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Size Distribution of Fine Particles from Coal Combustion

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Summary. Measurements of the particle size distribution at the outlets of six coal-fired utility boilers showed a peak at a particle diameter near 0.1 micrometer. This submicrometer mode appears to be a general feature of coal combustion that results from a volatilization-condensation process in the boiler. At the boilers tested, the submicrometer mode contained 0.2 to 2.2 percent of the total fly ash mass. The importance of this mode is greater than its small quantity suggests because particles in the submicrometer size range are often much more difficult to collect with conventional particulate control devices than larger particles. Thus, the submicrometer mode may significantly influence the design and selection of future power plant emission controls. The particle mass in the submicrometer mode was correlated with the nitric oxide concentration in the flue gas. This correlation suggests that control of nitric oxide by modification of the combustion conditions may reduce the generation and emission of submicrometer particles.

Coal-fired utility boilers consume more than 500 million tons of coal per year to produce nearly half of the nation's electricity (*1*). By 1995 the utility demand for coal is expected to increase by 900 million tons per year to supply fuel for 337,000 megawatts of new electrical generating capacity (*2*). Since coal typically contains 2 to 30 percent noncombustible mineral material, enormous quantities of by-product fly ash (particulate matter) are produced in power generation. Particulate emission controls are essential to minimize emission of fly ash from coal-fired power plants to the atmosphere. These controls are dictated by federal and local environmental regulations, which limit allowable stack emissions. Since the early 1970's federal regulations increased mass removal requirements from about 90 percent to 99.7 percent. This change represents a reduction in emissions by a factor of 30. Because of the projected growth in coal-based generating capacity, we expect that particulate emission control will continue to be an important environmental consideration.

Present particulate emission standards are based on total mass per unit of coal heat input and do not differentiate with regard to chemical composition or particle size. However, fine particles (less than 10 micrometers in diameter) have been considered potentially hazardous to health because they can penetrate deeply into the lungs (*3, 4*) and may contain a variety of trace metal compounds originally bound in the coal (*5*). Furthermore, fine particles can contribute to deterioration of atmospheric visibility. Accordingly, the U.S. Environmental Protection Agency has announced that it is considering promulgation of a size-dependent inhalable particle standard in the early 1980's (*6*).

In response to increased concern among the electric utilities and the general public, the Electric Power Research Institute (EPRI) initiated a major particulate emission control research program in 1974. One facet of this program was to characterize the emission control performance of state-of-the-art particulate control devices installed at a variety of coal-fired boilers. This article is primarily a review of significant results from this work (*7–12*).

A major emphasis of this program was to determine the removal efficiency as a function of size for particles 0.05 to 20 μm in diameter. This range encompasses nearly all fine particles generated in a coal-fired boiler. Special attention was given to the size range 0.05 to 2 μm. For this task, new particle measurement methods were developed (*13–15*), since accurate measurements for particles smaller than about 0.3 μm were not routinely possible in the field. With the new methods, one feature of the particle size distribution in the flue gas leaving the boiler was clearly observed for apparently the first time (*7, 15*). This feature, a sharp peak in the mass size distribution near a particle diameter of 0.1 μm, was observed at all boilers tested. Earlier investigations at coal-fired utility boilers by Schultz *et al.* (*16*) and Ragaini and Ondov (*17*) suggested a distinct submicrometer mode. McCain *et al.* (*18*) saw a peak in the submicrometer number distribution. The data from Schmidt *et al.* (*19*) gave results similar to those we report here when we considered the particle-size selectivity of their electrical aerosol analyzer. This submicrometer mode in the fly ash size distribution, its chemical composition, and its potential consequences are major subjects of this article.

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Coal-Fired Boilers

The average generating capacity of today's coal-fired utility boilers is 500 MW, although units generating as much as 1200 MW are in operation. These boilers are designed to burn a variety of U.S. coals, ranging from low-rank lignites to high-quality bituminous coals. Coal-fired power plants are often large energy complexes; they may contain several independently operated boilers and can have a total generating capacity of more than 2500 MW.

The primary role of a coal-fired boiler is to extract heat energy from coal to produce steam at a high temperature and pressure. This steam is expanded in a turbine coupled to an electric generator. Figure 1 schematically illustrates the basic features of a modern boiler to show the sequence of events leading to the generation of fly ash. First, the coal is pulverized to a consistency resembling that of talcum powder (typically 70 percent by weight smaller than 75 μm in diameter). The coal particles are then blown into the furnace, where they are mixed with air and burned in suspension, generating peak flame temperatures near 1650°C. During the combustion process, the organic coal constituents burn and the noncombustible mineral matter is released as fly ash particles. These particles mostly remain in suspension as they are carried through the boiler by the gaseous combustion products (flue gas). During the passage through the boiler, heat extraction cools the gases and fly ash, normally to 400°C. On leaving the boiler, the flue gas is further cooled to about 150°C in the air heater, which is the final heat extraction stage.

Before the flue gas reaches the atmosphere, the fly ash must be removed for utilization or disposal. Fly ash removal is usually accomplished with electrostatic precipitators or fabric filter baghouses (*20, 21*). Generally, these particulate control devices are located on the cold side of the air heater (150°C). However, at some plants electrostatic precipitators have been installed on the hot side of the air heater (400°C) to collect high-resistivity fly ash.

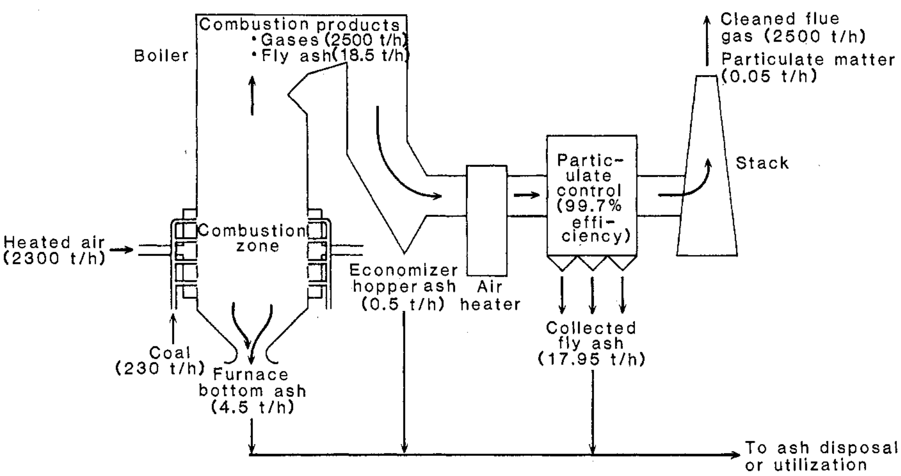
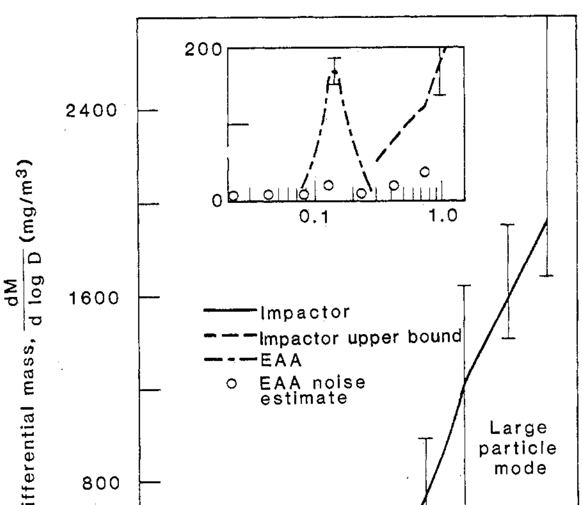


Fig. 1. Schematic of a 500-MW, coal-fired power plant, illustrating the origin and major paths of the fly ash, assuming a typical coal with a 10 percent ash content. Of the 23 tons per hour (*t/h*) of ash introduced into the boiler with the coal, all but 0.2 percent is collected for subsequent disposal or use. Advanced particulate emission control technologies will reduce this emission to less than 0.1 percent.

Fig. 2. Typical bimodal differential size distribution at boiler outlet (electrostatic precipitator inlet). The submicrometer mode contains 1½ percent of the total mass. The large-particle mode reaches a peak and then tails off at particle sizes greater than 10 μm. Electrical aerosol analyzer data are averages of two sampling periods; cascade impactor data are the averages of four runs. The dashed line is the upper bound indicated by cascade impactor data. (Inset) Submicrometer data with the vertical scale expanded by a factor of 5. Error bars on cascade impactor data indicate the standard deviation of individual values. The error bar on the submicrometer peak indicates the variation of peak height.



Measurement Techniques

The distribution of fly ash mass as a function of particle diameter (subsequently referred to as particle size distribution) was measured at the inlet and outlet of particulate emission control devices at six pulverized-coal utility boilers. To document boiler operating conditions, flue gas concentrations of nitric oxide, carbon monoxide, sulfur dioxide, and excess oxygen were continuously monitored and recorded. Samples of coal and fly ash were also collected and analyzed. The test programs at each site typically lasted several weeks and included a number of specific boiler and control device operating conditions.

Cascade impactors from Meteorology Research, Inc. (MRI), were used to measure, in situ, size distributions of particles above about 0.3 μm in diameter (*22*). The size-segregated samples were collected on greased stainless steel foils at all sites except one, where measurements were performed on the hot side of the air heater. In this case, samples were collected on glass fiber filter material clamped onto the steel foils because the grease was unstable at the high flue gas temperatures (*11*). The particles passing the last stage of the cascade impactor were collected on a filter. Impactor data reduction is described by Markowski and Ensor (*23*).

Size distributions of particles from about 0.05 to 1.0 μm in diameter were measured simultaneously at the particulate control device inlet and outlet with factory-calibrated TSI, Inc., model 3030 electrical aerosol analyzers (EAA's) (*24,* 25). Flue gas samples were diluted, typically by a factor of 80, to reduce the aerosol concentration to within EAA limits, and the charge on the particles was neutralized with radioactive sources before introduction to the EAA (*26, 27*). The EAA was the primary instrument used to measure size distributions of particles below 0.5 μm in diameter.

Sample mass flow rates through the EAA were reduced at the test sites at elevations above 600 meters to compensate for reduced atmospheric pressure. The relation between aerodynamic drag, particle diameter, and mean free path does not permit a single change in flow rate to compensate for the effects of reduced analyzer pressure over all particle sizes. The flow was reduced so that the analyzer response to particles 0.15 μm in diameter was unchanged. At three sites, the EAA charger current-to-voltage ratio was adjusted for the change in ion mobility due to atmospheric pressure. These changes are expected tc fairly accurately correct the EAA response for particle sizes of interest here (*28*).

The smaller particle size channels in the EAA tend to be dominated by fluctuations in the total aerosol concentration because the size distribution is measured in cumulative steps (*7, 14, 24*). At most sites, a 3.8-liter bottle was inserted between the diluter outlet and the EAA inlet to reduce the noise from concentration fluctuations. To further reduce noise, the output from several analyzer measurement cycles was averaged before size distributions were computed.

Since there is considerable cross sensitivity between the EAA channels for larger particle sizes, two data inversion techniques were used to calculate size distributions from the averaged EAA output. Twomey's algorithm (*29*) with the EAA cross-sensitivity matrix of Liu *et al.* (*25*) was the primary inversion technique used. This technique does not assume a functional form of the size distribution and adjusts the concentration for each size included in the cross-sensitivity matrix to give a best fit to the measured currents. To check the Twomey results, a commercially available computer routine (*30*) developed at the University of Minnesota was used. This second technique assumes that the measured size distribution is the sum of two lognormal distributions and adjusts its distribution to give a best fit to the EAA output.

Samples of the diluted aerosol being measured with the EAA were collected on Nuclepore filters at two test sites. These filter samples and collection foils and backup filters from selected MRI impactor tests at three sites were examined with a scanning electron microscope (SEM) to independently confirm the EAA and impactor size distribution results.

In addition to the size distribution measurements, size-segregated samples were collected for chemical analysis. The results gave size distributions of individual elements between particle diameters of 0.05 and 20 μm. These samples were collected with a University of Washington low-pressure cascade impactor and MRI cascade impactors. The low-pressure impactor separated the fly ash samples into 27 (somewhat overlapping) size increments. The diameters of particles in the two smallest size ranges (0.09 to 0.23 μm and 0.05 to 0.09 μm) were somewhat uncertain because the jet velocities of the last two stages were close to sonic. However, the EAA and low-pressure impactor data were in good agreement.

The low-pressure impactor samples were collected on greased Kapton disks attached to the collection foils on each impactor stage. The Kapton disks with the particulate sample were peeled off the collection foil and prepared for analysis. The impactor samples were analyzed for 40 major and trace elements by neutron activation analysis, performed under the direction of R. Filby at the Nuclear Radiation Center of Washington State University, Pullman.

Submicrometer Particle Mode in Flue Gas from Coal Combustion

The largest electrostatic precipitator known to be operating on a coal-fired power plant was the first particulate control device to be evaluated (*7*). This precipitator was designed to remove fly ash from a 520-MW boiler at an overall particle removal efficiency of 99.7 percent by mass.

The size distribution of fly ash at the boiler outlet (upstream of the electrostatic precipitator) is shown in Fig. 2 (*7, 15*). These data are, to our knowledge, the first that quantitatively show a well-defined peak in the submicrometer particle size distribution measured in the flue gas from a utility boiler. They show that fly ash generated in the boiler was distributed into at least two distinct modes: (i) a submicrometer mode with particles approximately 0.1 μm in diameter and (ii) a large-particle mode with particle sizes greater than 0.5 μm.

The data in Fig. 2 are presented in differential mass coordinates so that the contribution of particulate mass within a specific size range to the total mass can be easily visualized by comparing the area under the curve in the region of interest to the total area. Clearly, the submicrometer mode represents a very small fraction of the total mass of fly ash leaving the boiler. In this case, the mass of the submicrometer mode is roughly 1½ percent of the total mass, but con-

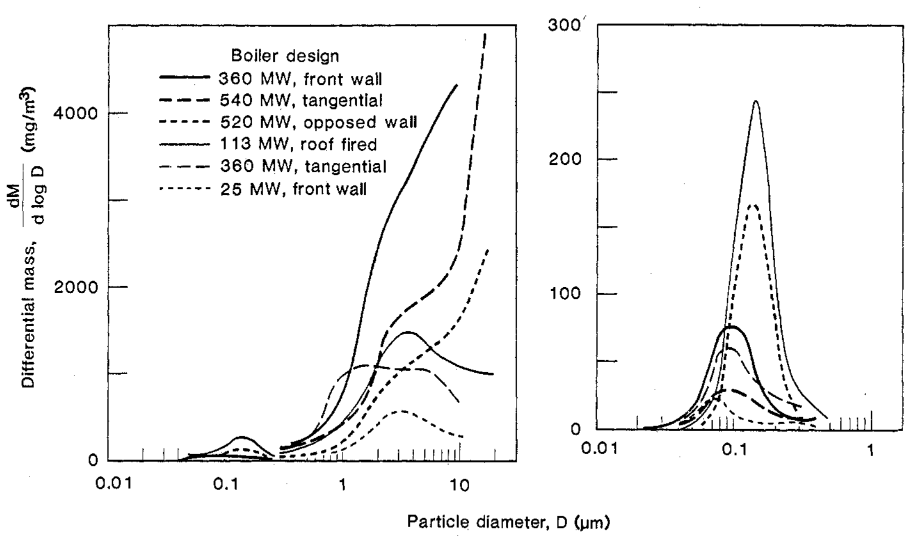


Fig. 3 (left). Summary of differential size distributions at the outlets of six utility boilers. All boilers exhibit a submicrometer mode (Fig. 4) and a large-particle mode. The variability in both modes from boiler to boiler cannot be attributed to differences in coal ash content. The complex structure of the large-particle modes suggests a superposition of more than one discrete particle mode. Submicrometer particle measurements were performed with an electrical aerosol analyzer. Large-particle measurements were made with cascade impactors. Fig. 4 (right). Expanded view of the submicrometer mode region of Fig. 3, showing the variability of the mass. Characteristic features are a distinct, sharp peak and confinement to a limited particle size region centered around 0.1 μm. All data are well above the noise limits of the electrical aerosol analyzer.

tains nearly all of the total number of particles and particle surface area.

Although the contribution of the submicrometer mode to the total fly ash mass is small, its impact on plant stack emissions can be significant. Due to fundamental characteristics of particulate control devices, particles in this size range are generally more difficult to collect than larger particles. Thus the submicrometer mode can contain a disproportionately large fraction of the total outlet mass emissions. The submicrometer mode at this site contained about 20 percent of the particulate mass in the plant stack emissions (*7, 15*).

A general feature of coal combustion. Since the data in Fig. 2 were obtained, particulate measurements at five additional coal-fired boilers have been performed. A submicrometer mode and a bimodal particle size distribution were measured in the flue gas from all the boilers. Figure 3 summarizes particle size distribution data from the six utility boilers. The boilers represent a variety of designs and burn widely different coals. An obvious feature of these data is that both the large-particle mode and the submicrometer mode are highly variable from boiler to boiler. The structure of the large-particle data suggests that the large-particle mode may be a superposition of two or more discrete particle modes. Furthermore, the shape and variability of the large-particle mode are not simply functions of the total coal ash content. However, the large-particle distribution is considered here as a single particle mode.

The mass of fly ash contained in the submicrometer mode is also highly variable. This is more evident in Fig. 4, which is an expanded view of the submicrometer particle region. The significant features of the submicrometer mode are that it is sharp and that it has about the same mean particle diameter in all cases.

Table 1 provides brief descriptions of the boilers tested and a summary of the submicrometer mass data shown in Figs. 2 to 4. Note that the ash content and total mass emissions vary over the tests by nearly an order of magnitude. The percentage of total mass contained in the submicrometer mode is also variable, but no simple correlation between coal ash content and mass in the submicrometer mode is apparent.

Prediction of submicrometer particle mode. Shortly before the data in Fig. 2 were collected, Flagan and Friedlander (*31*) predicted that a submicrometer mode would be a general feature of pulverized coal combustion. This prediction was based on a theoretical model of particle formation involving (i) high-temperature volatilization of ash components during combustion followed by (ii) condensation and coagulation of the volatile material as the combustion products cool and travel toward the boiler exit.

Figure 5 compares the model predictions to the field measurements shown in Fig. 2; for this comparison the results are presented as particle number distributions. Although the model indicates an order of magnitude higher number concentration of submicrometer particles and a shift to smaller particle sizes, the qualitative agreement is good. Part of the difference is due to coagulation of particles in our sampling system, an effect that was not included in the model calculations (*23*). In recent investigations the submicrometer aerosol mode has been measured in small laboratory coal combustors by Taylor and Flagan (*32*) and by Sarofim *et al.* (*33*). Taylor and Flagan reported close agreement between the

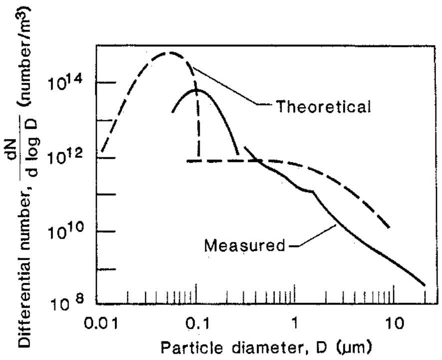


Fig. 5. Comparison of theoretical particle number distribution and distribution based on field measurements. The theoretical prediction (*31*) is based on input parameters from the boiler. Qualitative agreement in the region of the submicrometer mode is considered good. The theory is based on a model of particle formation involving volatilization and condensation of fly ash during coal combustion.

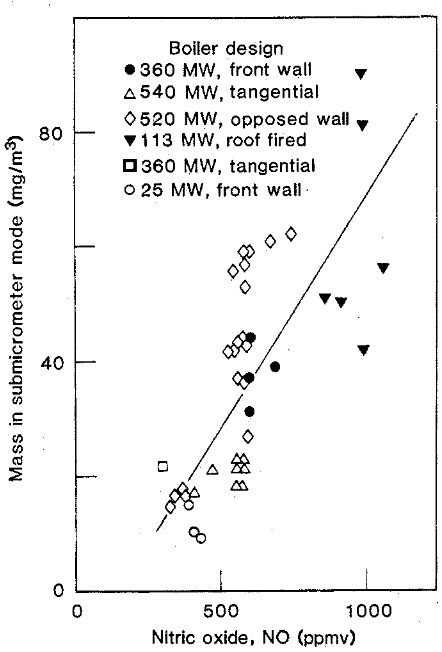


Fig. 6. Relation between NO and mass in the submicrometer mode from measurements at the outlets of six utility boilers. The trend indicates increases in submicrometer aerosol mass at higher NO levels. These results suggest that coal combustion conditions in the boiler play a significant role in the formation of submicrometer particles. The least-squares regression line and standard errors are given by mass = (0.080 ± 0.010) NO − (11.3 ± 6.4). Particle density is assumed to be 2.4 g/cm³, which is the approximate average density measured for the large-particle mode. All concentrations are based on dry weight and have been corrected to 21°C, 1 atmosphere, and 3 percent flue gas oxygen content; ppmv, parts per million by volume.

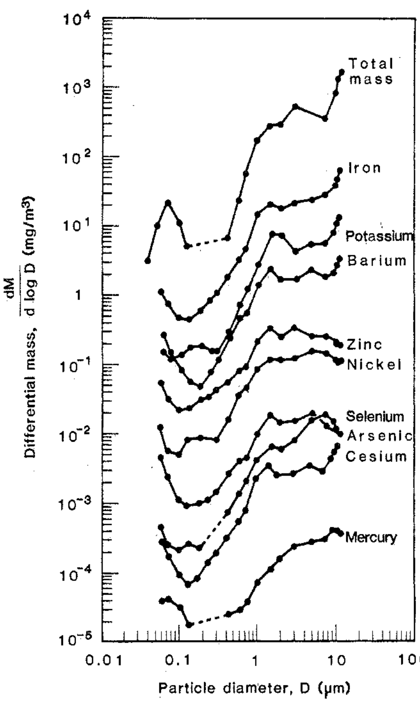


Fig. 7. Size distribution of selected trace elements and total mass at the outlet of the 25-MW boiler. Results are based on low-pressure cascade impactor measurements and neutron activation analysis of individual impactor stages plus backup filter. For clarity, only nine of the 30 elements analyzed are shown. Virtually all elements exhibit bimodal size distribution profiles qualitatively resembling the distribution for total mass. The submicrometer mode evident in the total mass distribution is measured with the electric aerosol analyzer. Insufficient quantities of sample were collected in this size range with the impactor to permit accurate gravimetric analysis. This limitation does not influence the neutron activation analysis results. A distinct concentration of trace elements is apparent in the region of the submicrometer mode. This mode is not completely defined for the trace elements due to inability to segregate by size the material collected on the impactor backup filter. Dashed lines indicate regions of low-confidence data.

measured size distribution and the model prediction.

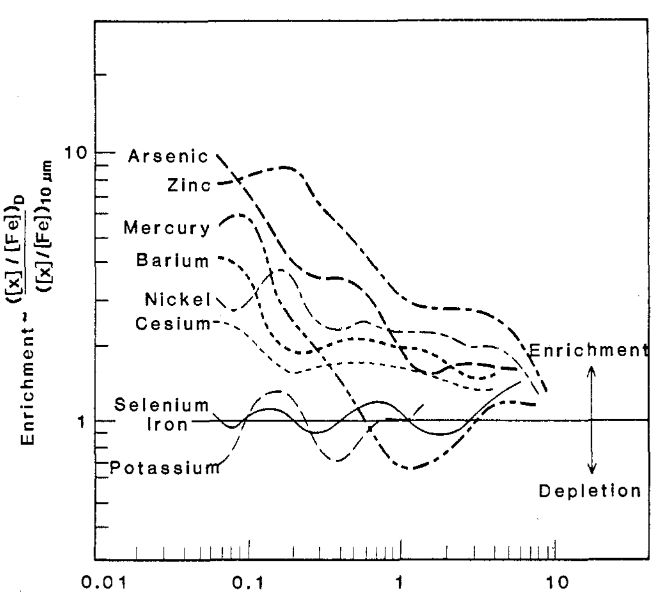
Influence of combustion conditions. Flue gas concentrations of nitric oxide were measured at each boiler during the submicrometer particle measurements. Although the NO measurements were primarily intended to monitor the boiler combustion processes and confirm steady test conditions, we found a significant correlation (least-squares linear regression fit correlation coefficient, $r^2 = .61$; Student's t distribution probability, $P < .001$) between NO and the mass of submicrometer particles (*7, 34*). The mass of submicrometer particles increases as NO increases, as shown in Fig. 6. While several complex NO formation mechanisms have been identified, it is widely accepted that combustion temperature plays an important role (*35*). In fact, reduction of peak furnace combustion temperatures is a major element in NO emission control in coal-fired power plants. We speculate that the boilers with high NO emissions operate at higher flame temperatures and volatilize a larger coal ash fraction, which in turn condenses to form a larger submicrometer mode.

Considering the complexities of NO and submicrometer particle formation in the boiler combustion environment, we do not expect an exact correlation between NO and the mass in the submicrometer mode. The scatter in Fig. 6 illustrates the uncertainty in the simple correlation above. Nevertheless, on the basis of the data in Fig. 6 and data reported in (*34*), it appears that reduction of NO through combustion control will have the beneficial side effect of reducing fine particle generation and emissions. The possibility of a reduction in submicrometer particle production at NO levels below the range of data presented here remains to be investigated.

Chemical characterization. Concerns about health and environmental effects in recent years have prompted numerous studies to establish the size-dependent chemical composition of particulate emissions from a variety of sources, including coal-fired power plants (*8, 17, 36*). Since submicrometer particles are potentially more hazardous than larger particles, our work on trace elements has been focused on chemical characterization of particles in the smaller size range. To our knowledge, little information on this particle size region for coal-fired power plants has been reported, probably because a relatively short time has elapsed since the recognition of the submicrometer mode and because it is difficult and expensive to collect sufficient

Table 1. Summary of test boilers, coal ash content, and outlet particulate matter emissions.

Boiler description	Coal ash content (%, dry weight)	Total particulate mass concentration (g/m^3)	Particles of diameter <2 μm (% of total mass)	Particles in submicrometer mode (% of total mass)
360 MW, front wall fired, western, low sulfur, subbituminous	22	10.5	7	0.3
540 MW, tangential fired, eastern, high sulfur, bituminous	20	9.5	4	0.2
520 MW, opposed wall fired, western, low sulfur, subbituminous	12	6.4	4	1.3
113 MW, roof fired, western, low sulfur, subbituminous	9	3.4	8	2.2
360 MW, tangential fired, western, low sulfur, subbituminous	10	2.3	20	0.9
25 MW, front wall fired, western, low sulfur, subbituminous	4	1.7	8	0.5



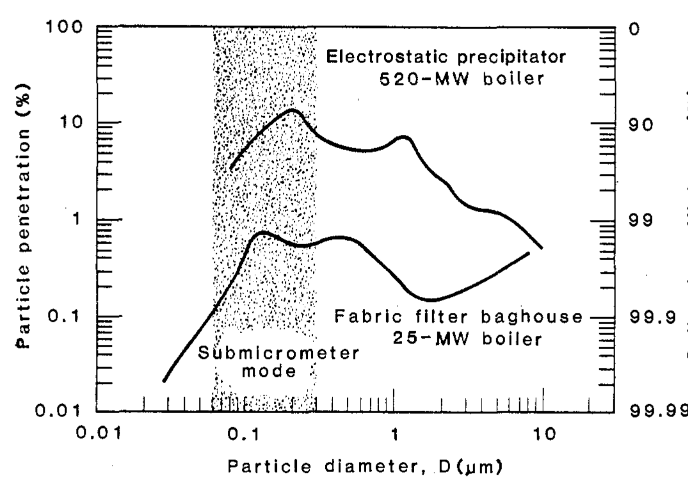


Fig. 8 (left). Relative enrichment of selected trace elements as a function of particle diameter. Enrichment is defined as the concentration ratio of the element to iron at a specific particle diameter divided by the concentration ratio at a particle diameter of 10 μm; that is, enrichment = $([x]/[Fe])_D/([x]/[Fe])_{10\ \mu m}$, where x and D represent the element and diameter of interest, respectively. The advantage of this format is that the enrichment of all elements can be readily compared. Values greater than 1.0 indicate enrichment relative to iron; values less than 1.0 indicate depletion relative to iron. Iron was selected as the reference element because of the similarity of its size distribution to that of the total mass. Generally, elements with the highest enrichments are those considered to be more volatile during the combustion process. A notable exception is selenium, which was not enriched at the boiler outlet; however, significant enrichment of selenium was measured downstream of the particulate control device (*9*). Fig. 9 (right). Particle size–dependent collection efficiency comparison between a fabric filter baghouse and an electrostatic precipitator. Data are considered reasonably representative for the two control technologies. Both control devices have a minimum in collection efficiency in the particle size region of the submicrometer mode. The contribution of particles in this mode to control device outlet mass emissions was 20 percent for the electrostatic precipitator and 2 percent for the baghouse.

quantities of the material and perform the chemical analyses.

Figure 7 shows the results of chemical analyses of particulates from the 25-MW boiler referred to in Table 1. These results are for the low-pressure cascade impactor samples obtained at the boiler outlet. Although more than 30 major and trace elements were detected, the presentation here is limited to nine elements to more clearly illustrate the overall trends.

In general, all the elements are continuously distributed over the entire particle size range and have concentration profiles qualitatively similar to the total mass profile. Furthermore, virtually all the elements are characterized by a bimodal distribution with a peak in the region of the submicrometer mode. These results suggest that volatilization of nearly all the elements occurs to some degree during combustion, since they appear in the submicrometer mode. This is true for the elements generally considered to be volatile (Hg, Se, As, Ni, Zn) as well as the refractory elements (Fe, Al, Mg).

Previous studies have shown preferential concentration or enrichment of certain trace elements in the smaller particle sizes (*7, 36*). The enrichments that we calculated are shown in Fig. 8. Our results are consistent with those from previous studies and indicate that enrichment continues into the region of the submicrometer mode. Further, the enrichment varies up to an order of magnitude for the elements in Fig. 8. Although our data are not complete for all elements, enrichment appears to be greater for the more volatile ones. The dissimilarity of size distributions and enrichments for different elements suggests that each element may follow a unique transformation path from the original coal matrix to the final fly ash particle size distribution.

Implications for Particulate Emission Control

From a practical standpoint, the primary significance of the submicrometer mode is that the particles in it may not be collected as efficiently as larger particles by particulate emission control devices. To illustrate this, the size-dependent collection efficiencies of a fabric filter baghouse and an electrostatic precipitator are shown in Fig. 9. We believe that these efficiencies are reasonably representative of the two control technologies, based on performance data from a number of studies (*7–9, 37*). In the particle size region of the submicrometer mode there is a minimum in collection efficiency for both control devices. Although the outlet mass emissions for both collectors are quite low, the submicrometer mode contribution can be significant (*15*). Figure 9 also shows that submicrometer particle control can be dependent on the type of particulate control device used. Economic, operational, maintenance, and reliability factors are also important considerations in control device selection.

Conclusion

Measurements of the particle size distribution at the outlets of six coal-fired utility boilers showed a distinct submicrometer mode at a diameter of about 0.1 μm. The submicrometer mode is characterized by a sharp distribution and contained up to 2 percent of the total fly ash mass generated in the boilers. We conclude that this mode is probably a general feature of coal combustion in utility boilers, a conclusion supported by laboratory studies in which a submicrometer mode was measured in the exhaust gases from small coal combustors (*32, 33*). In addition, particle size measurements at oil-fired utility boilers recently showed a submicrometer mode at similar particle diameters (*38*), which suggests that the phenomenon may not be limited to coal combustion.

Our data agree qualitatively with predictions of particle size based on a volatilization-condensation model of fine particle formation in coal combustion. Analysis of trace element enrichment in the submicrometer mode indicated a preferential concentration of the more volatile elements, including Hg, As, Zn, and Sb. This observation appears to be consistent with the vaporization-condensation model of formation. The observed relation between NO emissions and particle mass in the submicrometer mode gives additional support to the model.

The correlation between NO and the submicrometer mode can be explained simplistically by considering NO as an indicator of combustion temperature, which in turn strongly influences ash volatilization. Scatter in the data suggests that the mechanisms which may relate NO emission and the mass of submicrometer aerosol are poorly understood. Accordingly, the use of NO as a sole indicator without further verification is not warranted.

The primary environmental significance of the submicrometer mode is its possible adverse effect on particulate emission control. Specifically, the mode is in a particle size region where collection efficiency is generally reduced relative to that for larger and smaller particles. This has encouraged the development of particulate control devices that can efficiently collect these small particles (*20, 39–41*). The data suggest that control of NO emissions through combustion process modifications may also suppress the generation and emission of submicrometer particles.

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comparing results obtained simultaneously in the field with a sampling system having a 2-second residence time. The correction factors are in reasonable agreement with coagulation calculated theoretically for particles in Brownian motion.
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Neotropical Anachronisms: The Fruits the Gomphotheres Ate

Daniel H. Janzen and Paul S. Martin

Summary. Frugivory by extinct horses, gomphotheres, ground sloths, and other Pleistocene megafauna offers a key to understanding certain plant reproductive traits in Central American lowland forests. When over 15 genera of Central American large herbivores became extinct roughly 10,000 years ago, seed dispersal and subsequent distributions of many plant species were altered. Introduction of horses and cattle may have in part restored the local ranges of such trees as jicaro (*Crescentia alata*) and guanacaste (*Enterolobium cyclocarpum*) that had large mammals as dispersal agents. Plant distributions in neotropical forest and grassland mixes that are moderately and patchily browsed by free-ranging livestock may be more like those before megafaunal extinction than were those present at the time of Spanish conquest.

New World terrestrial biotas have long contained a rich fauna of large herbivores. During the Pleistocene, until around 10,000 years ago, the North American mammalian megafauna was comparable in its number of genera of large mammals (those exceeding 40 kilograms in adult body weight) to that of Africa in historical time (*1*). Although quantitative estimates of prehistoric biomass cannot be obtained directly from the fossil record, the high carrying capacity for domestic mammals of New World ranges—a capacity similar to that of African game parks—indicates that the Pleistocene biomass of native New World large herbivores was high. Martin (*2*) estimated an average preextinction biomass for unglaciated North America north of Mexico at 21 animal units per square kilometer or 28.2×10^6 metric tons on 7.8×10^6 square kilometers (1 unit = 1 cow plus a calf or 1 horse = 449 kilograms). While patchily distributed, the megafaunal biomass of lowland Central America must have been comparable, exceeding 50 animal units per square kilometer on favorable sites.

The number of species of large Central American Pleistocene herbivores in Neogene deposits of the last 10 million years greatly exceeds the number present in the past 10,000 years. Tapir, deer, peccaries, monkeys, and capybara occur as Pleistocene fossils, but the remains of gomphotheres (mastodon-like proboscidians), ground sloths, glyptodonts, extinct equids, *Mixotoxodon*, *Toxodon*, and other extinct large herbivorous animals (Table 1) are more common. If Neotropical ecologists and evolutionary biologists wish to determine who eats fruit, who carries sticky seeds, and who browses, grazes, tramples, and voids that segment of the habitat that would have been within reach of a variety of megafaunal trunks, tusks, snouts, tongues, and teeth, the missing megafauna must be considered.

There are prominent members of the lowland forest flora of Costa Rica whose fruit and seed traits can best be explained by viewing them as anachronisms. These traits were molded through evolutionary interactions with the Pleistocene megafauna (and earlier animals) but have not yet extensively responded to its absence. We first examine this evolutionary and ecological hypothesis by reconstructing the interaction between an extant palm and its Pleistocene megafauna. Without concerning ourselves with what caused the Pleistocene megafaunal extinctions (*3*), we are considering a portion of what happened when roughly three-quarters of all the species and individuals of large mammals were suddenly removed from a dry tropical region and its adjacent rain forests. The present-day analogy is a tropical, forested African habitat stripped of its elephants, rhinoceroses, zebras, elands, bush pigs, and other large herbivores and left alone for 10,000 years.

We focus on the trees that did not go extinct when their dispersal agents were removed. We do this because (i) tree-disperser interactions are not so tightly coevolved that a reasonable natural history consequence is extinction of one immediately following extinction of the other; (ii) if there is a large extinct Pleistocene megaflora in tropical America, it has so far escaped detection by paleobotanists; (iii) the plants that did go extinct cannot be directly studied; and (iv) we are confronted with a number of puzzling fruit and seed traits whose mystery disappears when interpreted in the light of the extinct Pleistocene megafauna. Although megafaunal extinction resulted in

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