SESSION 4B

ASH PROPERTIES AND PARTICULATE COLLECTOR PERFORMANCE

EFFECT OF COAL MINEROLOGY ON THE EFFECTIVENESS OF PARTICULATE CONTROL DEVICES IN COAL-FIRED POWER PLANTS

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ABSTRACT

Operation of particulate control devices in coal-fired power plants depends on, among other factors, the size and composition of flyash aerosol. Current models of ESP performance often assume that the flyash distribution is the same for all coals or for all coals of a similar rank. In this study, three bituminous coals with similar ash content and ash chemistry are characterized with respect to flyash aerosol size distribution. Advanced analytical techniques used to determine the size and composition of the coal minerals show that the coals have different mineral size distributions. A model of mineral transformations during coal combustion shows that the initial coal mineral size is correlated with with the final flyash aerosol size distribution. Laboratory combustion experiments confirm the model predictions of flyash size distribution. The differences in ash particle size distributions will result in differences in ESP performance in spite of a similarity in bulk ash properties such as ASTM ash content and ash fusion temperatures.

INTRODUCTION

Coal properties affect ESP performance in several ways. The sulfur content of the coal determines, in part, the SO_3 content of the gas in the ESP which is important in determining ash resistivity. The ash content of the coal directly determines mass loading of flyash. The chemical composition of the ash affects the flyash resistivity. The flyash size distribution is also a very important input to all models of ESP performance. The size distribution is determined by the coal type, by the coal minerology, and by the type of combustion system.

Coal rank or coal particle size distribution by themselves are not always good predictors of flyash size distribution. The type and size of the *coal minerals* exerts an important influence on the ash particle size after combustion. We have developed models that accurately predict the ash particle size distribution and chemical composition based on analysis of the coal and coal minerology. In this paper, three bituminous coals with similar ash content, sulfur content, and bulk ash compositions are examined. Ash aerosol size distributions generated in the laboratory are compared with those predicted by the model. The effect of the ash particle size distribution on ESP performance is then assessed.

PREDICTION OF ASH PARTICLE SIZE DISTRIBUTION

The first step in the development of an improved methodology for predicting the effect of coal quality on ESP performance is the development of a model to predict ash particle size distribution and chemical composition. This requires an understanding of the fundamental processes contributing to the formation of ash particles during combustion. As discussed in detail previously,[1] several mechanisms may contribute. Mineral coalescence, char fragmentation, and mineral fragmentation (excluded minerals) all affect the size and composition of large fly ash particles. Vaporization and recondensation[2,3] and possibly convective release during devolatilization[4] affect the size and composition of the submicron ash. This paper treats the first phase of model development: prediction of ash particle size distribution for ash particles greater than one micron.

In a detailed study of ash formation pathways, it was established that knowledge of coal *mineralogy* is an essential component. By conducting detailed studies with several coals, it was determined that the processes of mineral coalescence, char fragmentation, and in some cases mineral fragmentation are the dominant fly ash formation pathways for ash particles greater than 1 μm. For many coals, complete mineral coalescence - one ash particle generated per coal particle was suggested by the experimental data. For others, particularly low ash highly swelling bituminous coals, char fragmentation was observed to produce many ash particles per coal particle. In all cases, however, the results were invariant with respect to reactor size. The composition of ash particles observed in one facility were identical to those observed in another. This suggests that coal mineralogy is the most critical factor in determining the chemical composition of individual ash particles for similar combustion conditions. Coal particle sizes, while somewhat important in determining ash particle composition, is the other essential factor in determining ash particle size distributions.

Using these experimental results, an ash formation model based upon coal mineralogy, coal particle size, and combustion conditions was developed. As discussed in detail elsewhere,[5] computer-controlled scanning electron microscopy (CCSEM) data provide much of the necessary input to the model. Coal mineralogy is measured by CCSEM on a sample of pulverized coal. Although a pulverized coal sample is analyzed by CCSEM, measured mineral size distributions are not determined for specific coal particle size ranges. While CCSEM can distinguish between excluded and included minerals, it currently cannot correlate the included minerals with the size of the coal particles containing them. Thus, pulverized coal particles containing representative amounts of mineral matter must be simulated using measured coal particle size distributoin and mineralogy data. In the model, minerals are randomly distributed among the various size classes of coal particles in proportion to their measured frequency of occurrence. This is done using a combination of Poisson statistics for the smallest coal particles and Monte Carlo techniques for the largest

(20 μm and above). At the end of the redistribution step, a reconstituted coal with included and excluded minerals results.

Once the minerals are redistributed amongst the pulverized coal particles, the combustion portion of the model begins. A simplified particle combustion model, which solves the single (porous) particle radiative and convective heat balance equation, is used to predict burnout times and particle temperatures as a function of particle size and coal rank. Depending upon the coal, mineral coalescence may be allowed to proceed fully within each individual coal (char) particle, barring char fragmentation. No kinetic barriers to mineral coalescence within a burning char particle are assumed. Excluded pyrite minerals are treated separately by solving a mass transfer controlled pyrite combustion rate model.[6] In some instances, char fragmentation is allowed to interrupt the coalescence process. Char fragmentation is currently treated empirically in the model, as a limitation on coalescence of the included mineral matter. The values used in this empirical parameter have been defined by comparing predicted values with laboratory scale combustion testing results to obtain a reasonable fit in the number of large ash particles formed. A more detailed treatment, using the volatile matter content and swelling index of a coal to calculate char cenosphere shell thicknesses and subsequent cenosphere fragmentation, is currently being developed.[7] Once combustion is completed in the above fashion, ash particles are classified according to size and chemical composition for comparison with experimental data. The Mineral Transformation Model (MMT) has been used successfully to predict boiler slagging in coal-fired power plants.[8]

Three coals were selected for this study from PSIT's coal database (Table 1). All are bituminous coals that have been burned at an opposed wall-fired boiler. The coals contain from 6 to 9 percent ash by weight and approximately 3 wt% sulfur. The ash fusion temperatures of all the coals are low and nearly identical, indicating that the bulk ash composition of the ash is similar for all coals. Based on the similar coal analyses, similar combustion behavior is expected.

Mineral analyses for these coals were determined by computer-controlled scanning electron microscopy (CCSEM). To make this measurement, an electron beam is rastered (scanned) across a cross-sectioned sample of the pulverized coal. Minerals are distinguished from the carbon matrix by the greater intensity of their backscattered electron images. Sizes are determined by measuring the size of the cross-section and inverting the data using an analytical inversion technique. CCSEM measures 2000 to 3000 mineral particles in each coal sample to obtain statistically significant representations of the mineral size and mineral composition. Mineral types are identified by comparing the chemical composition of each mineral particle with a library of standard mineral types and compositions.

The mineral particle size distributions as determined by CCSEM reveal differences among the coals (Table 2). Coal 1 has the coarsest mineral distribution with only 45% of the minerals less than 10 μm in diameter. Coal 3 has the finest mineral size distribution with 80% of the minerals being smaller than 10 μm. Coal 2 is intermediate. This CCSEM analysis suggests that Coal 1 should produce large ash particles despite having the lowest ash content. Conversely, Coal 3 should produce the finest ash.

Table 1
ASTM Coal Analysis

Coal Properties	Coal 1	Coal 2	Coal 3
Proximate Analysis, wt%			
Moisture	1.54	4.47	7.12
Ash	6.41	8.65	6.90
Fixed Carbon	53.04	51.92	48.35
Volatiles (diff.)	39.04	34.96	37.63
Ultimate Analysis, wt%			
Carbon	78.26	71.06	69.14
Hydrogen	5.14	4.53	4.44
Sulfur	2.89	2.90	3.05
Nitrogen	1.41	1.49	1.38
Oxygen (diff.)	4.35	6.90	7.97
Ash	6.41	8.65	6.90
Moisture	1.54	4.47	7.12
Heating Value, Btu/lb	13,968	12,566	12,334
Ash Fusion, °F Initial	1983	1967	1950
Softening	2113	1998	1975
Hemispherical	2156	2052	2000
Fluid	2394	2388	2343

Total ash samples were collected on filters obtained from PSIT's drop tube furnace when the coals were burned at 1623 K (2462°F) at 3 seconds residence time. Coals 2 and 3 were burned at 1-2% excess oxygen. Coal 1 was burned at 6% excess oxygen in order to produce similar carbon-in-ash levels for all coals. Ash particle size distributions were measured by Malvern analysis.

Figures 1 through 3 compare the measured ash particle size distributions with those predicted by MMT. The model provides a good prediction of the *ash* particle size distribution based on an analysis of the *coal minerals*. Figure 4 compares the predicted ash size distributions for the three coals. As expected from the minerological analysis of the coal, Coal 3 produced the finest ash particle size distribution and Coal 1 produced a coarser ash. Table 3

Table 2
CCSEM Results: Coal Mineral Size Distributions (wt% of ash)

Size (μm)	Coal 1	Coal 2	Coal 3
1 to 2.2	15.7	15.6	24.2
2.2 to 4.6	21.4	22.4	34.3
4.6 to 10	17.0	21.5	19.4
10 to 22	18.5	18.4	13.1
22 to 46	16.3	15.2	7.7
46 to 100	11.0	6.8	1.3

compares the predicted mass median diameter of the three coals which confirms these trends. Based on these results, it is clear that the ash content (i.e., the proximate analysis) is insufficient to predict the ash particle size distribution. The coal mineral size is a key parameter in determining the ash size.

The ash particle size distributions predicted by the model correspond to the flyash size distributions at the end of the combustion process. To estimate the ash loading at the inlet to the particulate control device, an ESP in this case, the following procedure was used. The amount of ash per cubic meter of gas was calculated from the ultimate analysis assuming 17% excess air which was the observed plant stoichiometry. The loss of ash from the furnace exit to the ESP inlet was assumed to be 20% of the mass in each particle size range. That is, the loss of ash due to deposition was assumed to be independent of particle size.

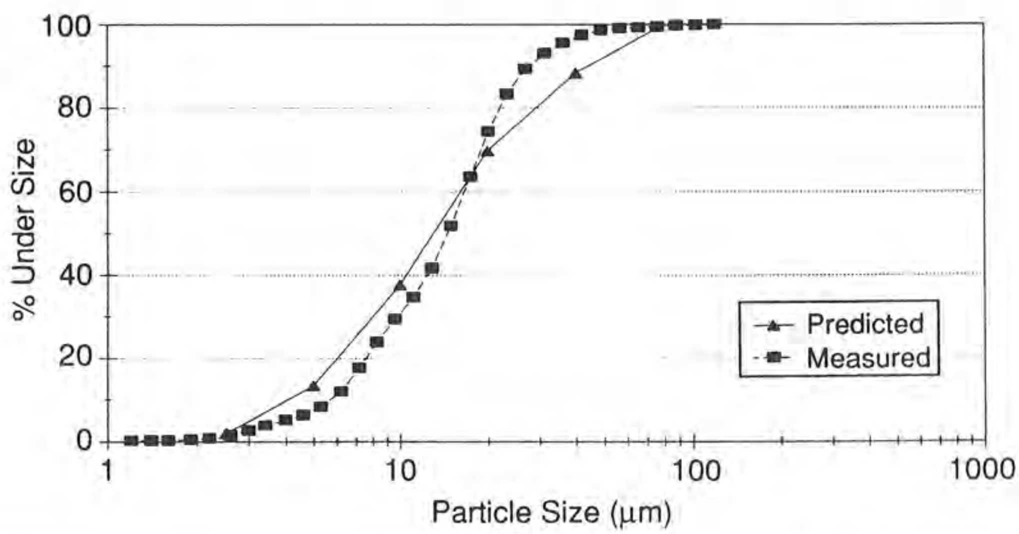

Figure 1. Cumulative Ash Particle Size Distribution for Coal 1

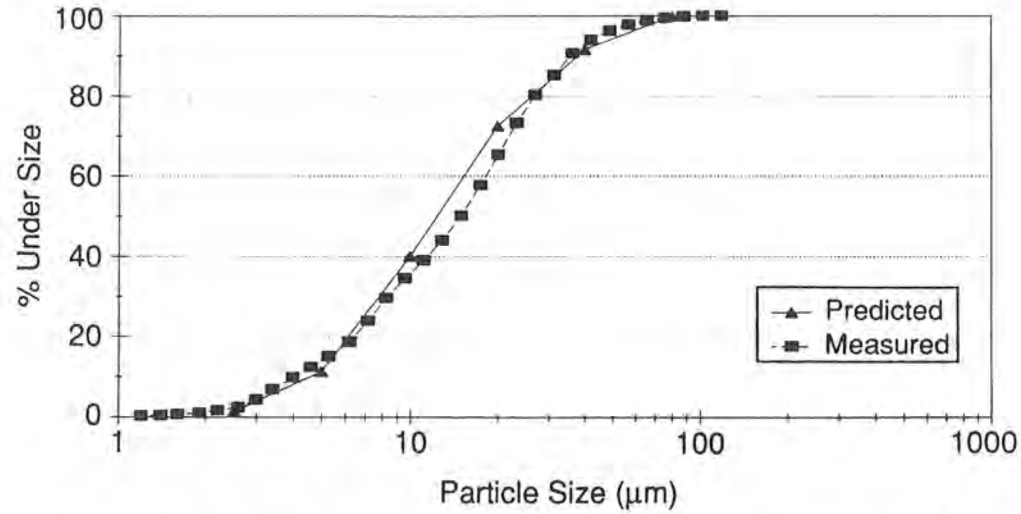

Figure 2. Cumulative Ash Particle Size Distribution for Coal 2

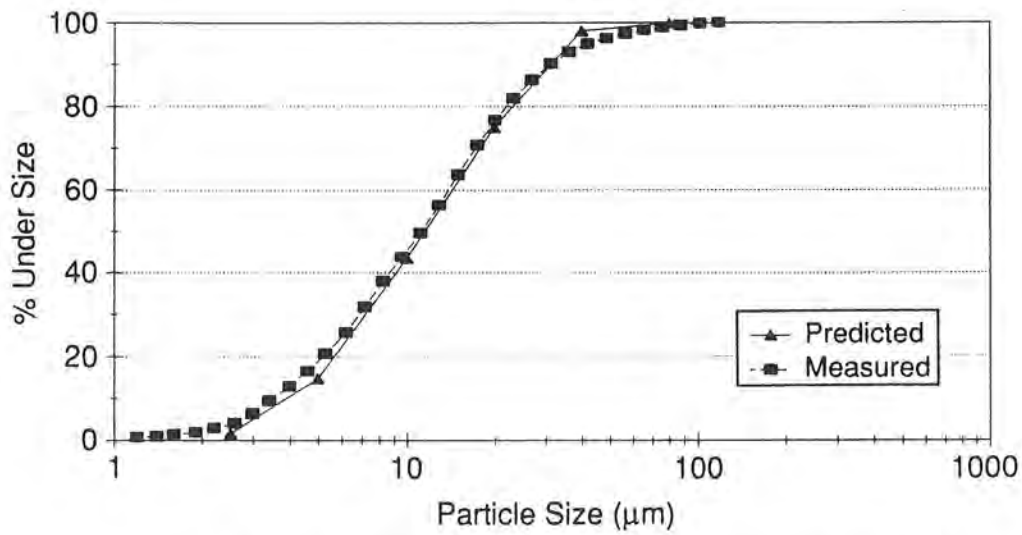

Figure 3. Cumulative Ash Particle Size Distribution for Coal 3

Observations at the ESP inlet revealed that the O_2 level was approximately 7% due to leakage. Thus, the ash loading has been corrected to 7% O_2.

Figure 5 shows the particle loading as a function of particle size at the ESP inlet. Coals 2 and 3 produce more fine ash particles (<5 μm) than Coal 1. Coal 1 produces more ash particles in the large (> 20 μm) which should be relatively easy to remove from the flue gas.

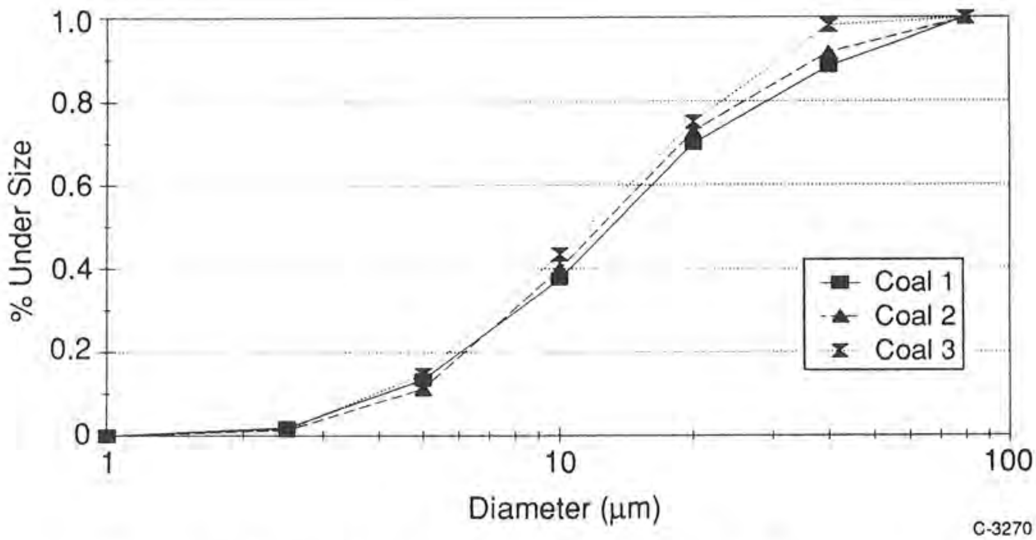

Figure 4. Comparison of Predicted Ash Particle Size Distributions

Table 3.
Predicted Mass Median Diameters

Coal	Diameter [μm]
1	13.0
2	12.1
3	11.5

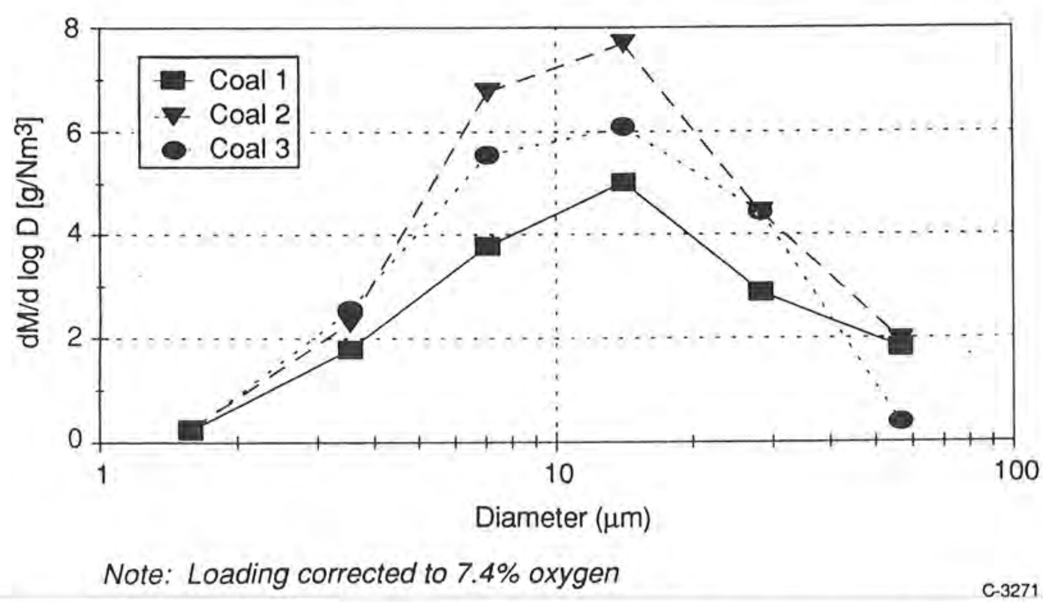

Figure 5. Calculated Ash Loading at ESP Inlet as a Function of Particle Size

EFFECT OF PARTICLE SIZE DISTRIBUTION ON ESP PERFORMANCE

The performance of an electrostatic precipitator is a strong function of the size distribution of the flyash particles. The particle diameter determines the aerodynamic resistance that opposes the electrical forces driving the particle across the streamlines to the collector plate. The mechanism of particle charging is proportional the particle diameter. Particle size can also affect electric fields within the ESP and have both detrimental and beneficial effects. Finally, the opacity at the stack is a strong function of particle size such that for fine particles it is possible to experience opacity problem even when the mass loading is well below emission limits.

As particle-laden gas moves through an electrostatic precipitator, it is charged by ions emanating from the corona electrode, and driven toward the collector plate by the electric field. The velocity of the particle toward the plate is called the drift or migration velocity and results from the electrical and viscous drag forces acting on each particle. It can be calculated using Eq. 1.

$$W_p = (q\ E\ C)/(6\ \pi V r) \tag{1}$$

where Wp is the migration velocity;
- q is the particle charge
- E is the electric field strength
- C is the Cunnings slip correction factor
- V is the gas viscosity
- r is the particle radius

The collection efficiency is directly related to the particle migration velocity. Therefore, any process that affects this velocity will affect the collection efficiency.

In addition to its role in drag resistance on the particles in ESPs, particle diameter also affects the electrical behavior of the ESP. For example the charging of particles is proportional to the square of the particle diameter. The process of particle charging is performed by two physical mechanisms, field charging and diffusion charging.[9-12] Field charging is produced when ions traveling along electric field lines are intercepted by the particles. Field charging is proportional to the electric field strength and is the primary mechanism for charging particles greater than 1 micrometer. Diffusion charging occurs when the thermal energy of the ions causes the ions to diffuse to the surface of a particle. Diffusion charging is a function of the ion density and residence time but not the field strength and is the predominant charging mechanism for particles less that 0.1 micrometers, Particles with a diameter between 0.1 and 1 μm are charged by both mechanisms.

As particles become charged in the ESP they establish a particulate space charge in the interelectrode spaces. This is due to the fact that the particles are much less mobile than the ions. The distribution of the particulate charge results in an electric field distribution which adds to the fields produced by the electrostatic field and the ionic space charge. The magnitude of the space charge effect is proportional to the number of fine particles in the interelectrode spaces. Therefore, the smaller the particle size distribution and the greater the mass loading, the greater the particulate space charge effects will be.

One effect of space charge is to alter the electric field so that the field gradient in the vicinity of the corona glow region is reduced, leading to a decrease in the corona current for a given applied voltage. This effect can be either beneficial or detrimental depending upon the magnitude of the space charge. For lower concentrations of fine particles, the space charge will often result in an increased operating voltage. However, at higher levels, the quenching or reduction of corona current can be severe which reduces the efficiency of the ESP. Corona quenching occurs primarily in the inlet sections of an ESP operating on a flue gas with a high particulate loading or a high concentration of small particles. The particle space charge has a second desirable effect in that it increases the electric field gradient near the collector plate, which produces an increased electrical force for collecting the particles.

ESP MODELS

Because of the importance of particle size in ESP perfomance, the complex Deutschian models such as the EPA/EPRI Model developed by Southern Research Institute (SRI),[13] the EPRI ESPM model developed by Research Triangle Institute,[14] and the DOE ESP model developed by ADA Technologies, Inc.[15] all use particle size as a primary input parameter. The basic approach used in these models is to apply the Deutsch equation to narrow particle size bands in short length increments of the ESP. This accounts for the effect that both particle charge and collection efficiency vary with particle size. To account for the fact that as particles are collected, the electrical conditions change along the length of a precipitator, the model divides the ESP into individual electrical sections which are subsequently subdivided into incremental lengths approximately equal to the wire spacing. Model self-consistency is obtained by explicitly calculating the ion distribution, voltage distribution including particle space charge, particle charges, and current density using an iterative technique until mathematical convergence is achieved for each length increment within the ESP. For each particle size interval, the efficiency calculation is performed subsequently on each incremental length to determine the total collection efficiency.

Although the algorithms used in the ESP models adequately account for the effects of particle size, the limitation on the accuracy of predicting performance is in the precision of the input data. An analysis of the propagation of errors from the input data was performed using a sensitivity analysis of the SRI ESP model.[16] The study concluded the main sources of error among estimated input data for the model are the uncertainties in the inlet particle size distribution.

Ideally, the input data for particle size data should come from measurements made on the particular boiler burning the specific coal of interest. However, the particle size distribution measurements can be expensive and these measurements are not an option and in cases of new installations being built or when selecting coals for future use. For these cases, it is necessary to predict the resulting size distribution of the flyash from the coal characteristics.

The ESP model developed by ADA Technologies, Inc. was used to calculate collection efficiency corresponding to the three calculated ash particle size distributions. There was, however, little difference between the collection efficiency for the three coals. The predicted mass median diameters and standard deviations were similar for all coals. More importantly, the Mineral Matter Transformation model in its current form does not predict the submicron ash particle size distribution. Since submicron particles are more difficult to charge and collect, these fine particles will have a large impact on collection efficiency.

Although PSIT's Mineral Transformation Model in its current form can predict the formation of residual ash (approximately greater than 1 micron), it cannot simulate mineral matter vaporization and submicron ash formation. Mineral matter vaporization and submicron ash formation has been studied extensively by many researchers[2,17,18] using coals and synthetic chars under well-controlled experimental conditions. Addition of submicron ash formation models to PSIT's model is currently in progress.

When the model is extended to include the formation of submicron particles, it will be possible to interface the PSIT model with an ESP model to predict opacity due to scattering and absorption of particles penetrating the ESP. The opacity is a function of particle size, concentration, composition, and width of the stack. For particles greater than 1 μm, the light extinction is determined by the total projected area of the aerosol particles. However, for smaller particles, the composition of the particle plays an important role, and the theory developed by Mie[19] is used to calculate opacity. These relationships, which are described in detail elsewhere,[20] can be used to calculate the extinction coefficient of particles as a function of refractive index and radius of the particle.

CONCLUSIONS

This paper has shown that the particle size distribution of large ash particles (> 1 μm) can be predicted accurately using the Mineral Matter Transformation model coupled with advanced analytical methods applied to coal. However, to accurately predict ESP performance and outlet opacity, it will be necessary to extend this predictive capability to particles smaller than one micron.

Submicron particles are important for several reasons. In an ESP, the finer particles are more difficult to charge and collect. Submicron ash provides a considerable portion of the catalytic surface area for oxidation of SO_2 to SO_3. The high specific surface area of submicron ash also captures toxic metals efficiently.[21] The new Clean Air Act requires decreasing emissions of metals from coal-fired boilers. Finally, the submicron particles are very efficient at scattering visible light and are often the cause of opacity problems.

The capability to predict the ash particle size distributions for both submicron and supermicron particles from coal analysis will reduce one of the main sources of error in making ESP performance predictions. This will allow consideration of the effects of coal quality on ESP operation without expensive field testing. Utilities will then have a more effective tool for use in selecting coals and avoiding opacity problems.

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