Attn: Dr. Steve Benson

Professor John P. Longwell
Chemical Engineering Department
Massachusetts Institute of Technology
Room 66554
Cambridge, MA 02139

Professor Reginald E. Mitchell
High Temperature Gasdynamics Lab
Stanford University
Mechanical Engineering Department
Palo Alto, CA 94305

Professor Ronald Pugmire
Vice President for Research
University of Utah
210 Park Building
Salt Lake City, UT 84112

Professor Daniel E. Rosner
Director, High Temperature Chem Engr Lab
Yale University
P.O. Box 2159
New Haven, CT 06520-8167

Professor Adel Sarofim
Department of Chemical Engineering
Massachusetts Institute of Technology
66-466
Cambridge, MA 02139

Professor Philip Smith
Department of Chemical Engineering
University of Utah
2250 Merrill Engineering Bldg
Salt Lake City, UT 84112

Professor Terry Wall
Department of Chemical & Materials Engr.
The University of Newcastle
Newcastle, NSW 2308
Australia

Professor Jost Wendt
Department of Chemical Engineering
University of Arizona
Tuscon, AZ 85721

Dr. Seymour B. Alpert
P.O. Box 10412
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94308

Dr. Richard Bain, Manager
Biomass Power Program
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393

Mr. Richard W. Borio
Combustion Engineering Inc.
1000 Prospect Hill Road, P.O. Box 500
Windsor, CT 06095
Attn: Mr. Michael Hargrove

Chester M. Bowling
Manager Tech. Support & Mrktng
ARCO Coal Company
555 Seventeenth St.
Denver, CO 80202

Mr. Richard W. DeSollar
Fuels Coordinator
Central Illinois Public Service Co.
607 East Adams Street
Springfield, IL 62701

Mr. Larry Dora
Engineering Supervisor
Northern Indiana Public Service Co.
P.O. Box M-720
Gary, IN 46401

Dr. Woodrow Fiveland, Supervisor
Heat Transfer & Fluid Mechanics Section
Babcock & Wilcox
1562 Beeson St.
Alliance, OH 44601

Dr. J. Peter Gorog
Research and Development
Pulp, Paper and Packaging
Weyerhaeuser Company
WTC 2H22
Tacoma, WA 98477

Mr. Peter Torslev Jensen
ELSAM
Fuel Department
DK-7000 Fredericia
Denmark

Dr. Flynt Kennedy, Vice President
Research & Development
Consolidation Coal Co.
4000 Brownsville Road
Library, PA 15129
Attn: Dr. Anthony Fonseca

Dr. John Lytle
Mineral Engineering Laboratory
Illinois State Geological Survey
Oak and Gregory Sts.
Champaign, IL 61820

Dr. John S. Maulbetsch
Exploratory Research
EPRI
3412 Hillview Avenue
Palo Alto, CA 94303

Dr. Arun K. Mehta
P.O. Box 10412
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94308

Mr. Thomas R. Miles
Consulting Design Engineer
5475 SW Arrowwood Lane
Portland, OR 97225

Dr. Thomas Milne
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401-3393

Dr. Ralph P. Overend
National Renewable Energy Lab
1617 Cole Boulevard
Golden, CO 80401-3393

Mr. Eric H. Reichl
P.O. Box 472
Princeton, NJ 08542

Dr. Dan Seery
United Technologies Research Center
Combustion Sciences
Silver Lane, MS 30
East Hartford, CT 06108

Mr. Ian W. Smith, Manager
Coal Utilization Program
CSIRO
51 Delhi Road, P.O. Box 136
North Ryde, NSW, 2113
Australia

Professor L. Douglas Smoot
Consulting Design Engineer
5475 SW Arrowwood Lane
Portland, OR 97225

Mr. Jerry Sullivan
Project Director
PSI Energy
1000 East Main Street
Plainfield, IN 46168

Dr. David A. Tillman
Foster Wheeler Environmental Corporation
2525 Natomas Park Drive, Suite 250
Sacramento, CA 95833-2900

Mr. Stanley Vecchi, Director
Energy Systems Lab/Research Dev Div
Babcock & Wilcox
1562 Beeson Street
Alliance, OH 44601
Attn: Mr. John Berthold
Mr. Thomas Morris
Mr. Larry Rodgers
Dr. Hamid Sarv
Mr. James Warchol
Mr. Ralph Bailey
Mr. George Farthing

Mr. Ben Ziesmer
Fuel Coordinator
Northern Indiana Public Services Co.
5265 Hohman Ave.
Hammond, IN 46320

MS0701 R.W. Lynch, 6100

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