TITLE: **ELECTROSTATIC SURFACE STRUCTURES OF COAL
AND MINERAL PARTICLES**

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ABSTRACT

We have developed a video image analyzer for measuring the size and charge of airborne particles. Particles are illuminated by laser light and subjected to a sinusoidal electric field while images of the trajectories of the particles are captured using a video camera and a frame grabber. Analysis of the particle tracks allows the size and charge of the particles to be determined. The instrument can be used to measure size and charge spectra of charged coal and mineral particles in real time. Appendix I shows size and charge distributions of coal and flyash particles measured with the image analyzer.

A second instrument, an Ultraviolet Photoelectron Spectrometer (UPS) for measuring effective work functions of insulator and semiconductor surfaces in air is under development. Work function data for individual macerals and minerals in a coal matrix will be related to triboelectric charging properties. In this instrumental method, originally developed by Kirhata, the surface of a test sample is bombarded by monochromatic ultraviolet light of known wavelength. At atmospheric pressure, the photo-ejected electrons attach to air molecules forming negative ions. The ions are attracted by an applied electric field into a detector where they are accelerated to sufficient energy that they cause momentary dielectric breakdown or discharge in the air inside the detector. The rate at which these discharges occur is

proportional to the rate at which photoelectrons are generated at the sample surface. From a plot of the discharge rate as a function of photon energy the minimum energy needed to remove an electron can be determined. The mechanical components of our instrument have been completed. A number of electronic circuit difficulties remain to be solved. The counting circuits are able to produce a count rate proportional to the ion concentration generated using a corona gun. However, when the high voltage accelerating potential is applied the circuit oscillates preventing proper operation. Our current focus on this instrument is to attain stability of operation.

In this past year we have performed comprehensive analyses on electrostatically beneficiated Pittsburgh No. 8 coal powders as a function of grind size and processing atmosphere. Both feed and processed powders were measured for moisture, ash, total sulfur, and pyritic sulfur content. Total sulfur was determined both gravimetrically and by titration of sulfur oxides from. Only small differences in beneficiation were observed for freshly ground as compared to ground coal exposed to air for 24 hours prior to electrostatic separation. The most finely ground powders exhibited the greatest degree of beneficiation since entrained pyrites are predominantly submicron sized. For example, finely ground 45-75 μm size classified powders yielded an average total sulfur content of 1.5 wt% and 4.1 wt% in the clean and refuse processed fractions, respectively. Only 17% of the total sulfur in the clean coal was pyritic whereas 92% of the total sulfur in the refuse was pyritic, consistent with the mineral specificity of this cleaning method. Larger dimension powders (e.g. $>150\ \mu\text{m}$) did not acquire sufficient charge to give efficient separation. The composition of the refuse varied as a function of size classification of the feed powders, however, there was remarkable uniformity in analytical values determined for the clean coal fraction regardless of the degree of grinding. Consistent ash and sulfur content in the clean coal powders may be ascribed to a predominance of vitrite maceral in the clean fraction since vitrite is the most chemically and physically uniform of microlithotypes. Thus, a practical limit to beneficiation may be defined by the vitrite fraction in the coal.

Studies have also begun concerning the efficacy of grinding and sieving alone to separate pyrite and other minerals from coal without electrostatic beneficiation. Though pyrite has a small size and high density relative to other coal components, preliminary results indicate that pyritic sulfur is not appreciably enhanced in sieved fines. Pyrite dimensions are so small that electrostatic surface charging effects may predominate. Total sulfur content, however, was found to be higher in fines, which may be attributed to the presence of sulfate minerals such as gypsum.

A primary focus of current efforts is preparation of manuscripts for publication in peer reviewed journals. A draft of a manuscript in preparation to be submitted to the journal "Coal Preparation" is included. Another focus is the extension of previous studies concerning Pittsburgh No. 8 coal to Illinois No. 6 coal and other coals. Analyses and processing of Illinois No. 6 powders by Albert Nutsukpul (graduate student UALR Department of Chemistry) show that Pittsburgh No. 8 is cleaned more effectively than is Illinois No. 6 coal. Factors affecting beneficiation under investigation include grind size of feed; moisture, sulfur, pyritic sulfur, and ash content of feed and processed powders; petrographic analyses; use of acetone as conditioning agent, and effects of ambient air oxidation on coal powder. Also, studies are currently underway to further elucidate the nature of carbon losses so as to increase clean coal recovery after processing. Negative charging of macerals leads to carbon losses which is caused either by

Beneficiation of Pittsburgh No. 8 versus Illinois No. 6

Comparative total sulfur analyses of feed and beneficiated Illinois No. 6 and three different feed and beneficiated Pittsburgh No. 8 coal powders by gravimetric determination as barium sulfate are shown in Figure 1. Although Pittsburgh No. 8 feed had less sulfur than Illinois No. 6 feed, it was cleaned to a greater degree and the refuse of both coal types exhibited the same average sulfur content. The ash percentages for the same coals as shown in Figure 2 also indicated better beneficiation of Pittsburgh No. 8 than for Illinois No. 6. The Pittsburgh No. 8 refuse had a higher ash content than that of Illinois No. 6 even though the converse was true for the feed.

Figure 1. Average total sulfur beneficiation of Pittsburgh No. 8 is greater than for Illinois No. 6.

Figure 2. Ash beneficiation of Pittsburgh No. 8 is greater than for Illinois No. 6.

NOTE: The following is a manuscript in preparation to be submitted to the journal “Coal Preparation”.

Composition and Surface Factors Affecting Triboelectric Beneficiation of Coal Powders

ABSTRACT

In one type of electrostatic beneficiation, coal first was pulverized and charged by contact with copper. The coal (maceral) particles and mineral particles adopted positive and negative charge polarities respectively. The particles then were passed through and divided in an electrostatic separator consisting of two conducting electrodes, across which a high voltage was applied. Macerals were attracted towards the negative electrode and minerals towards the positive electrode. The efficiency of separation was dependent upon coal composition, fineness of powder grind, and atmospheric variables. Analyses of total sulfur content, pyritic sulfur content, and ash content of feed and processed coals were used to evaluate beneficiation success. A two stage electrostatic separation could clean Illinois #6 coal with 85 percent energy recovery with 3.5 percent ash forming mineral content. These results were close to the goals set by the Department of Energy on physical cleaning of coal to less than 3 percent ash and more than 80 percent energy recovery.

INTRODUCTION

There is uncertainty in implementing large scale commercial electrostatic beneficiation applied to coal. Charging properties of chemically complex insulating and semiconducting powders such as those of coal exposed to moisture and other atmospheric variables are often unpredictable and adequate cleaning is not consistently achieved. Triboelectric separation of materials is well documented yet the mechanisms operating remain poorly understood. Efforts to understand and improve electrostatic methods are warranted, particularly in light of the drawbacks of cleaning alternatives. For example, post combustion flue gas desulfurization is energy intensive and requires large quantities of limestone, whereas precombustion wet cleaning necessitates drying of the cleaned coal. In contrast to these methods, electrostatic beneficiation is a dry process requiring little or no additives.

Pyrite bearing coals are candidates for electrostatic beneficiation based on the fact that particles of pyrite and other minerals generally adopt a negative charge from triboelectrification and organic macerals a positive charge. Only the pyritic and sulfate mineral sulfur fractions are accessible by the method since organic sulfur is covalently bound with carbon in macerals. The sizes of mineral constituents in coal range from about 1 to 100 μ m, but unfortunately pyrites are on the lower end of this scale necessitating fine grinding for liberation and separation. A ready explanation for maceral particles to charge positively by triboelectrification is found in the large numbers of surface carbon free radicals available to release electrons to form aromatic carbocations. There is evidence that these cationic charges are delocalized over several atoms [Larsen]. Only perhaps one in one hundred thousand of the surface atoms is charged during triboelectrification [Cross] making it difficult to specify the surface chemical species involved in charging. If the coal powder for beneficiation is not fresh, then surface oxidation reduces the tendency of carbon to charge positively. A great variety of oxidized carbon functions may contribute to the altered charge properties. For example, carboxylic acid functions may lose a proton to form a carboxylate ion. The small pK_a values for carboxylic acids and other groups such as alcohols suggest that positive proton

ion transfer is a likely contributor to the negative charging character observed for oxidized coal carbon surfaces.

EXPERIMENTAL METHODS

1. Separator Design and Operation

A drawing of the electrostatic separator design is shown in Figure 1. Powdered coal was supplied to a powder pump through a Fritsch vibratory feeder (Gilson Company, Inc. Model LCA-129). Pressurized nitrogen was used to operate the powder pump which controlled the flow of coal powder at a desired mass flow rate. The coal powder then was charged by a copper static mixer (KoFlo, Inc.) of internal diameter 1.6 cm and length 30 cm. The coal particles impacted on the internal plates of the static mixer as the gas flowed through the mixer changing direction to move around these internal plates. The bipolarly charged powder then entered into an electrostatic separator. The velocity of air in the static mixer was approximately 10 m/s while the air velocity at the entrance of the separator was approximately 0.5 m/s. The separator consisted of two electrically conducting plates 30 cm wide by 90 cm long spaced 25 cm apart at the top and angled such that the spacing between them decreased linearly to 10 cm at the bottom just above the filter. The two electrodes were connected to two HV power supplies (Glassman High Voltage, Inc. Models MJ20P0700-11 and MJ20N0700-11): one was positive from 0 to 20 kV, and the other negative from 0 to -20 keV. In general, a 15keV voltage was applied to the collection plates of the separator during each experiment. The electric field was higher at the bottom of the plates than at the top because of the geometry used in the separator. The V-shaped walls were chosen to reduce air turbulence in the separator. Room air flowed into the separator in a sheath around the static mixer. The room air passed first through a flow straightener consisting of a 2.5 cm layer of open cell foam atop a 10 cm thick plastic honeycomb with cell diameters of 0.65 cm. Inside the separator, the particles that were highly charged were deposited near the top of the plates and the particles that have lower charge or lower electrical mobility deposited nearer the bottom since they required higher field and longer path for separation.

2. Grinding and classification

Pittsburgh No. 8 or Delta Mine 6/7 (Illinois No. 6) coal was finely ground in either ambient air, or alternatively in N₂ atmosphere inside a glove bag using a Micro-Hammer Cutter Mill (Gilson Company, Inc. Model LC-5). Size classified powders were prepared by mechanically vibrating ground coal for a minimum of 20 minutes through a stack of progressively finer copper screen sieves (150, 105, 75, 45 μ m). Typically, only a third of the quantity of sub 45 micron powder went through the bottom sieve in the second 10 minutes as accumulated during the first 10 minutes of sieving. After 20 minutes each fraction was assumed to be largely depleted of sub sized powder.

3. Exposure conditions

Typically coal was ground in ambient air and beneficiated in air immediately following. Alternative processing conditions also were investigated because of the high chemical reactivity of coal powder surfaces. To augment air exposure, freshly ground coal powders were exposed to air in open containers for 24 hours before beneficiation. Alternatively, to minimize the effects of air exposure powders were ground in an N₂ atmosphere in a glove bag and beneficiated in N₂ by fitting the inlet of the electrostatic separator with an N₂ filled glove bag. The effects of three potential conditioning agents: ammonia gas, sulfur dioxide (SO₂), and acetone also were tested using Illinois No. 6 coal powders as follows. For SO₂

exposure Illinois No. 6 coal was finely ground and sieved to –200 mesh powder in a glove bag under nitrogen atmosphere. Half of the coal (about 100 mL in volume) was reserved in a sealed container as a control sample and the other half was placed in a stoppered flask equipped with side arms. The coal then was exposed to SO₂ gas in an argon environment. SO₂ was generated by the reaction of copper powder with concentrated sulfuric acid in a heated flask. Argon was purged over the mixture to carry the gas through a water-ice cooled tube in order to condense any water present and then the cooled gas passed over the coal. The coal was shaken during the entire 15-minutes of exposure. Next, the flask of SO₂ exposed coal was processed through the electrostatic separator in N₂ atmosphere. The other half of the coal sample which had not been exposed to SO₂ was beneficiated similarly as an experimental control. Control samples were also used for the both the acetone and ammonia conditioning agent experiments. To prepare acetone conditioned coal, N₂ gas was bubbled through acetone and the vapors directed over coal powder shaken in a flask for ten minutes. A similar exposure time of anhydrous ammonia vapor from a cylinder was employed for ammonia conditioned coal powder.

4. Coal Analytical Methods

Quantitative determination of: total sulfur content, pyritic sulfur content, ash content, and moisture content of both feed and beneficiated coals were determined according to ASTM methods: D3177-84, D2492-84, D3174-89, and D3173-87 respectively. In general, duplicate analyses were conducted for each sample. Triplicate gravimetric total sulfur analyses were conducted on samples from the acetone, ammonia, and sulfur dioxide conditioning experiments.

Petrographic analysis of powders was used to monitor the behavior of the various coal macerals under the influence of electrostatic beneficiation. Samples of clean and refuse coal powders deposited on the plates of the separator were prepared for petrographic analysis by casting in epoxy resin followed by polishing of the resin surface with a water-alumina slurry. A minimum of 800 particles from each plate were individually identified using an optical microscope and classified by maceral type (i.e. vitrinite, liptinite, or inertinite). If the particle was composed of more than one maceral type, the particle was classified according to the dominant maceral component present in the particle. Particles readily identifiable as minerals or macerals in which entrained minerals could be clearly seen were also classified.

Diffuse reflectance infrared fourier transform (DRIFT) spectroscopy of feed and electrostatically separated coal powders was used to monitor composition differences with respect to organic functional group vibrational frequencies. Samples were prepared as a 2 wt% mixture of coal with finely ground dry KBr. Spectra were obtained on a Nicolet Instrument model Magna-IR 500 Series II spectrometer and DRIFT cell (International Crystal Laboratories). The spectral outputs were adjusted for scattering effects using the Kubelka-Munk algorithm provided with the instrument software.

RESULTS AND DISCUSSION

1. Effects of coal maceral composition on beneficiation

One hurdle to commercialization of coal electrostatic beneficiation is the need to minimize carbon losses to the mineral refuse. These losses could be due to organic particles themselves charging negatively, or more facilely caused by mineral inclusions not liberated from organic particles. The comminution studies of R. Peter King have quantified that many pyrites remain entrained in macerals even when coal is ground to dimensions of a few tens of microns.[King, King, King] The varied distribution and compositions of macerals and minerals within the coal matrix are also factors which influence efficiency of grinding and separation. Petrographic analyses of powders were conducted in order to shed light on the nature of carbon

losses in relation to maceral composition.

The macerals of coal are of three major types: vitrinite, liptinite, and inertinite. Vitrinite, derived primarily from cellulose and lignin has the highest oxygen and also organic sulfur content of macerals.[Davidson] Vitrinite is predominant, comprising 80 to 95 percent of the organic fraction in low rank coals. Liptinite, from fatty acid residues as found in cutine and spores, is rich in aliphatic structures with greater hydrogen and lesser oxygen content than other macerals. Liptinite is chemically similar to amber, known to charge by friction since ancient times. Liptinite exhibits ultraviolet stimulated fluorescence properties in the optical microscope due to the existence of metastable excited electronic states. Carbon rich inertinite, which contains significant amounts of fused aromatic ring carbon structures, most resembles graphite. Inertinite may be presumed to be the best electrical conductor among macerals due to electron delocalized pi bonding. Relevant to coal cleaning, inertinite macerals often contain plant cell remnant cavities which harbor mineral inclusions.

If coal is very finely ground, then a large portion of the coal is reduced to particles consisting largely of individual macerals. Petrographic analyses of processed finely ground –200 mesh (<75µm) Illinois No. 6 coal powders as described in the experimental section are summarized in Table 1. Each value in Table 1 represents the number of particles of each type as a percentage of all particles counted in the clean or refuse samples respectively.

	Vitrinite	Liptinite	Inertinite	Vitrinite w/Mineral	Liptinite w/Mineral	Inertinite w/Mineral	Mineral
Clean Coal	78.0 %	6.3 %	6.8 %	6.4 %	0.7 %	0.6 %	1.1 %
Refuse Coal	66.1 %	10.5 %	9.2 %	5.3 %	1.4 %	0.6 %	6.9 %

Table 1. Petrographic analyses of beneficiated Illinois No. 6 powders

The values of Table 1 illustrate the enrichment of liptinite and inertinite in the refuse and of vitrinite in the clean fraction. There is error of undercounting for maceral particles containing minerals as given in Table 1. This is because pyrites in maceral particles are difficult to observe in the optical microscope since they are exceedingly small and the macerals, particularly inertinite, are opaque. The higher inertinite content in the refuse was independently confirmed by diffuse reflectance infrared fourier transform (DRIFT) spectroscopy. DRIFT spectra of powders from several experiments with both Illinois No. 6 and Pittsburgh No. 8 coals have consistently indicated a greater intensity for the aromatic ring vibration at 1608 cm⁻¹ for refuse relative to clean coal. This intensity increase was attributed to inertinite. Others also have found, by petrography, a higher inertinite content in the negatively charged processed fraction. [Inculet] Mineral inclusions in this maceral type are a likely cause. Similarly, the greater quantity of liptinite in the refuse may be attributed to trapped minerals promoting negative polarity during tribocharging.

The cause of greater inertinite and liptinite content in the refuse also may be discerned considering the distribution of macerals and minerals in the matrix of coal. Commonly, a microscopic layered matrix of homogeneous vitrinite bands alternating with complex layers composed of all maceral types is observed in bulk coal. The complex layers are appropriately named trimacerite. This alternating microstructure is the result of the original plant depositions which evolved to form coal. Whereas bulk plant parts such as leaves and stems were converted to vitrinite during coalification, the surface of the

parts were sullied with fine mineral and organic material from the environment. It is thus the interface of two plant part surfaces which produced the complicated trimacerite. Bacterial action also prevails on plant surfaces yielding increased pyrite in trimacerite in conjunction with inertinite and liptinite. Conversely, vitrinite being relatively free of mineral matter, shows the expected preference to charge positively and is found in greater abundance in the clean coal fraction.

2. Comparative beneficiation of Illinois No. 6 and Pittsburgh No. 8.

As expected, pyrite bearing coals from different mines showed differences in beneficiation. Illinois No. 6 powders did not beneficiate as well as those of Pittsburgh No. 8. The average sulfur content determined for similarly ground feed and processed powders of both types of coal are shown in Figure 1.

Average Total Sulfur Beneficiation of Pittsburgh #8 is Greater than for Illinois #6

Figure 1

Although the Pittsburgh No. 8 feed had less sulfur than that of Illinois No. 6, it was cleaned to a greater degree and the refuse of both coal types exhibited nearly the same sulfur content. The ash percentages for the same coals as shown in Figure 2 also indicated better beneficiation of Pittsburgh No. 8 than for Illinois No. 6. The Pittsburgh No. 8 refuse had a higher ash content than that of Illinois No. 6 even though the converse was true for the feed.

Average Ash Content Beneficiation of Pittsburgh #8 is Greater than for Illinois #6

Figure 2

3. Effects of particle size on beneficiation

Since many pyrites are submicron sized, modest improvements in electrostatic beneficiation may be realized with increasingly fine grinding of feed. Figure 3 below shows comparative values of total sulfur content for size classified 45-75 μm and 75-105 μm feed and beneficiated Pittsburgh No. 8 coal powders.

Pittsburgh #8 Total Sulfur Beneficiation Improves with Fine Grinding

Figure 3

As seen in Figure 3, the refuse from 45-75 μm size classified powder was appreciably enriched in sulfur relative to that of 75-105 μm powder and the clean fraction of the 45-75 μm processed powder had a slightly lower sulfur content. However, it should be noted that the percentage of the total mass of feed coal recovered as clean coal was not improved for the smaller sized powder. The average mass percentages of clean coal recovered from two separate beneficiation experiments conducted for each of the two powders were 63.2% and 63.5% for the 45-75 μm and 75-105 μm powders respectively. Therefore, carbon loss was not ameliorated by the finer grinding and clean coal yield was not significantly improved by fine grinding. However, the smaller dimension powder did yield a cleaner coal.

4. Effects of conditioning agents on beneficiation

Conditioning agents to enhance electrostatic beneficiation would preferably be gaseous so as to provide rapid and uniform treatment of coal powders. Both SO_2 and NH_3 function as chemical reducing agents and each was tested with the expectation of functioning by inhibiting powder surface oxidation during beneficiation. Acetone was chosen for study since others had noted improvements in beneficiation using it as a conditioning agent.[Zhou] The analytical results from the conditioning agent experiments are summarized in Figures 4 and 5.

Figure 4. Results of SO₂ conditioning agent experiments.

Figure 5. Results of acetone and ammonia conditioning agent experiments.

The data in Figure 4 illustrate that SO₂ is not an effective conditioning agent under the experimental conditions used. The percentage sulfur and ash values are better for the control sample than for SO₂ treated coal. However, the ash contents were nearly the same for both the treated and control powders indicating that adsorbed SO₂ does not provide a pronounced detriment to beneficiation of mineral content.

Data in Figure 5 show that ammonia gas was actually detrimental to beneficiation perhaps as a result of increasing the hydrophilic properties of the coal powder. By contrast, beneficiation was slightly enhanced using acetone as conditioning agent.

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APPENDIX I
SIZE AND CHARGE DISTRIBUTIONS MEASURED WITH THE
IMAGE ANALYZER

Fig.1 Cumulative Number Distribution of Pittsburgh No. 8 Coal Particles

Fig. 2 Cumulative Volume Distribution of Pittsburgh No. 8 Coal Particles

Fig. 3. Differential Number Distribution of Pittsburgh No. 8 Coal Particles

Table I. Size and Charge Spectral Analyses of Pittsburgh No. 8 Coal Particles Charged by Copper Static Charger

No.	Dia.(um)	----- Negative -----		----- Positive -----		Total	
		Count	femto-C	Count	femto-C	uC/g	uC/g
3	1.27	9	-0.95	0	0.00	0.00	-70.24
4	1.40	11	-0.93	0	0.00	0.00	-42.43
5	1.54	9	-1.21	2	0.05	9.94	-39.78
6	1.69	16	-2.32	1	0.03	9.64	-38.08
7	1.86	12	-1.76	0	0.00	0.00	-31.23
8	2.04	27	-5.49	1	0.07	11.95	-30.92
9	2.25	17	-3.46	3	0.17	6.64	-19.79
10	2.47	32	-8.32	2	0.15	6.59	-21.67
11	2.72	29	-8.20	5	1.06	14.37	-14.22
12	2.99	35	-11.93	5	0.49	5.04	-14.56
13	3.29	55	-20.63	7	1.55	8.48	-11.77
14	3.62	48	-18.90	5	1.04	5.96	-9.69
15	3.98	61	-26.40	9	1.99	4.77	-7.53
16	4.38	79	-37.62	5	1.40	4.55	-6.99
17	4.82	95	-50.58	12	1.73	1.76	-5.56
18	5.30	77	-52.81	8	1.47	1.68	-5.53
19	5.83	90	-58.16	11	2.59	1.62	-3.79
20	6.41	73	-56.74	16	6.08	1.96	-2.94
21	7.06	98	-73.93	16	6.32	1.53	-2.30
22	7.76	70	-64.02	22	9.53	1.26	-1.73

Table I. Size and Charge Spectral Analyses of Pittsburgh No. 8 Coal Particles Charged by Copper Static Charger (Continued)

		----- Negative -----		----- Positive -----		Total		
No.	Dia.(um)	Count	femto-C	uC/g	Count	femto-C	uC/g	uC/g
23	8.54	63	-57.22	-1.99	23	12.84	1.22	-1.13
24	9.39	74	-68.85	-1.53	23	12.24	0.88	-0.96
25	10.33	78	-84.58	-1.34	25	16.25	0.80	-0.82
26	11.36	67	-78.25	-1.09	40	28.33	0.66	-0.43
27	12.50	85	-90.25	-0.74	26	23.32	0.63	-0.42
28	13.75	59	-87.76	-0.78	45	43.46	0.51	-0.22
29	15.12	67	-109.26	-0.64	32	48.48	0.60	-0.24
30	16.64	53	-79.32	-0.44	38	47.92	0.37	-0.10
31	18.30	46	-88.98	-0.43	28	44.99	0.36	-0.13
32	20.13	59	-177.23	-0.50	28	65.33	0.39	-0.22
33	22.14	36	-133.21	-0.46	26	104.66	0.51	-0.06
34	24.36	31	-109.81	-0.33	33	147.01	0.42	0.05
35	26.79	16	-101.80	-0.45	32	146.81	0.33	0.07
36	29.47	23	-141.33	-0.33	18	85.58	0.25	-0.07
37	32.42	25	-197.68	-0.32	25	218.08	0.35	0.02
38	35.66	20	-229.70	-0.35	15	130.99	0.26	-0.08
39	39.23	9	-179.17	-0.45	5	39.05	0.18	-0.23
40	43.15	10	-183.44	-0.31	8	58.37	0.12	-0.12
41	47.47	8	-127.80	-0.20	8	114.34	0.18	-0.01
42	52.22	4	-77.32	-0.19	3	93.59	0.30	0.02
43	57.44	7	-285.58	-0.29	5	118.17	0.17	-0.10
44	63.18	6	-309.81	-0.28	6	285.98	0.26	-0.01
45	69.50	2	-129.76	-0.26	4	100.93	0.10	-0.02
		Negative		Positive		Neutral		Total
Count		1791		626		66		2483
Mass (nano-gram)		8624.24		7622.72		549.04		16796.01
Charge (femto-C)		-3632.46		2022.43		-1610.04		
Charge/Mass (uC/g)		-0.42		0.27		-0.10		

Max particle charge (neg) = -98.48 femto-C
 Max particle charge (pos) = 95.33 femto-C
 Count Median Diameter = 9.604 micrometers
 Mass Median Diameter = 42.156 micrometers
 Count Weighted Geometric Std. Deviation = 2.227
 Mass Weighted Geometric Std. Deviation = 1.656
 Particle Density = 1.40 g/cm³

Figure 4. Charge Distribution of Pittsburgh No. 8 Coal Particles

Figure 5. 3D Display of Number, Diameter, and Charge of Pittsburgh No. 8 Coal Particles

Fig.6 Cumulative Number Distribution of Illinois No. 6 Coal Particles

Fig. 7 Cumulative Volume Distribution of Illinois No. 6 Coal Particles

Fig. 8. Differential Number Distribution of Illinois No. 6 Coal Particles

Fig. 9. Differential Number Distribution of Illinois No. 6 Coal Particles

Table II. Size and Charge Spectral Analyses of Illinois No. 6 Coal Particles Charged by Copper Static Charger

No.	Dia.(um)	----- Negative -----		----- Positive -----		Total		uC/g
		Count	femto-C	uC/g	Count	femto-C	uC/g	
3	1.27	12	-0.67	-37.17	19	1.33	46.61	14.18
4	1.40	19	-1.28	-33.70	19	1.47	38.92	2.61
5	1.54	17	-1.20	-26.68	12	1.14	35.80	-0.82
6	1.69	21	-2.32	-31.23	17	1.72	28.65	-4.44
7	1.86	34	-3.85	-24.08	23	2.21	20.39	-6.13
8	2.04	51	-7.59	-23.77	32	5.12	25.59	-4.74
9	2.25	33	-5.17	-18.80	35	3.73	12.78	-2.54
10	2.47	41	-6.17	-13.57	37	7.09	17.29	1.07
11	2.72	67	-12.80	-12.95	49	7.73	10.69	-2.96
12	2.99	76	-17.75	-11.89	51	9.36	9.34	-3.36
13	3.29	102	-24.53	-9.20	82	15.56	7.26	-1.87
14	3.62	130	-32.76	-7.24	83	18.75	6.49	-1.89
15	3.98	142	-41.91	-6.37	108	25.12	5.02	-1.45
16	4.38	142	-46.64	-5.33	104	26.07	4.07	-1.36
17	4.82	137	-45.62	-4.06	130	44.37	4.16	-0.06
18	5.30	178	-70.93	-3.65	129	43.83	3.11	-0.81
19	5.83	160	-78.46	-3.37	146	55.47	2.61	-0.52
20	6.41	157	-74.31	-2.45	124	60.00	2.50	-0.26
21	7.06	143	-77.28	-2.10	124	48.00	1.50	-0.43
22	7.76	133	-74.18	-1.63	110	65.37	1.73	-0.11
23	8.54	110	-68.43	-1.36	140	82.14	1.29	0.12
24	9.39	116	-81.88	-1.16	102	75.69	1.22	-0.05
25	10.33	97	-73.91	-0.94	103	77.09	0.93	0.02
26	11.36	110	-123.73	-1.05	120	91.16	0.71	-0.13
27	12.50	106	-79.76	-0.53	116	99.11	0.60	0.06
28	13.75	99	-83.81	-0.44	118	116.26	0.52	0.08
29	15.12	93	-109.94	-0.47	102	102.43	0.40	-0.02
30	16.64	114	-149.97	-0.39	84	105.76	0.37	-0.07
31	18.30	91	-166.47	-0.41	77	150.47	0.43	-0.02
32	20.13	74	-136.70	-0.31	64	140.33	0.37	0.00
33	22.14	75	-236.40	-0.40	64	133.94	0.26	-0.09
34	24.36	47	-147.89	-0.30	56	216.09	0.36	0.06
35	26.79	41	-184.31	-0.32	57	225.03	0.28	0.03
36	29.47	40	-221.72	-0.30	51	312.48	0.33	0.05
37	32.42	25	-266.71	-0.43	37	200.82	0.22	-0.04
38	35.66	26	-261.97	-0.30	21	176.55	0.25	-0.05
39	39.23	12	-130.93	-0.25	19	252.67	0.30	0.09
40	43.15	21	-255.70	-0.21	15	233.47	0.26	-0.01
41	47.47	11	-131.16	-0.15	17	255.59	0.19	0.06
42	52.22	10	-219.74	-0.21	10	248.23	0.24	0.01
43	57.44	8	-275.74	-0.25	11	467.77	0.31	0.07

Table II. Size and Charge Spectral Analyses of Illinois No. 6 Coal Particles Charged by Copper Static Charger (Continued)

----- Negative -----			----- Positive -----		Total			
No.	Dia.(um)	Count	femto-C	uC/g	Count	femto-C	uC/g	uC/g
44	63.18	9	-428.97	-0.26	6	190.65	0.17	-0.09
45	69.50	5	-144.18	-0.12	6	288.36	0.20	0.05

	Negative	Positive	Neutral	Total
Count	3135	2830	246	6211
Mass (nano-gram)	13915.45	14859.77	2497.96	31273.17
Charge (femto-C)	-4605.41	4685.51	80.10	
Charge/Mass (uC/g)	-0.33	0.32	0.00	

Max particle charge (neg) = -160.86 femto-C

Max particle charge (pos) = 115.34 femto-C

Count Median Diameter = 7.693 micrometers

Mass Median Diameter = 41.437 micrometers

Count Weighted Geometric Std. Deviation = 2.202

Mass Weighted Geometric Std. Deviation = 1.700

Particle Density = 1.40 g/cm³

Figure 10. 3D Display of Number, Diameter, and Charge of Pittsburgh No. 8 Coal Particles

Fig. 11. Size Distribution of Flyash Particles Collected from the Positive Plate of the Separator

Fig. 12. Cumulative Number Distribution of Flyash Particles Collected from the Positive Plate of the Separator

Figure 13. Cumulative Volume Distribution of Flyash Particles Collected from the Positive Plate of the Separator

Figure 14. Charge Distribution of Flyash Particles Collected from Positive Plate of Separator

Figure 15. 3D Display of Charge, Diameter, and Number of Flyash Particles Collected from the Positive Electrode of the Separator

Table III. Size and Charge Spectral Analysis of Flyash Particles Collected from the Positive Electrode of the Separator

No.	Dia.(um)	----- Negative -----		----- Positive -----		Total		
		Count	femto-C	uC/g	Count	femto-C	uC/g	uC/g
3	1.27	17	-1.50	-58.80	0	0.00	0.00	-58.80
4	1.40	19	-1.43	-37.77	1	0.02	11.67	-35.30
5	1.54	21	-2.52	-45.15	0	0.00	0.00	-45.15
6	1.69	27	-2.64	-27.64	0	0.00	0.00	-27.64
7	1.86	18	-2.74	-32.39	0	0.00	0.00	-32.39
8	2.04	26	-3.24	-19.92	0	0.00	0.00	-19.92
9	2.25	33	-5.11	-18.61	2	0.14	8.15	-17.08
10	2.47	35	-5.53	-14.26	3	0.42	12.62	-12.13
11	2.72	75	-13.04	-11.79	0	0.00	0.00	-11.79
12	2.99	73	-14.78	-10.31	1	0.03	1.36	-10.15
13	3.29	99	-22.98	-8.88	1	0.11	4.33	-8.75
14	3.62	133	-31.19	-6.74	3	0.45	4.31	-6.50
15	3.98	192	-51.92	-5.84	3	0.38	2.73	-5.71
16	4.38	278	-77.15	-4.50	3	0.34	1.86	-4.43
17	4.82	318	-108.19	-4.15	8	1.35	2.06	-3.99
18	5.30	366	-136.57	-3.42	5	0.96	1.77	-3.35
19	5.83	423	-186.26	-3.03	13	2.59	1.37	-2.90

Table III. Size and Charge Spectral Analysis of Flyash Particles Collected from the Positive Electrode of the Separator (Continued)

No.	Dia.(um)	----- Negative -----		----- Positive -----		Total	
		Count	femto-C	uC/g	Count	femto-C	uC/g
20	6.41	467	-250.98	-2.78	6	0.98	0.85
21	7.06	426	-255.17	-2.33	9	2.23	0.96
22	7.76	364	-225.59	-1.81	8	3.51	1.28
23	8.54	315	-240.87	-1.68	14	4.46	0.70
24	9.39	297	-243.53	-1.35	15	3.55	0.39
25	10.33	257	-252.78	-1.22	20	9.56	0.59
26	11.36	215	-227.81	-0.99	15	5.59	0.35
27	12.50	184	-226.68	-0.86	20	10.49	0.37
28	13.75	160	-191.03	-0.63	23	9.03	0.21
29	15.12	137	-171.40	-0.49	27	16.73	0.24
30	16.64	132	-237.55	-0.53	26	22.72	0.26
31	18.30	121	-207.96	-0.38	22	21.50	0.22
32	20.13	120	-269.77	-0.38	14	13.31	0.16
33	22.14	114	-286.17	-0.32	20	30.01	0.19
34	24.36	80	-224.94	-0.27	17	45.17	0.25
35	26.79	54	-173.59	-0.23	14	25.72	0.13
36	29.47	64	-195.79	-0.16	16	47.97	0.16
37	32.42	43	-171.01	-0.16	9	28.24	0.13
38	35.66	30	-138.58	-0.14	12	60.75	0.15
39	39.23	25	-156.20	-0.14	8	73.50	0.21
40	43.15	21	-116.73	-0.09	9	77.82	0.15
41	47.47	10	-63.90	-0.08	6	53.81	0.11
42	52.22	13	-101.73	-0.07	2	24.42	0.12
43	57.44	4	-39.39	-0.07	0	0.00	0.00
44	63.18	2	-23.83	-0.06	5	184.69	0.20
45	69.50	3	-36.04	-0.05	8	122.55	0.06

	Negative	Positive	Neutral	Total
Count	5811	388	200	6399
Mass (nano-gram)	15812.13	6386.05	1815.82	24014.01
Charge (femto-C)	-5395.82	905.11	-4490.72	
Charge/Mass (uC/g)	-0.34	0.14	-0.20	

Max particle charge (neg) = -36.75 femto-C
 Max particle charge (pos) = 59.58 femto-C
 Count Median Diameter = 7.562 micrometers
 Mass Median Diameter = 35.391 micrometers
 Count Weighted Geometric Std. Deviation = 1.963
 Mass Weighted Geometric Std. Deviation = 1.747
 Particle Density = 1.40 g/cm³

Figure 16. Size Distribution of Flyash Particles Collected from the Negative Plate of the Separator

Figure 17. Cumulative Number Distribution of Flyash Particles Collected form the Negative Plate of the Separator

Figure 18. Charge Distribution of Flyash Particles Collected from Positive Plate of Separator

Figure 19. Cumulative Volume Distribution of Flyash Particles Collected from the Negative Plate of the Separator

Figure 20. 3D Display of Charge, Diameter, and Number of Flyash Particles Collected from the Negative Electrode of the Separator

Table IV. Size and Charge Spectral Analysis of Flyash Particles Collected from the Negative Electrode of the Separator

No.	Dia.(um)	----- Negative -----		----- Positive -----		Total		uC/g
		Count	femto-C	uC/g	Count	femto-C	uC/g	
3	1.27	3	-0.09	-20.86	0	0.00	0.00	-20.86
4	1.40	4	-0.39	-48.50	2	0.22	55.43	-13.86
5	1.54	7	-0.70	-37.88	4	0.20	18.89	-17.24
6	1.69	8	-0.96	-33.90	4	0.19	13.56	-18.08
7	1.86	10	-1.16	-24.77	3	0.35	24.84	-13.32
8	2.04	5	-0.49	-15.74	3	0.39	20.92	-1.99
9	2.25	10	-1.64	-19.65	10	1.03	12.32	-3.67
10	2.47	14	-2.04	-13.11	5	0.65	11.69	-6.59
11	2.72	22	-5.28	-16.26	14	1.62	7.86	-6.88
12	2.99	31	-5.81	-9.55	10	1.68	8.57	-5.13
13	3.29	37	-10.74	-11.10	19	3.36	6.77	-5.04
14	3.62	42	-9.88	-6.76	27	6.34	6.75	-1.48
15	3.98	51	-15.91	-6.74	32	6.80	4.58	-2.37
16	4.38	97	-28.65	-4.79	58	13.72	3.84	-1.56
17	4.82	94	-30.68	-3.98	57	14.77	3.16	-1.28
18	5.30	110	-45.09	-3.75	58	20.38	3.22	-1.35
19	5.83	137	-56.84	-2.85	65	25.83	2.73	-1.06

Table IV. Size and Charge Spectral Analysis of Flyash Particles Collected from the Negative Electrode of the Separator (Continued)

No.	Dia.(um)	----- Negative -----		----- Positive -----		Total		uC/g
		Count	femto-C	uC/g	Count	femto-C	uC/g	
20	6.41	136	-81.43	-3.09	62	24.81	2.07	-1.48
21	7.06	113	-65.17	-2.24	50	24.45	1.90	-0.97
22	7.76	124	-84.70	-1.99	40	29.76	2.17	-0.98
23	8.54	113	-103.68	-2.01	58	35.68	1.35	-0.87
24	9.39	109	-114.79	-1.73	58	40.02	1.14	-0.74
25	10.33	81	-80.60	-1.23	54	41.73	0.96	-0.36
26	11.36	89	-86.34	-0.90	39	29.30	0.70	-0.41
27	12.50	64	-64.60	-0.71	38	23.55	0.43	-0.28
28	13.75	79	-93.97	-0.62	46	36.40	0.42	-0.24
29	15.12	55	-56.00	-0.40	44	43.02	0.39	-0.05
30	16.64	55	-74.78	-0.40	39	50.40	0.38	-0.08
31	18.30	63	-93.98	-0.33	41	50.49	0.27	-0.09
32	20.13	61	-96.17	-0.26	31	49.60	0.27	-0.08
33	22.14	66	-111.25	-0.21	32	57.82	0.23	-0.07
34	24.36	42	-83.25	-0.19	17	27.45	0.15	-0.09
35	26.79	46	-115.73	-0.18	26	57.86	0.16	-0.06
36	29.47	25	-57.05	-0.12	19	42.79	0.12	-0.02
37	32.42	37	-103.55	-0.11	16	54.91	0.14	-0.04
38	35.66	27	-123.39	-0.14	7	13.29	0.06	-0.10
39	39.23	15	-68.91	-0.10	14	128.63	0.21	0.05
40	43.15	15	-111.18	-0.13	3	16.68	0.09	-0.09
41	47.47	14	-73.99	-0.07	10	94.17	0.12	0.01
42	52.22	5	-24.42	-0.05	4	32.55	0.08	0.01
43	57.44	7	-93.55	-0.10	1	4.92	0.04	-0.08
44	63.18	5	-35.75	-0.04	1	5.96	0.03	-0.03
45	69.50	5	-79.30	-0.06	2	72.09	0.15	0.00

	Negative	Positive	Neutral	Total
Count	2133	1123	256	3512
Mass (nano-gram)	11847.99	5572.57	2927.08	20347.64
Charge (femto-C)	-2393.85	1185.88	-1207.96	
Charge/Mass (uC/g)	-0.20	0.21	-0.07	

Max particle charge (neg) = -50.46 femto-C
 Max particle charge (pos) = 64.88 femto-C
 Count Median Diameter = 8.921 micrometers
 Mass Median Diameter = 37.979 micrometers
 Count Weighted Geometric Std. Deviation = 2.068
 Mass Weighted Geometric Std. Deviation = 1.659
 Particle Density = 1.40 g/cm³