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and Space Administration

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SUMMARY

As part of a continuing investigation of high-temperature-combustion aerosols, a study of the elemental composition of size-differentiated aerosols emitted from a local municipal incinerator has been completed. Aerosols were aerodynamically separated into eight diameter groups ranging from 0.43 μm to 20 μm and analyzed by charged-particle-induced X-ray emission technique. On-line data collection and reduction codes generated aerial densities for elements from Na to U with sensitivities in the ng/m^3 range for most elements. From the total weights of aerosols collected per stage, their size distribution was determined to be bimodal, with one group centered at a diameter of 0.54 μm and the other at a diameter of 5.6 μm. Measured elemental concentrations in various size ranges also indicate similar bimodal component distributions, though the relative intensities of the two components are not always the same as for the total mass distribution. For K, S, Ni, and Mn, the ratios of the intensity of the 5.6-μm component to that of the 0.54-μm component are 4/12, 4/13, 8/11, and 12/18, respectively, as opposed to 5/3 for the total mass distribution. The relative intensities of the two components for the other elements are approximately the same as those for the total mass distribution. The higher intensity of the smaller size component for these four elements has been interpreted to imply a preference for surface residence. This interpretation has been confirmed by the following additional observations: (1) The observed elemental mass distributions for K and S (and to a lesser extent for Ni and Mn) lie between the calculated surface mass distribution and the experimental bulk mass distribution, and (2) the ratio of elemental mass to total mass for K and S (and to a lesser extent for Ni and Mn) increases as the smaller sizes are approached, in a manner similar to that expected for elements concentrated in thin layers on aerosol surfaces.

INTRODUCTION

Previous experimental studies of the elemental characteristics of the aerosols emitted from high-temperature combustion sources, such as aircraft engines (ref. 1) and oil-fired heating plants (ref. 2), have indicated that certain heavy elements have a strong tendency to concentrate on the surfaces of the aerosols - presumably as a result of condensation of volatile substance vapors on the available surfaces. Because of the anticipated[1] future increase in the

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[1] A recent projection (ref. 3) of per capita refuse generation in the United States suggested that the amount of waste production will rise to 3.64 kilograms per capita per day by the year 1980, based on a 1968 per capita production of 2.42 kg. Thus a city with a population of 100 000 will be generating approximately 364 000 kg/day of waste in 1980 - a horrendous amount to be disposed of. One of the increasingly accepted methods of disposing of these large quantities of solid wastes is by incineration. The advantages of incineration are twofold: (1) It saves high land costs needed for sanitary landfills and (2) it provides access to potentially recyclable metals and the thermal content of the waste materials.

number of municipal incinerators for combustible solid wastes, it was believed that similar measurements on incinerator aerosols would be useful. The problem is anticipated to be all the more severe because of the diverse nature of the household and industrial wastes that are incinerated. It is possible that some of the trace elements contained in waste products such as photographic paper, plastics, paints, textiles, and minerals will vaporize and then condense on smaller combustion aerosols or the air-entrained submicron particles. Such submicron aerosols will present a possible health hazard, because it is difficult to eliminate them from the stack gases. In view of these arguments, it was decided to collect size-differentiated aerosols from an incinerator, analyze their elemental composition, study the behavior of the elemental mass distribution as a function of the aerosol sizes, and determine which elements - if any - exhibit a surface preference.

Such measurements have been completed on aerosols emitted from a local municipal incinerator. The incinerator is of a continuous-feed type and accepts domestic solid wastes as well as combustible industrial wastes totaling about 370 000 kg/day. An outline of the experimental procedure used in the collection of aerosols and their elemental analysis as well as a discussion of the results are given herein.

Trade names are used in this report to adequately describe the instruments used. Mention of these trade names does not constitute official endorsement, expressed or implied, of such instruments or their manufacturers by the National Aeronautics and Space Administration.

SYMBOLS

A	amplitude of first term in lognormal distribution function defined by equation (2)
B	amplitude of second term in lognormal distribution function defined by equation (2)
D_ℓ	lower 50-percent cutoff aerodynamic aerosol diameter
D_m	log mean aerodynamic aerosol diameter
d_m	actual aerosol diameter
D_{M1}	mean diameter for mode 1 particles
D_{M2}	mean diameter for mode 2 particles
D_p	aerodynamic aerosol diameter
D_u	upper 50-percent cutoff aerodynamic aerosol diameter
R_{exp}	ratio of experimentally measured elemental mass to total aerosol mass on a stage

R_s	ratio of elemental mass expected for exclusive surface residence to total aerosol mass on a stage
t	surface layer thickness
ΔM	total aerosol mass on a sampler stage
$\Delta M_{el,i,s}$	elemental mass on ith stage for exclusive surface residence
ρ	bulk aerosol density
ρ_{el}	elemental density in surface layer
σ_1,σ_2	standard deviation of lognormal distribution for modes 1 and 2, respectively

Subscripts:

i	impactor stage
j	order of polynomial function

EXPERIMENTAL PROCEDURE

Aerosol Collection

Two factory-calibrated eight-stage Andersen cascade impactors loaded with preweighed Nuclepore filters were located about 90 m downstream from the incinerator. The ambient air was drawn through the impactors at 0.00047 m^3/s and deposited its aerosol burden on eight stages, whose aerodynamic size limits range from 0.43 μm to 20 μm, as summarized in table I. The secluded location of the incinerator ensured that most of the aerosols collected would be coming from the incinerator. The total aerosol collection time was $21\frac{1}{4}$ hours spread over a 2-week period, with active collection confined to those intervals in which the wind direction was from the incinerator toward the collection site. At the end of the aerosol collection operation, the impactors were transferred to a clean, controlled-environment room, where they were stored overnight. The Nuclepore filters were then removed from the impactors, reweighed, and mounted on specially prepared trays for in situ bombardment with 18-MeV alpha particle beams for aerosol elemental analysis. A blank Nuclepore filter was also mounted to allow for loading and matrix corrections. Table II summarizes the masses of the filters before and after the aerosol deposition as well as the total masses of the aerosols deposited on the various stages. Table III summarizes average particulate mass loading per cubic meter of air as a function of the aerosol sizes.

Elemental Analysis of Aerosols

The 1.9-m isochronous cyclotron at the University of California, Davis, California (ref. 4), was used to study the aerosol filters by the particle-induced X-ray emission (PIXE) technique. This work was performed under contract to NASA Langley Research Center. PIXE was preferred over commonly used X-ray fluorescence analysis because of its higher sensitivity, capability to detect light elements as well as heavy elements,[2] and the ready availability of a variable-energy, charged-particle (protons, alpha particles, etc.) accelerator. Alpha particles, rather than protons of the same velocity, were selected as projectiles for the following reasons: (1) availability of detailed pre-existent data on cross sections for alpha-particle-induced X-ray production, (2) lower alpha particle bremsstrahlung, (3) convenient Coulomb barrier that prevents target activation, and (4) an increase in the ultimate sensitivity by approximately $\sqrt{2}$ over protons for an equal integrated charge. An alpha particle energy of 18 MeV was chosen because it is reasonably optimum for realizing good sensitivity over the whole range of interesting elements. Furthermore, the energy loss for the 18-MeV alpha particles in aerosol samples can be neglected. Figure 1 shows a schematic diagram of the aerosol analysis system. The experimental arrangement selected allows uniform beam intensity across large target areas (up to a 2.5-cm-diameter circle), permits simultaneous detection of elastically scattered alpha particles as well as ion-excited X-rays, accepts aerosol filters mounted in the target tray without any special pretreatment or preparation, and permits a quick examination of a large number of samples (up to 100) without disturbing the target vacuum chamber.

A schematic diagram of the data acquisition system is shown in figure 2. The sequence of operation is as follows: (1) <u>insert</u> selected target slide in the beam line; (2) turn <u>on</u> current integrator, <u>enable</u> ADC, turn <u>on</u> beam; (3) <u>count</u> X-rays for preset incident charge; (4) <u>disable</u> ADC, turn <u>off</u> beam, <u>record</u> data; (5) <u>reset</u> current integrator; (6) <u>advance</u> target tray to next target slide; and (7) <u>repeat</u> steps 2 to 6 for each filter specimen.

The data thus acquired were reduced at Davis by use of the code RACE (refs. 5 and 6). Essentially, the data reduction program starts with the highest energy X-ray line present in the sample spectrum, identifies the source element for this line and computes the complete spectrum for it, subtracts this elemental spectrum from the sample spectrum, and continues the process until the lowest energy X-ray line has been accounted for. From the measured intensities of the X-ray lines for the source elements, the concentrations of the source elements are calculated on the basis of known production cross sections for these X-ray lines. The concentrations of the various elements thus determined are summarized in table IV.

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[2] Alpha scattering is used to obtain values for elements H through Na, thus allowing total atmospheric mass values to be obtained for elements H through U.

DATA ANALYSIS TECHNIQUES

The experimental data are available in the following two forms: (1) total aerosol mass, collected during the entire sampling period, per sampler stage (i.e., for a selected aerosol size range) and (2) total elemental mass in the aerosols, collected during the entire sampling period, per sampler stage. These two sets of data have been used to establish the aerosol size distribution function and the elemental surface preferences, respectively.

Aerosol Size Distribution

The first set of data (total aerosol mass) has been used to establish the aerosol size distribution function in the manner described in the following sections.

Polynomial distribution function.- It is expected that a generalized polynomial function of the aerosol size should provide a better approximation to the experimental mass distribution data than any simple mathematical function such as a lognormal or exponential distribution. Consequently, the experimental aerosol mass data were first fitted by least squares to a generalized polynomial expression of the following form:[3]

$$f(x) = \frac{dM}{dx} = \frac{\Delta M}{\Delta \log D_p} = \sum_{j=0}^{n} a_j x^j \tag{1a}$$

where

x = $\log D_p$

ΔM aerosol mass on a stage

D_p aerosol diameter

$\Delta \log D_p = \log \left(\frac{\text{Upper 50\% cutoff size}}{\text{Lower 50\% cutoff size}} \right)$ for a stage

The least-squares calculations indicated that the minimum value of the polynomial order n needed to best approximate the experimental data to equation (1a) was six. The best-fit sixth-order polynomial function $f(x)$ is

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[3] The mass distribution function $\frac{\Delta M}{\Delta \log D_p}$ was chosen because areas of equal size under the curve represent equal volumes or masses. It was believed that this type of representation conveys a meaningful impression of the size distribution for volume or mass.

$$f(x) = 27.7(0.45 - 1.55x + 2.66x^2 - 9.54x^3 - 8.77x^4 - 6.30x^5 + 5.21x^6) \tag{1b}$$

The computed mass values per stage ΔM_i obtained by equation (1b) are summarized in column 3 of table V. The agreement between the measured and the computed values is quite good. The comparison between the experimental values and the mass values computed from equation (1b) is illustrated in figure 3(a). This figure clearly illustrates the presence of two distinct modes in the aerosol size distribution. It also suggests that the size distribution might be described quite well by a compound lognormal distribution.

Compound lognormal distribution.- As just mentioned, the experimental mass distribution function has two distinct modes. It has, therefore, been fitted to a compound lognormal distribution function of the following form:

$$f(x) = \frac{dM}{dx} \equiv \frac{\Delta M}{\Delta \log D_p}$$

$$= A \exp - \frac{1}{2}\left(\frac{\log D_p - \log D_{M1}}{\log \sigma_1}\right)^2 + B \exp - \frac{1}{2}\left(\frac{\log D_p - \log D_{M2}}{\log \sigma_2}\right)^2 \tag{2}$$

where D_{M1} and D_{M2} are the aerosol mass diameters at which the two mass groups are concentrated and σ_1 and σ_2 are the standard deviations of the two mass distributions. The aerosol masses per stage ΔM_i were computed by using an expression of the form of equation (2) and are summarized in column 4 of table V. The experimental mass distribution and the mass distribution computed by equation (2) are illustrated in figure 3(b). The agreement is quite good over most of the aerosol size ranges. It is apparent that the aerosol sizes are grouped in two modes, one group being centered at a diameter of 0.54 µm and the other at a diameter of 5.6 µm. The appearance of a bimodal distribution is of interest, since it suggests the occurrence of competing mechanisms of aerosol growth and formation. Such a bimodal distribution is in agreement with the reported urban aerosol size distribution (ref. 7).

It is obvious from the preceding discussion that both the generalized polynomial distribution and the compound lognormal distribution provide equally good approximations to the data for total experimental aerosol mass. In the discussion of the elemental results, however, reference will be made to the results mainly in terms of the lognormal distribution function, since it provides a graphic illustration of the elemental surface preference whenever it occurs.

Criteria for Surface Preference

As indicated in the Introduction, one of the main objectives of the present study was to analyze the behavior of the elemental mass distribution as a function of the aerosol sizes and to determine which elements if any exhibit surface preference. The three methods described in the following sections have been used to infer whether any element prefers residence on the surface of the aerosols.

Analysis of elemental mass distribution in terms of compound lognormal distribution function.- Data for elemental mass per sampler stage as a function of aerosol size are fitted to equation (2), and the values of the amplitudes A and B are determined. Relative values of amplitudes A and B should indicate whether an element is concentrated in one or the other peak. Thus the ratio B/A can be a measure of the extent to which an element prefers size group B over size group A. Excess mass concentration in the smaller size group is indicative of preference for surface residence.

Comparison of elemental mass values observed experimentally with those predicted by the exclusive surface residence model.- If an element is concentrated in a thin surface layer on the aerosols, which for this calculation are assumed to be spherical, its mass on any stage of the sampler $\Delta M_{el,i,s}$ can be computed as follows:

$$\Delta M_{el,i,s} = (\text{Number of aerosols})_i \times (\text{Mean surface area of single aerosol})_i$$

$$\times\ (\text{Surface layer thickness}) \times (\text{Elemental density in surface layer})$$

$$= \left[\frac{\dfrac{\text{Total aerosol mass on stage } i}{\text{Aerosol density}}}{\text{Mean volume of a single aerosol on stage } i}\right] \times \left[\begin{array}{l}\text{Mean surface area} \\ \text{of a single aero-} \\ \text{sol on stage } i\end{array}\right]$$

$$\times\ (\text{Surface layer thickness}) \times (\text{Elemental density in surface layer})$$

$$= \left[\frac{\Delta M_i/\rho}{\dfrac{4}{3}\pi\left(\dfrac{d_{m,i}}{2}\right)^3}\right]\left[4\pi\left(\frac{d_{m,i}}{2}\right)^2\right] t\rho_{el}$$

$$= \frac{3t\rho_{el}}{\rho}\,\frac{\Delta M_i}{(d_{m,i})/2}$$

$$\Delta M_{el,i,s} = \frac{6t\rho_{el}}{\rho} \frac{\Delta M_i}{d_{m,i}} \tag{3}$$

where

ρ total aerosol density

ρ_{el} elemental density in the surface layer

t surface layer thickness (expected to be the same for aerosols of all sizes (ref. 2); the absolute value of t is immaterial for the purposes of calculations reported here, as long as $t \ll d_m$ (for all stages); it has been estimated that $t \ll d_{m,i}$ ($t \leqq 0.0085$ μm as opposed to ≈0.4 μm for $d_{m,7}$))

$d_{m,i}$ actual mean diameter of an aerosol on stage i;[4] $d_{m,i} = \frac{1}{\rho^{1/3}}(D_\ell D_u)^{1/2}$, where D_ℓ and D_u represent the lower and upper 50-percent cutoff aerodynamic size limits for a stage; $d_{m,i} = \frac{D_{m,i}}{\rho^{1/3}}$

Upon substituting the value of $d_{m,i}$ in equation (3), the following expression for $\Delta M_{el,i,s}$ is obtained:

$$\Delta M_{el,i,s} = \frac{6t\rho_{el}}{\rho^{2/3}} \frac{\Delta M_i}{D_{m,i}}$$

$$= \text{Constant} \times \frac{\Delta M_i}{D_{m,i}} \tag{4a}$$

The term $6t\rho_{el}/\rho^{2/3}$ is nearly constant for all stages for a given element. (The stage-to-stage variation in ρ is estimated to be less than 5 percent.)

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[4] The actual diameter $d_{m,i}$ is interpreted as being the diameter of a sphere with the same mass as the particle (whose density is 1 g/cm^3) being considered, i.e.,

$$\frac{4}{3}\pi\left(\frac{d_{m,i}}{2}\right)^3 \rho = \frac{4}{3}\pi\left(\frac{D_{m,i}}{2}\right)^3$$

where $D_{m,i} = (D_\ell D_u)^{1/2}$ is the log mean aerodynamic diameter of the ith stage.

The value of the constant will, however, be different for different elements. Therefore,

$$\Delta M_{i,el,s} \propto \frac{\Delta M_i}{D_{m,i}} \qquad (4b)$$

A comparison of the predictions of equations (4) and the experimental elemental mass distribution should indicate whether the element exhibits surface preference.

Comparison of R_{exp} and calculated R_s as a function of impactor stage.- The values of R_s needed for this comparison can be calculated as follows:

$$R_s = \frac{\Delta M_{el,i,s}}{\Delta M_{i,total}}$$

Substituting the value of $\Delta M_{el,i,s}$ from equation (4b) gives

$$R_s = \frac{\text{Constant} \times \dfrac{\Delta M_i}{D_{m,i}}}{\Delta M_i}$$

$$= \frac{\text{Constant}}{D_{m,i}} \qquad (5a)$$

Therefore,

$$R_s \propto \frac{1}{D_{m,i}} \qquad (5b)$$

For the elements uniformly distributed in the bulk of the aerosols, R_{exp} is expected to be a constant, independent of the sampler stage - unless the element happens to be present only in the aerosols of certain sizes, in which case R_{exp} will exhibit localized increases at those sizes. Thus a comparison between R_{exp} and R_s for an element should indicate whether the element has a tendency for surface concentration.

RESULTS AND DISCUSSION

Attention should now be directed to figure 4, where the experimental total aerosol masses on various stages have been compared with the following compound lognormal distribution function:[5]

$$\frac{\Delta M}{\Delta \log D_p} = 24.93 \exp - \frac{1}{2}\left(\frac{\log D_p + 0.2676}{0.2000}\right)^2 + 41.55 \exp - \frac{1}{2}\left(\frac{\log D_p - 0.7482}{0.2562}\right)^2 \qquad (6)$$

where ΔM is in $\mu g/m^3$ and D_p is in micrometers. By comparing equation (6) with equation (2), the following distribution parameters are noted:

$A = 24.93$

$B = 41.55$

$\log D_{M1} = -0.2676$; that is, $D_{M1} = 0.54\ \mu m$

$\log D_{M2} = 0.7482$; that is, $D_{M2} = 5.60\ \mu m$

$\log \sigma_1 = 0.2000$

$\log \sigma_2 = 0.2562$

Thus the relative amplitudes of the two mass components are $\frac{B}{A} = \frac{5}{3}$.

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[5] It is possible that the aerosol size distribution may even be trimodal, with the 5.6-μm peak made of two groups centered at 4.7 μm and 10 to 12 μm, respectively. This is indicated in figure 4. This hypothesis is supported by the following supplementary information: (1) The width of the 5.6-μm peak is rather large ($\log \sigma_2 = 0.2562$), though it is recognized that the heterogeneous source aerosols are expected to have large widths; (2) the calculated lognormal value of ΔM for stage 0 is less than the experimental value, indicating the presence of a possible, weak, third lognormal component centered at 10 to 12 μm; (3) the elemental mass peaks centered on large size particles tend to suggest a slightly smaller (≈4.7 μm) medium size than the average total mass peak at 5.6 μm (see fig. 5). However, the quality as well as the quantity of the data is such that a definitive statement regarding a possible trimodal distribution cannot be made.

The data for individual elemental concentration as a function of aerosol size have also been fitted to a compound lognormal distribution of the form of equation (2). It was found that all elements - except K, S, Ni, and Mn - have B/A values close to 5/3, as expected for elements uniformly distributed in the bulk of the aerosols. Figure 5 shows distributions of $\frac{\Delta M}{\Delta \log D_p}$ as a function of $\log D_p$ for K, S, Mn, and Ni. The relative amplitudes B/A of the two lognormal distribution components are summarized in the following table:

Impactor stage	Element	$\frac{B}{A}$	Comments
1	K	$\frac{4}{12}$	Strong concentration in the smaller size aerosols
2	S	$\frac{4}{13}$	Strong concentration in the smaller size aerosols
3	Mn	$\frac{12}{18}$	Significant tendency to concentrate in smaller size aerosols
4	Ni	$\frac{8}{11}$	Significant tendency to concentrate in smaller size aerosols

It is obvious that K and S (and to a lesser extent, Mn and Ni) show a marked tendency to concentrate on the smaller aerosols. This may be the result of a tendency by these elements to reside on aerosol surfaces. This conclusion is further supported by the data illustrated in figure 6, where experimentally observed elemental masses as a function of impactor stage are compared with surface masses as a function of impactor stage. Also shown in this figure are the trends in elemental masses anticipated for uniform bulk presence of these elements. The surface masses of the aerosols on various stages of the impactor were calculated in the manner explained earlier. (See eqs. (4) and the discussion thereof.)

Although none of the elements in figure 6 exhibit trends consistent with exclusive surface residence, K and S show marked preference for surface over bulk residence. A weaker surface preference is also exhibited by Mn and Ni. These conclusions are further supported by the data shown in figure 7, where the ratio $R_{exp} = \frac{\text{Elemental mass on the stage}}{\text{Total aerosol mass on the stage}}$ is plotted as a function of impactor stage for K, S, Mn, and Ni. Also shown in this figure are the R_s values expected for elements preferring exclusive surface residence. These latter values have been calculated in the manner described earlier. (See eqs. (5).)

Clearly, R_{exp} values are much higher for K and S (and to a lesser extent for Mn and Ni) for later stages, where smaller aerosols are collected. Such a behavior would be expected for elements preferring surface residence, as indicated by equations (5).

It has been noted that S and K (and to a lesser extent Mn and Ni) show surface preference. This is not altogether surprising in view of the reported (ref. 3, p. 40) results of spectrochemical analyses of a large number of municipal incinerator slags. These reported results are summarized in the following table:

Chemical	Range of analysis of 25 slag samples, percent
SiO_2	20.9 to 76.0
Al_2O_3	0.2 to 28.3
TiO_2	0.3 to 4.9
Fe_2O_3	1.8 to 40.0
CuO	Trace
CaO	7.3 to 17.0
MgO	1.1 to 2.6
SO_3	0.2 to 20.4
ZnO	0.2 to 6.3
PbO	Trace
P_2O_5	0.6 to 2.2
Na_2O	0.6 to 11.6
K_2O	0.3 to 8.1
Li_2O	0.03 to 0.13
MnO_2	0.04 to 0.9
BaO	Trace
Nickel compounds	Trace[a]

[a] Ni, which was detected in slags only in trace quantity, has been reported in larger quantities in ashed incinerator particulate emissions (ref. 3, p. 85). Its concentration in stack effluents ranges from 1 to 10 percent by weight.

The presence of certain elements in the incinerator slags is expected to be accompanied by their presence in the particulate and the gaseous emissions also. Potassium, which is known (ref. 8) to be a major matrix element in fly ash, shows a surprisingly strong surface trend in the incinerator aerosols. This may be, in part, the result of the presence of the various potassium-based chemical compounds in the feed mix, since the chemical wastes from the local medical clinics and hospitals as well as the schools and colleges are included in the waste incinerated. Even though the gaseous sulfur oxide emissions from the municipal incinerator have been reported (ref. 3) to be generally low, it is found that sulfur shows the highest measured total concentration among the elements detected in the particulate emissions in the present study. It is quite possible that part of the excess sulfur in smaller aerosols may result from sulfides formed on combustion aerosol surfaces or the presence of small elemental sulfur aerosols themselves. As in the case of potassium, the chemical wastes in the feed mix could also be a contributing factor to the excess sulfur in smaller size aerosols. Manganese and nickel have been previously reported (ref. 9) in increasing concentrations in smaller aerosols emitted from urban sources, such as municipal incinerators.

Surface preference for toxic elements like K, S, Mn, and Ni is undesirable, since it implies concentration of these elements on submicron size aerosols which are difficult to eliminate from the stack gases. These submicron aerosols easily penetrate the human bronchial passages to enter the lungs, where they can be harmful to health. However, absolute concentrations of these elements on aerosols of diameters less than or equal to 3 μm are small compared with the safe limits set by the National Institute for Occupational Safety and Health (refs. 9 and 10), as seen from the data in table VI.

CONCLUDING REMARKS

It has been determined that the incinerator aerosols exhibit a bimodal size distribution, with one mode centered at a diameter of 0.54 μm and the other at a diameter of 5.6 μm. Only a few elements (K, S, Mn, and Ni) exhibit a preference for surface residences in the municipal incinerator aerosols. Most of the constituent elemental atoms are uniformly distributed in the bulk of the aerosols. This is rather surprising in view of the extremely mixed and diverse nature of the urban solid waste burnt in the incinerator. It implies that the presence of a strong aerosol group at a larger mean diameter competes effectively against the smaller size aerosols in providing recondensation surfaces to the volatile vapors formed in the combustion zone.

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TABLE I.- AERODYNAMIC DIAMETERS OF AEROSOLS FOR AN IMPACTION EFFICIENCY OF 50 PERCENT AND A FLOW RATE OF 0.00047 m^3/s (1 ft^3/min)

Stage	Particle diameter,[a] D_p, μm
0	11.0
1	7.0
2	4.7
3	3.3
4	2.1
5	1.1
6	.65
7	.43

[a] These values have been supplied by the manufacturer, for the impactors used in this study, for a flow rate of 0.00047 m^3/s. Before the impactors are put to use, the air flow is adjusted to be exactly 0.00047 m^3/s to ensure the accuracy of the stage sizes listed.

TABLE II.- SUMMARY OF FILTER MASSES, BEFORE AND AFTER AEROSOL COLLECTION, AND MASSES OF AEROSOLS COLLECTED

[The total volume of air passed through each impactor was 36.104 m^3 ($21\frac{1}{4}$ hours at a flow rate of 0.00047 m^3/s)]

Stage	Impactor 1			Impactor 2		
	Filter mass before aerosol deposition, mg	Filter mass after aerosol deposition, mg	Net aerosol mass, mg (a)	Filter mass before aerosol deposition, mg	Filter mass after aerosol deposition, mg	Net aerosol mass, mg (a)
0	34.13	34.39	0.26	31.69	31.99	0.30
1	30.78	30.93	.15	31.69	31.93	.24
2	33.12	33.37	.25	32.32	32.58	.26
3	31.64	31.77	.13	31.25	31.49	.24
4	31.09	31.19	.10	31.49	31.57	.08
5	30.37	30.37	0	31.42	31.58	.16
6	31.67	31.84	.17	33.39	33.46	.07
7	31.86	31.90	.04	31.60	31.85	.25

[a] All values accurate within ±0.050 mg.

TABLE III.- AVERAGE PARTICULATE MASS LOADING OF AIR AS A FUNCTION OF AEROSOL SIZES

Stage	Aerosol size range, µm	Mass loading, µg/m^3
0	11 to 20 (?)[a]	7.76 ± 1.38
1	7.0 to 11.0	5.40 ± 1.38
2	4.7 to 7.0	7.06 ± 1.38
3	3.3 to 4.7	5.12 ± 1.38
4	2.1 to 3.3	2.49 ± 1.38
5	1.1 to 2.1	2.22 ± 1.38
6	0.65 to 1.10	3.32 ± 1.38
7	0.43 to 0.65	4.02 ± 1.38

[a] Large particle cutoff due to intake design has been assumed to be 20 µm on stage 0 for particles whose density is 1 g/cm^3.

TABLE IV.- SUMMARY OF CONCENTRATIONS OF ELEMENTS PRESENT IN AEROSOLS COLLECTED AT VARIOUS STAGES OF THE SAMPLING UNITS[a]

[Errors are less than 25 percent unless otherwise listed; all loading and matrix corrections have been applied]

Element	Elemental concentration, ng/m^3, at stage -							
	0	1	2	3	4	5	6	7
[b]Na	125.2	142.5	118.9	117.0	114.5	113.6	112.7	107.8
[b]Mg	73.4	84.2	70.3	68.4	67.2	67.2	66.2	63.3
Al	121.1 ± 42.0	84.1	70.2	199.0 ± 80.0	67.1	47.2 ± 22.9	66.2	63.2
Si	67.2	77.1	128.6 ± 22.4	63.1	99.5 ± 20.7	61.1	60.1	58.1
S	87.5 ± 24.5	35.9	47.7 ± 16.0	54.8 ± 16.3	43.3 ± 17.9	50.1 ± 13.6	168.3 ± 23.4	226.7 ± 28.3
[b]Cl	52.1	60.0	50.1	49.1	48.0	76.0	46.0	44.0
K	30.0	18.4 ± 10.2	21.2 ± 9.1	31.9 ± 8.5	27.0 ± 6.0	21.1 ± 7.6	41.5 ± 8.2	105.6 ± 14.5
Ca	85.4 ± 11.4	42.5 ± 9.7	66.5 ± 8.9	52.0 ± 7.1	41.5 ± 8.5	27.7 ± 6.6	43.8 ± 6.8	15.9 ± 4.0
Ti	64.1 ± 10.0	49.3 ± 10.2	37.4 ± 8.2	8.9 ± 7.4	23.0	23.0	22.0	21.0
[b]V	20.0	23.0	19.0	19.0	18.0	18.0	18.0	17.0
[b]Cr	15.0	17.0	15.0	14.0	14.0	14.0	14.0	13.0
Mn	9.6 ± 3.5	13.3 ± 6.0	13.0	19.4 ± 5.1	10.4 ± 4.2	13.3 ± 4.1	13.0	31.5 ± 6.3
Fe	21.4 ± 4.9	21.0 ± 5.0	30.8 ± 5.3	24.8 ± 4.7	16.4 ± 4.0	13.1 ± 3.6	24.8 ± 4.7	12.0
Ni	11.0	13.0	11.0	8.2 ± 3.4	10.0	10.0	19.8 ± 9.4	11.0 ± 3.7
[b]Cu	11.0	13.0	11.0	10.0	10.0	10.0	10.0	9.0
Zn	14.0	16.0	13.0	11.8 ± 5.4	10.8 ± 4.8	12.0	12.0	12.0
[b]Br	25.0	33.0	23.0	22.0	21.0	21.0	20.0	21.0
[b]Ba	81.1	93.0	77.0	76.0	74.0	74.0	70.0	69.0
[b]Pb	46.0	61.0	42.0	42.0	40.0	39.0	38.0	39.0

[a] These aerosols have also been studied with the thermal neutron activation analysis (NAA) technique. There are some minor differences in the pattern of elemental fractionations. For example, V - which according to PIXE data shows only a slight preference for surface residence - shows a much stronger surface trend in the NAA data; a surface trend for Mn is not observed in the NAA data; Co and I - neither of which was detected in the PIXE analysis - exhibit slight surface trends in the NAA data. By the NAA technique, Si, S, and Pb were not detected and Ni data were also very unreliable.

[b] Listed values represent upper limits.

TABLE V.- OBSERVED AND COMPUTED TOTAL AEROSOL MASSES PER STAGE

Stage	Experimental mass, mg	Computed mass, mg, by -	
		Polynomial distribution	Lognormal distribution
0	0.280 ± 0.050	0.240	[a]0.163
1	0.195 ± 0.050	.255	.219
2	0.255 ± 0.050	.257	.255
3	0.185 ± 0.050	.174	.191
4	0.090 ± 0.050	.128	.135
5	0.080 ± 0.050	.096	.078
6	0.120 ± 0.050	.133	.118
7	0.145 ± 0.050	.146	.154

[a] See footnote 5, page 10.

TABLE VI.- EXPERIMENTALLY OBSERVED TOXIC ELEMENT CONCENTRATIONS IN AEROSOLS EMITTED FROM THE LOCAL MUNICIPAL INCINERATOR COMPARED WITH SAFE LIMITS SET BY NIOSH (REF. 9)

Stage	Element	Observed concentration of particles 0.43 µm to 3.3 µm in diameter[a]	Natl. Inst. Occup. Safety & Health (NIOSH) limits
1	[b]K	200 ng/m^3	<21 mg/m^3, for KCN <196 mg/m^3, for KBH_4 <429 mg/m^3, for KF <447 mg/m^3, for KOH
2	S	468 ng/m^3	250 µg/m^3, for SF_5
3	Mn	67 ng/m^3	5 mg/m^3, for Mn
4	Ni	59 ng/m^3	[c]1 µg/m^3, for $Ni(CO)_4$ 1 mg/m^3, for Ni

[a] It should be borne in mind that particles smaller than 0.43 µm will also provide strong carriers for these elements, thereby increasing their concentration to considerably higher levels.

[b] The potassium compounds listed in column 4 have been proved to be toxic at levels listed. Their concentration in air must always be kept lower than the toxicity thresholds listed.

[c] The USSR and Rumania have lower standards of 0.07 ppb [90 ng/m^3] and 0.7 ppb [0.9 µg/m^3], respectively, for nickel carbonyl vapor (ref. 10).

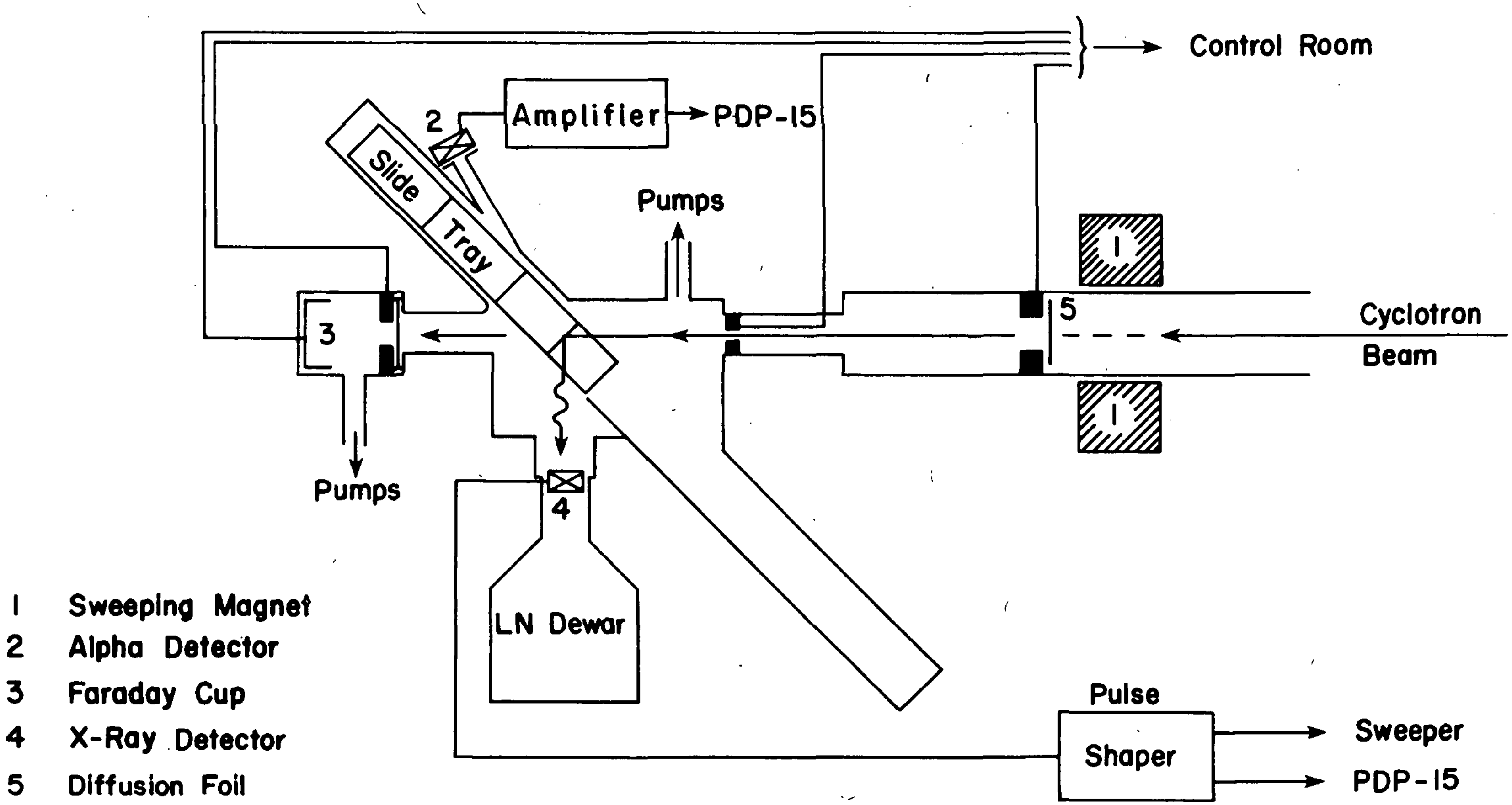


Figure 1.- Schematic diagram of the aerosol analysis system (ref. 4).

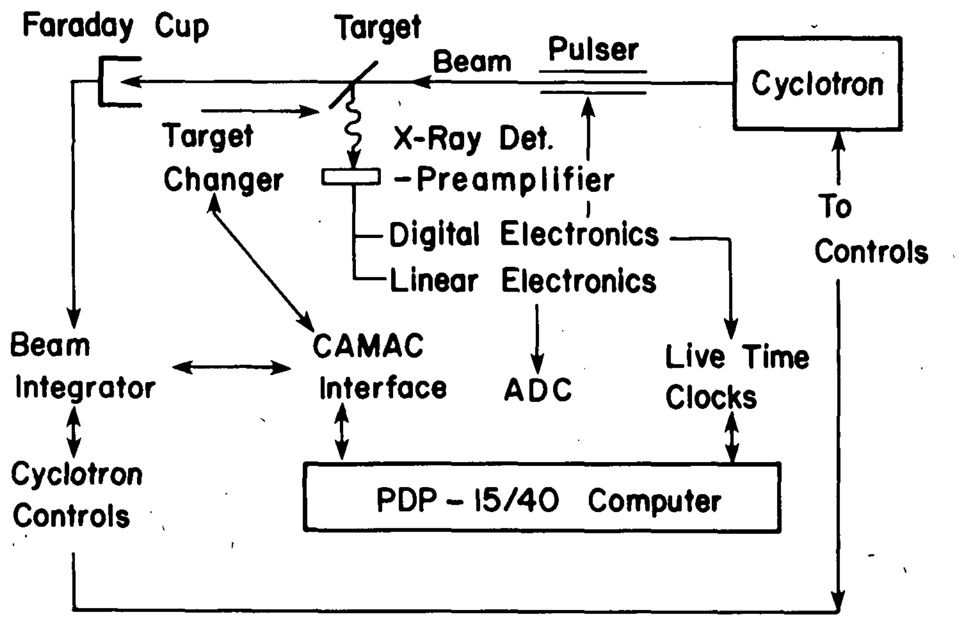
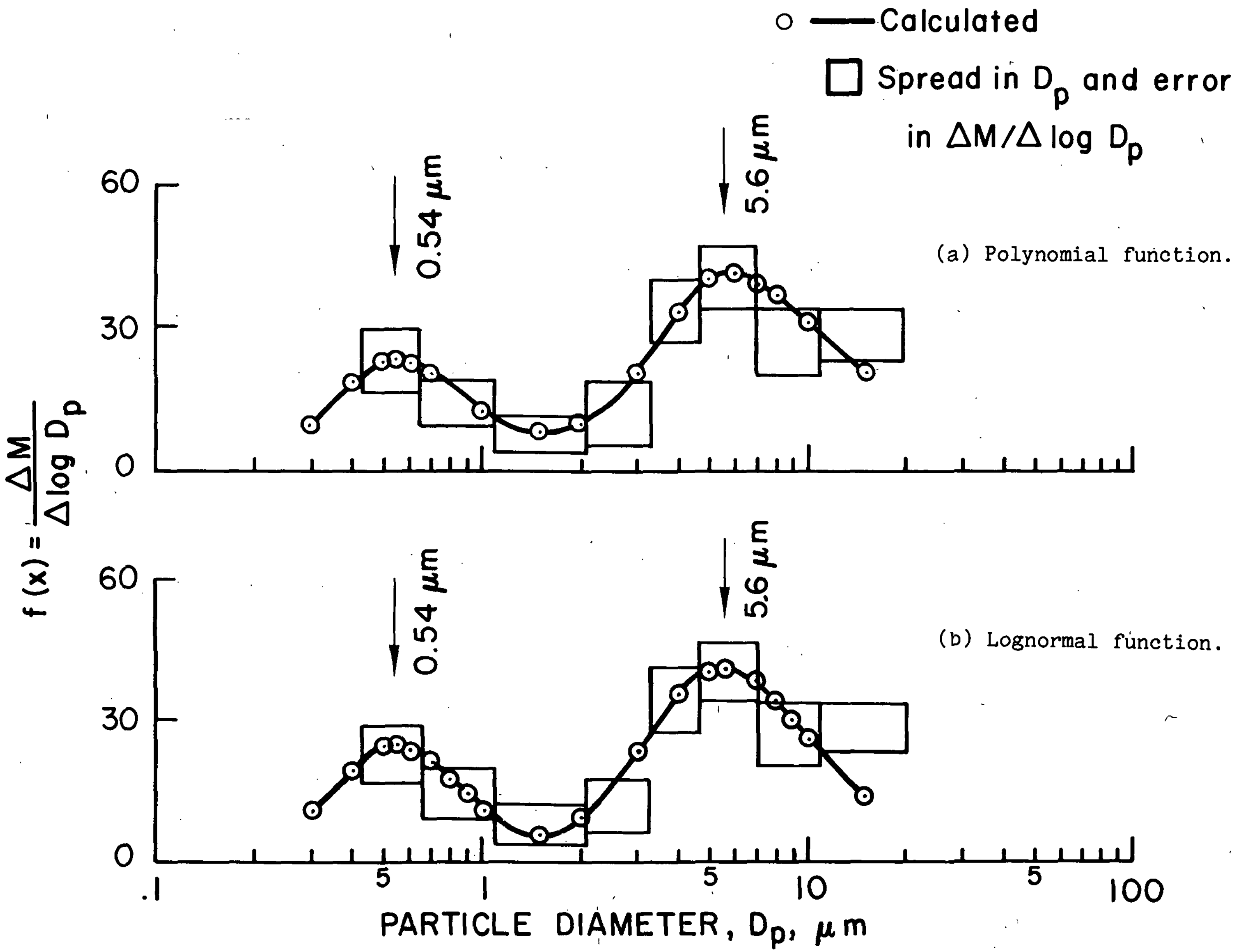


Figure 2.- Schematic diagram of the data acquisition system (ref. 4).



(a) Polynomial function.

(b) Lognormal function.

Figure 3.- Experimental aerosol mass distribution and mass distribution computed by two commonly used aerosol size distribution functions. (Aerosol mass ΔM is in $\mu g/m^3$.)

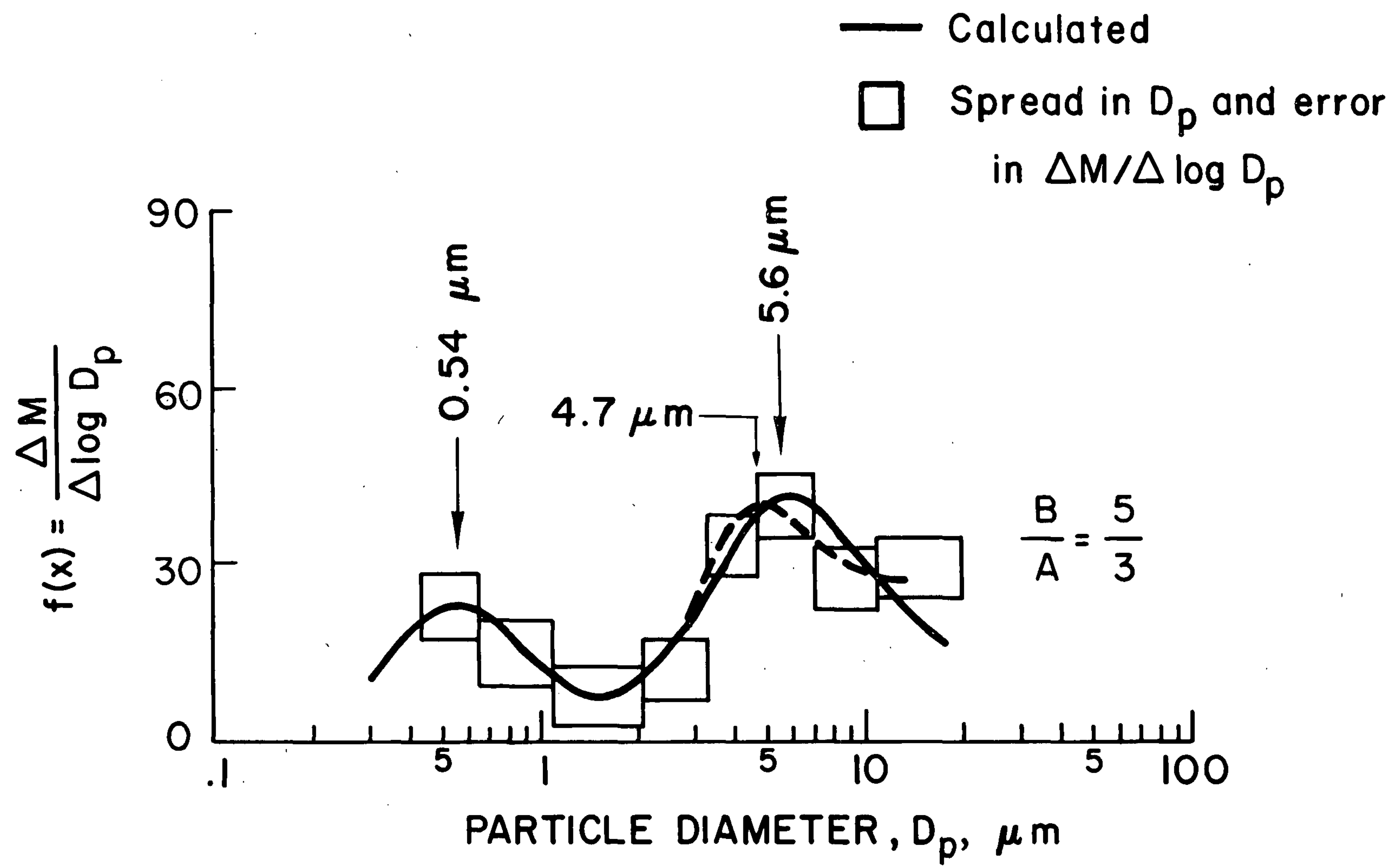


Figure 4.- Average mass distribution of aerosols collected at the municipal incinerator. Dashed line indicates possibility of size distribution being trimodal, with the 5.6-μm peak made up of two groups centered at 4.7 μm and 10 to 12 μm, respectively. (Aerosol mass ΔM is in $\mu g/m^3$.)

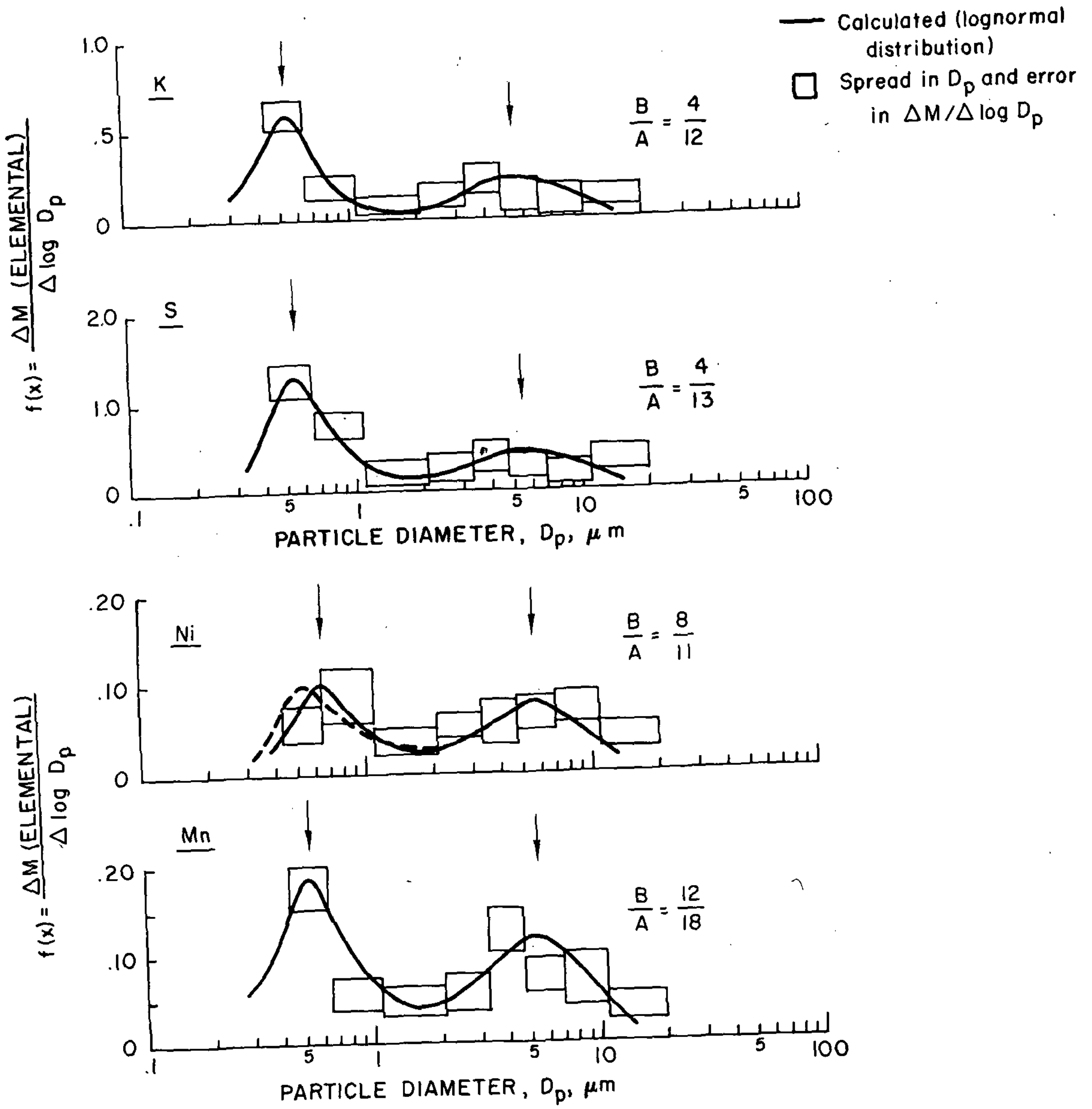


Figure 5.- Average elemental mass concentration in aerosols collected at different stages of the sampler. (Elemental mass ΔM is in μg/m^3.)

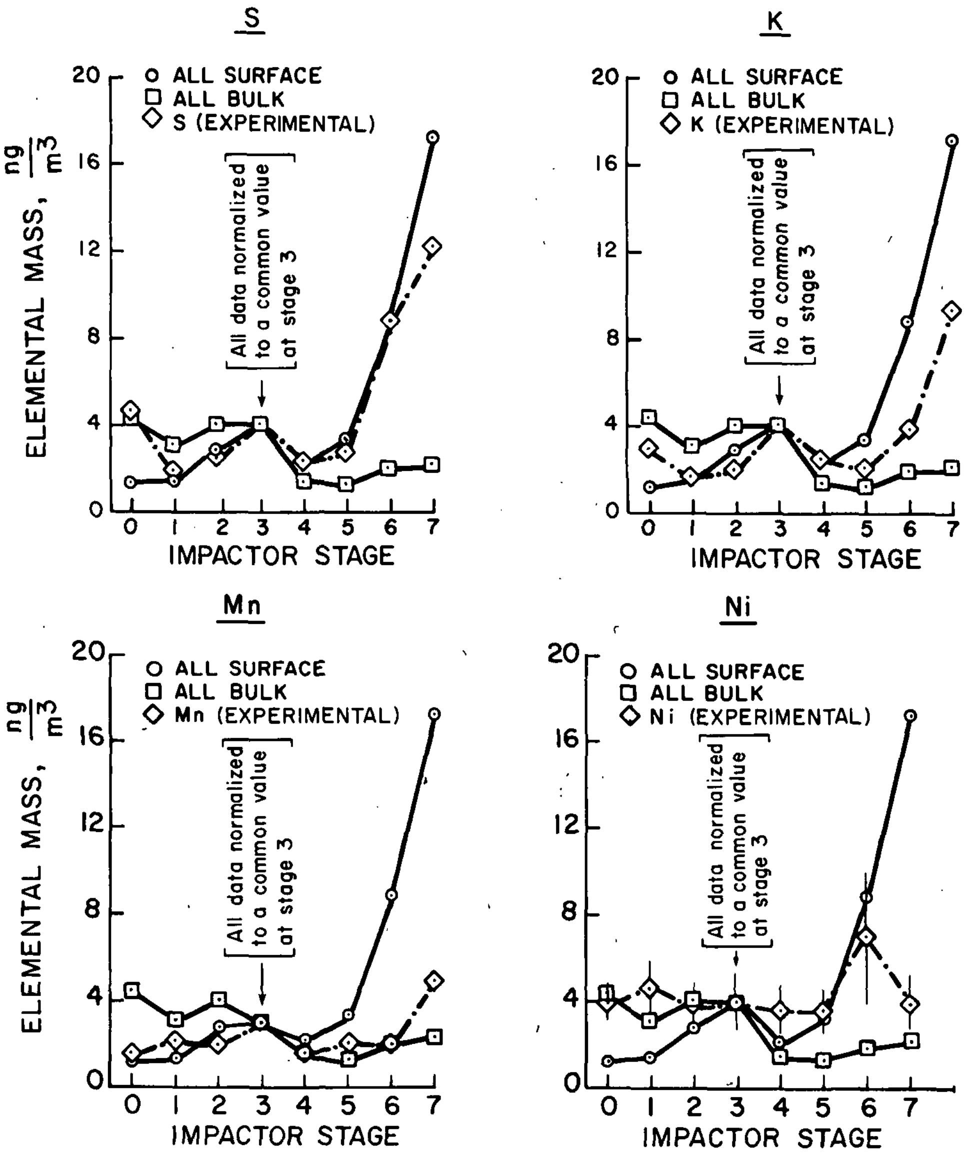
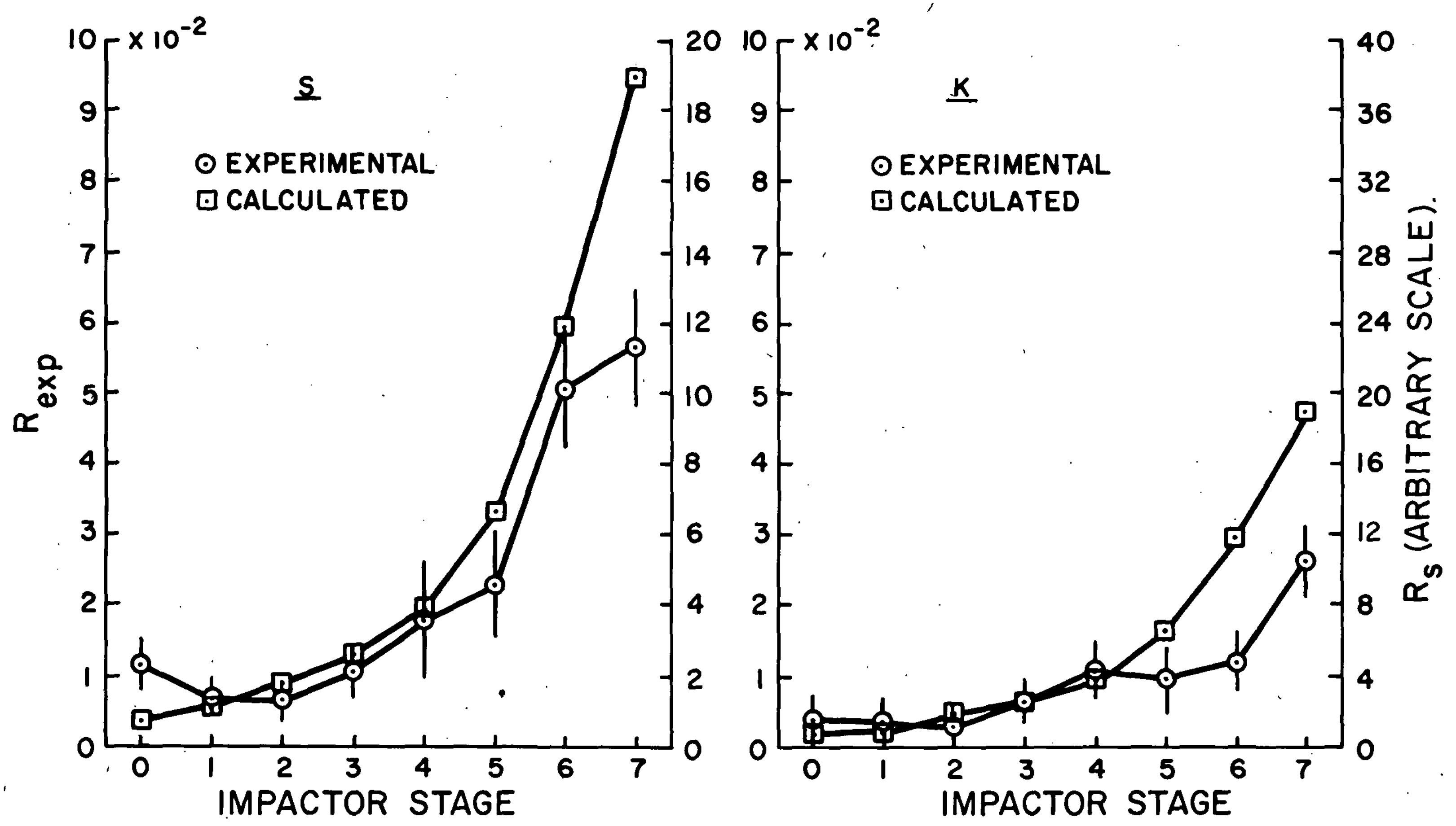
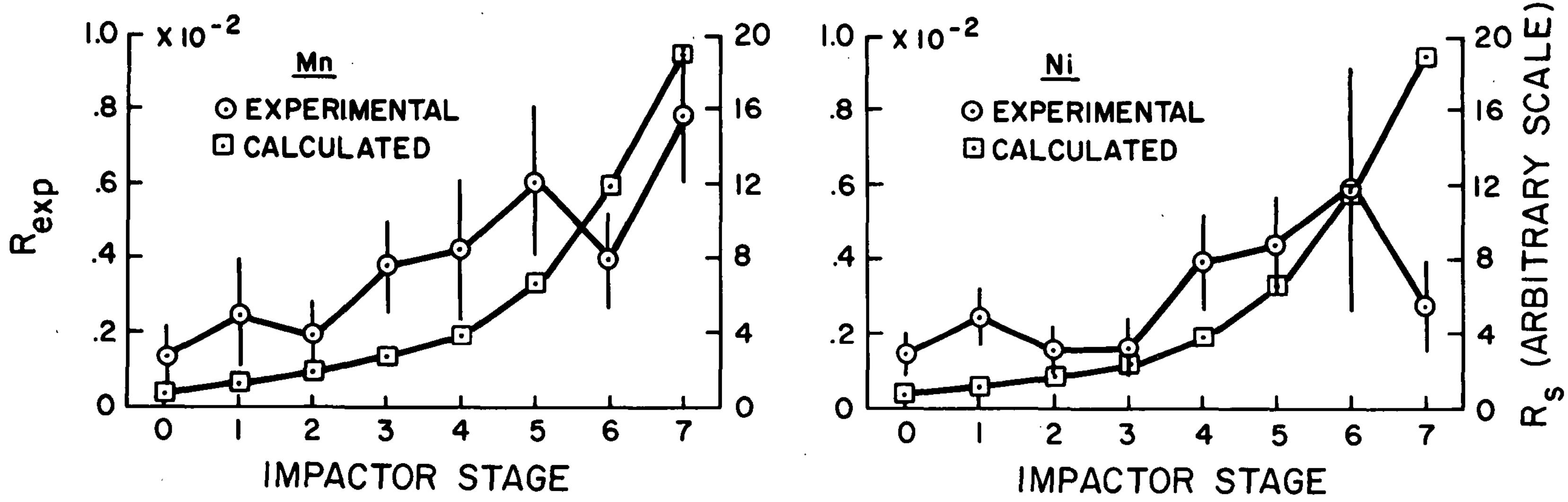


Figure 6.- Comparison of experimentally observed elemental mass distributions with surface and bulk distributions.



(a) S and K.

Figure 7.- Ratio of elemental mass to total mass as a function of impactor stage. (Absolute values of R_s cannot be determined without a knowledge of the constant in eqs. (4). However, absolute values of R_s are not needed for the purpose of comparing relative values of R_s for various stages; hence, the R_s scale is marked arbitrary.)



(b) Mn and Ni.

Figure 7.- Concluded.

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16. Abstract

As part of a continuing investigation of high-temperature-combustion aerosols, a study of elemental composition of size-differentiated aerosols emitted from a local municipal incinerator has been completed. Aerosols were aerodynamically separated into eight diameter groups ranging from 0.43 µm to 20 µm, collected, and analyzed by charged-particle-induced X-ray emission technique. On-line data collection and reduction codes generated aerial densities for elements from Na to U with sensitivities in the ng/m^3 range for most elements. From the total weights of aerosols collected per stage, their size distribution was determined to be bimodal, with one group centered at a diameter of 0.54 µm and the other at a diameter of 5.6 µm. Measured elemental concentrations in various size ranges indicate that K and S show a strong tendency to concentrate on aerosol surfaces. A weaker trend for surface preference was also observed for Mn and Ni, but other elements show no such trend.

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