Assessment of Particle Size Distributions of Health-relevant Aerosol Exposures of Primary Lead Smelter Workers

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Experiments were conducted at a primary lead smelter to investigate the particle size distributions of lead-containing aerosol to which workers were exposed, using personal inhalable dust spectrometers (PIDS) in specific smelter process areas. A total of 46 PIDS samples were evaluated, taken from the ore storage/mill, sinter plant, blast furnace and dross furnace process areas. Continuous particle size distributions were derived from the raw PIDS data employing a recently-developed optimisation routine, enabling determination of the percentages of inhalable, thoracic and respirable aerosol (in terms of lead content) as fractions of total lead aerosol. In addition, the mass ratios thoracic/inhalable and respirable/inhalable were also determined. Although the parameters of the measured particle size distributions ranged widely, some clear trends emerged. Firstly, the aerosols were coarser than had been expected based on measurements of previously reported workplace particle size distributions. This is thought to be due to the fact that the PIDS collects larger particles more efficiently than other instruments which have been used for such measurements. Secondly, there were significant differences in particle size distribution between process areas, in particular that the aerosol in the blast furnace area was generally finer than in the sinter plant. Such results may be used to support the results of workplace studies (reported elsewhere) into the differences between exposures to inhalable and 'total' aerosol as measured using different sampling instruments, especially when they are used together with knowledge of the physical processes governing the performances of such instruments. 

INTRODUCTION

It has long been recognised that particle size is a primary determinant of the inhalation and deposition of particulate matter in the human respiratory tract. Early approaches by the British Medical Research Council (BMRC, 1952) and the American Conference of Governmental Industrial Hygienists (ACGIH, 1968) identified the role in certain types of respiratory ill-health (e.g., pneumoconiosis) of the fine fraction representing aerodynamically-fine particles capable of penetrating to the gas exchange region of the lung. More recently, the International Standards Organisation (ISO, 1983) and ACGIH (1985) went further to describe the fractions that can be inhaled through the nose and/or mouth during breathing (the inhalable fraction), and penetrate progressively into the lung below the larynx (the thoracic fraction) and beyond to the gas exchange region (the respirable fraction). More recently still, international agreement has been achieved on the quantitative definition of these fractions (ISO, 1992; the Comité Européen de Normalisation CEN, 1992; ACGIH, 1996). Each of the three definitions is expressed as a single function of particle aerodynamic diameter ($d_a$). Thus, the inhalable fraction ($I$) is described by

$$I(d_a) = 0.5(1 + \exp(-0.06d_a))$$  \hspace{1cm} (1)

where $d_a$ is expressed in [μm]. This expression applies for $d_a$ up to 100 μm. The thoracic fraction ($T$) takes the form

$$T(d_a) = I(d_a)(1 - T(d_a))$$  \hspace{1cm} (2)
where \( F(d_{\text{m}}) \) is a cumulative log-normal function with its median at \( d_{\text{m}} = 11.64 \mu m \) and a geometric standard deviation \((\sigma_{g})\) of 1.5. Similarly, the respiration fraction \((R)\) takes the form

\[
R(d_{\text{m}}) = I(d_{\text{m}}) \{1 - F_{R}(d_{\text{m}})\}
\]

where \( F_{R}(d_{\text{m}}) \) is a cumulative log-normal function with its median at \( d_{\text{m}} = 4.25 \mu m \) and geometric standard deviation \((\sigma_{g})\) of 1.5. It is likely that, in the future, occupational exposure limits (OELs) for aerosols will be based on these criteria, with Equations (1) to (3) then becoming ‘target’ curves for the performances of instruments for the individual inhalable, thoracic and respirable fractions respectively.

During recent years, occupational hygienists have become increasingly aware of the usefulness of measurements of the particle size distributions of workplace aerosols. Such information can aid in assessing and interpreting the performances of aerosol samplers in the field, and in considerations of the technical control of workplace aerosols by ventilation and filtration and by personal respiratory protection. But, most importantly in the context of the above, knowledge of the particle size distribution enables determination of the particle size distribution, and hence the mass, contained within the defined health-related fractions. Thus, for example, for a given collected air sample, if the frequency distribution of the mass concentration of total ambient aerosol is described as the probability density function \( f(d_{\text{m}}) \), then the mass contained within the inhalable fraction \((M_{i})\) is given by

\[
M_{i} = \int_{0}^{\infty} f(d_{\text{m}})I(d_{\text{m}})dd_{\text{m}}
\]

where, here and elsewhere in this paper, \( f(d_{\text{m}}) \) is unnormalised so that the total area under the curve it represents is the overall mass concentration of true total aerosol in the sample of interest; that is, \( f(d_{\text{m}}) \) is expressed in units of \([\text{mass}/\mu m]\). Similar expressions may be written down for the mass concentration for the thoracic and respirable fraction, \( M_{T} \) and \( M_{R} \) respectively.

For the practical measurement of the particle size distributions of workplace aerosols, cascade impactors have been favoured by most occupational hygienists (Lodge and Chan, 1986). In recent years, miniature versions of this instrument have been developed which can be worn by workers as personal samplers. Two such instruments are the sampler proposed by Professor V.A. Marple and colleagues at the University of Minnesota (Rubow et al., 1987) and the one proposed by workers at the Institute of Occupational Medicine, Edinburgh (Gibson et al., 1987). The latter was designed to aspirate the inhalable fraction and was demonstrated in the wind tunnel to do so up to particles with \( d_{\text{m}} \) up to at least 30 \( \mu m \). In use, the whole ‘catch’ of particulate material is analysed in order to yield the particle size distribution of specifically the inhalable fraction—or, if desired, by use of Equation (1), that for total ambient aerosol. An application of this instrument, referred to as the ‘personal inhalable dust spectrometer’ (PIDS), is the primary subject of the present paper.

The research described here applies the preceding ideas to worker exposures to lead-containing aerosol in a large primary lead smelter. It set out to achieve two goals. The first was to obtain estimates of the particle size distributions of the workplace exposures of primary lead smelter workers so that the relative amounts contained within the inhalable, thoracic and respirable aerosol fractions could be determined. The second was to apply the knowledge gained in interpreting the results of personal lead exposures made by different sampling instruments dedicated to collecting ‘total’ and inhalable aerosol respectively (as reported earlier by Spear et al., 1997).

**THE WORKPLACES STUDIED**

This research was carried out at a primary lead smelter in North America, whose main goal is to produce pure lead from the raw material in the form of lead-containing ores. Ore for smelting arrives at the smelter from the mine by truck or by rail. Upon arrival, a sample from each ore source is analysed to determine its elemental composition and moisture content. Following sampling, ores are transported to a large ore storage/mill building, where they are removed by overhead crane into either storage piles or large concrete feeder bins. Here materials are aggregated according to their chemical composition. These stored materials are subsequently routed by conveyor to the sinter plant where the ore is combined with fuel, ignited and burned to produce fused ‘sinter’ material (during which process the sulphur content is reduced). The resultant sinter is then crushed and graded. The crushed sinter—largely in the form of lead oxide—is mixed with coke and iron and transported to the top of the blast furnace into which oxygen-rich air is blown, causing the sinter to be converted to elemental lead and the release of carbon dioxide. The molten material descends to the bottom of the blast furnace, and collects in a settling basin where the molten lead-rich fraction settles to the bottom and the lighter ‘slag’ comes to the surface. This slag contains the iron which had been added, as well as zinc and lime. The lead fraction and slag are separated by draining the molten material out of the basin by ports located at different heights on the basin. Before cooling, railcars are used to transport the slag for disposal and the lead-rich fraction to the dressing area. The objective of the dressing process is to separate elemental lead from impurities not eliminated in the blast furnace. The molten material from the blast furnace is poured into a large kettle, heated, and allowed to cool slowly. As the kettle cools, the impure ‘dross’ fraction—rich in copper and arsenic—rises to the surface. This dross is skinned off the top of the cooling kettle and trans-
ported to a large reverberatory furnace. The remaining pure lead is poured into molds, forming lead ingots ready for sale. The dross material in the reverberatory furnace is again heated and allowed to cool slowly. During cooling, three distinct layers are formed. The top ‘matte’ layer is rich in iron and copper, while the middle ‘speiss’ layer is rich in arsenic. These two layers are extracted and shipped out to a different smelter for copper extraction. The bottom layer contains very pure lead, and is returned to the dressing kettles for further extraction.

In each of the operations described above, a number of administrative measures are in place to reduce exposure to airborne or ingestible lead. The plant has enacted a respiratory protection program, and each worker is fit tested for the assignment of a respirator and provided with respiratory protective equipment. Respirator use is mandatory in most work areas, including the ore storage building, the mill, the sinter plant, the blast furnace and the dressing area. The plant uses an automated respirator cleaning apparatus for removing ingestible lead from respirator surfaces. Workers are not allowed to eat or drink in work areas, and an air-conditioned lunch room is provided. Workers are issued cotton overalls to be worn in work areas. These overalls are not worn outside the plant and are removed before entering dining or office areas.

EXPERIMENTAL METHODS AND MATERIALS

The personal inhalable dust spectrometer (PIDS)

As mentioned earlier, the PIDS (flowrate 2 Lpm) is designed to collect the inhalable aerosol from the breathing zone of its wearer and to aerodynamic classify it in order to provide the aerodynamic size distribution of the inhalable particles (Gibson et al., 1987). It features a circular inlet with a diameter of 15 mm, similar to that of the IOM personal inhalable aerosol sampler (Mark and Vincent, 1986). The inlet is followed by an entry section, eight successive circular-jet impactor stages designed to collect progressively finer particles, and a backing filter. In the use of the instrument, ten aerodynamically-classified particulate masses are thus obtained as the raw data from which the desired particle size distribution is determined.

Sampling methodology: PIDS samplers were employed to measure workers’ exposures in the primary lead smelter at the four work areas referred to. In preparing each instrument prior to sampling, the PIDS was disassembled and all the internal surfaces coated with silicone grease (Cling-Surface, Orchard Park, NY) in order to reduce the occurrence of particle bounce within the instrument which, if uncontrolled, would lead to penetration of large particles beyond stages with which they first make contact, resulting in particle size distributions which are erroneously biased towards small particles. After such preparation, before each sampling run, the flowrate was set at the prescribed 2 Lpm. After sampling, the PIDS was disassembled again, and the particulate material at each of upper nine stages (i.e., all except the backing filter) was recovered by wiping the collection surfaces using cotton balls impregnated with isopropyl alcohol. Here, at least two, and usually as many as five, wipes were taken from each stage to assure that virtually all deposited material was included in the analytical sample. The material thus recovered from each stage was clearly labelled, packed and sent for analysis at an AIHA-accredited laboratory for elemental lead by atomic absorption spectrophotometry (AAS).

Sampling strategy

PIDS was deployed in its mode of intended use, as a personal sampler, to investigate the lead aerosol exposures of workers at the four process areas mentioned—that is, the ore storage area, the sinter plant, the blast furnace area and the dressing area. In each of these areas, workers were considered to be part of a similarly exposed group (SEG). Workers were selected in order to obtain at least one PIDS sample for each job class in these four process areas.

DATA ANALYSIS

Determination of particle size distributions

Particle size distributions were derived from the raw PIDS data using a new inversion routine developed specifically for this instrument (Ramachandran et al., 1996a and Ramachandran et al., 1996b). This is especially important for the PIDS because the deposition characteristic of the entry stage as a function of particle aerodynamic diameter, \(d_{ae}\), is very broad (see Gibson et al., 1987) so that the direct determination of particle size distribution becomes very ‘ill-posed’. This derives from the fact that particles of a given size may be found on more than one stage of the instrument, so that an infinite number of solutions are mathematically possible. The purpose, therefore, of the inversion routine is to find the ‘best’ solution, and several approaches have been proposed in recent years (e.g., as reviewed by Cooper, 1993). The approach taken here was to reconstruct a continuous particle size distribution from a set of \(N\) discrete measurements by solving a set of Fredholm integral equations of the first kind. The relationship between the discrete set of mass measurements \(\{m_k\}\) (where \(k = 1, 2, \ldots, N\)) and the unknown function \(f(d_{ae})\) is given by

\[
m_k = \int_a^b f(d_{ae}) \, dd_{ae} + \epsilon_k; \quad k = 1, 2, \ldots, N \tag{5}
\]

where \(f(d_{ae})\) is the particle aerodynamic size distribution (in terms of mass concentration) for the total aerosol in the ambient air, \(K_\epsilon\) is the kernel function for the \(k^\text{th}\) instrument stage, \(a\) and \(b\) define the range within which the particle size distribution lies, and \(\epsilon_k\) is the measurement error in that channel. \(K_\epsilon\) describes the instrument response, and is available...
from design and experimental calibration data (Gibson et al., 1987). The approach uses a weighted least-squares optimisation with zeroth-order regularisation to fit multi-modal distribution functions to PIDS raw data, having employed an intermediate step to make first estimates of the parameters of interest and so provide an appropriate starting point for the optimisation routine. The optimisation routine itself minimises the expression

\[ \sum_{i=1}^{N} \left( \frac{m_i - \int_{0}^{\infty} K_i(d_{w}) \cdot f(d_{w})dd_{w}}{E(t_i)} \right)^2 - N \]  

where \( N \) is the number of mass measurements, and \( E(t_i) \) is the expected value of the measurement error. Thus, the optimisation procedure finds a solution for the particle size distribution of the total aerosol in the ambient air that satisfies the measurements to just within experimental error. For aerosols encountered in the industrial workplace environment, it is reasonable from previous experience to assume that the basic form of the distribution \( f(d_{w}) \) is multi-modal log-normal. It was considered unrealistic to seek to resolve more than two such modes from as few as 10 discrete raw data points. Therefore the routine was designed to seek a solution for the bi-modal log-normal distribution, which may be described by five parameters. These are the median particle aerodynamic diameters (\( MMAD_1 \) and \( MMAD_2 \)) and the geometric standard deviations of the two modes (\( \sigma_1 \) and \( \sigma_2 \)), and the relative weighting of the masses between the two modes (\( \beta_1 \) and \( \beta_2 \), where \( \beta_1 + \beta_2 = 1 \)). It should be noted here that such bi-modality does not presume that the aerosol is necessarily bi-modal in the physical sense, but rather that the bi-modal combination is the best mathematical description of the observed data. It should also be noted that, since the value of \( d_{w} \) corresponding to 50% collection efficiency on the first impaction stage of the PIDS is as low as about 20 \( \mu m \), while it is expected that particles at least as large as 100 \( \mu m \) may enter the instrument, prediction of the shape of the particle size distribution will be less accurate for the larger sizes than for the smaller ones. Simply put, there is very little information available upon which to base the estimation of particle size distribution for \( d_{w} \) above about 20 \( \mu m \) — all we have is the broad deposition characteristic of the entry stage (i.e., much broader than the impaction stages of the impactor stages themselves) and one single number for the particulate mass which has deposited in that entry stage. So, in this range we cannot infer the specific shape of the size distribution, or therefore suggest for example whether or not an extra coarse mode might exist. All that can be said is whether there is a higher or lower proportion of coarser particles. However, in most practical uses of the PIDS, it is unlikely that the exact shape of the particle size distribution in the range above 20 \( \mu m \) will be important. We might possibly be interested if, for some reason, we needed to use the particle size distribution data to say something about the regional deposition of particles within the nasal passages. But, in the more common area of interest relating to penetration to and deposition in the lung, the limitation alluded to will have virtually no impact on the determination of the particle size distribution of, and the mass concentration for, the thoracic and respirable fractions.

The method described has been incorporated into a Microsoft EXCEL spreadsheet from which, using a modern personal computer, a given set of PIDS raw data can be processed in a few minutes.

**Determination of indices of health-related exposure**

The masses sampled in the three health-related fractions were obtained from direct application of the results of the optimisation routine together with Equation (4). Again, this is carried out within the EXCEL spreadsheet. Simulations have shown that the recovery of such fractions in this way is very accurate and robust over most of the ranges of particle size distribution parameters encountered in workers’ aerosol exposures (Ramachandran and Vincent, 1997).

**Statistical considerations**

It was desirable to develop a mechanism for treating individual raw data which reflected concentrations too low to be measured accurately or where sampling error is likely to have occurred. First, those PIDS samples for which more than four of the ten individual samples were found, upon quantitation, to be below the limit of detection were removed from further consideration. Further, those PIDS samples for which the masses observed on adjacent analytical stages were subsequently found to differ by a factor of 50 or more were also removed. This is justified based on our knowledge of observed workplace particle size distributions, which suggests that such sharp differences are highly unlikely to occur.

A primary objective in the research was to make comparisons of the various measures of particle size distribution obtained from the PIDS results from process to process within the smelter. These comparisons were performed by analysis-of-variance (ANOVA) methods and Tukey’s pairwise comparison test (Kleinbaum et al., 1988). The initial ANOVA model included terms for all possible interactions, with those terms found not to be significant dropped as the analysis proceeded.

**RESULTS**

Forty-six PIDS samples were obtained, distributed at locations within the four process areas identified, and the raw data they provided were analysed using the inversion method referred to above, and described and validated in full elsewhere (Ramachandran et al., 1996a. 1996b: Ramachandran and Vincent, 1997). Typical particle size distributions from samples taken
Fig. 1. Particle aerodynamic size distributions obtained from two typical PIDS samples: (a) at the sinter plant, and (b) at the blast furnace. Also shown are the raw data for each sample, expressed in terms of the mass concentration of lead collected at each of the 10 stages of the PIDS (i.e., the mass collected divided by the air volume sampled). Here the stage 'cut' points represent the 50% probability of deposition for each impactor stage 1 to 8.

in the sinter plant and blast furnace areas respectively are shown in Fig. 1. Here, as already mentioned, \( f(d_m) \) is expressed in terms of the mass concentration of total airborne lead, from which—as shown in the graphs—the corresponding particle size distributions of the various health-related fractions can also be determined. The raw data from which the curves were obtained are also shown. Here it is important to reiterate that detailed knowledge of the shape of the particle size distribution is relatively weak for particles in the range above about \( d_m = 20 \mu m \). So, in Fig. 1a for example, caution should be exercised in attempting to 'over-interpret' the very obvious coarse mode. All that can be stated with any confidence is the fact that this curve reflects the presence of a large proportion of the mass of lead-containing particulate in the larger particle size range.

The full results for the particle size distributions for total aerosol at those locations, \( f(d_m) \), are summarised in Table 1, in terms of \( MMAD_1, \sigma_1, MMAD_2, \sigma_2, \beta_1 \) and \( \beta_2 \). Here the subscript '1' refers to the coarser component. Average values and ranges for these coefficients are shown, and it is seen that they all range widely.

Table 2 summarises the results, derived from the samples described in Table 1, of the percentages (with
Table 1. Mean values for the parameters of the derived two-component log-normal distributions for lead-containing aerosol derived from PIDS sampling results for each of the four worksites studied (ranges in parentheses). The subscript 1 identifies the coarser of the two components.

<table>
<thead>
<tr>
<th>Worksite</th>
<th>n</th>
<th>$\beta_1$ (0.36-0.99)</th>
<th>MMAD$_1$ (18.8-84.3)</th>
<th>$\sigma_1$ (1.1-9.9)</th>
<th>$\beta_2$ (0.01-0.64)</th>
<th>MMAD$_2$ (0.8-50.6)</th>
<th>$\sigma_2$ (1.1-4.4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore storage/mill</td>
<td>10</td>
<td>0.80</td>
<td>41.6</td>
<td>3.4</td>
<td>0.20</td>
<td>17.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Sinter plant</td>
<td>16</td>
<td>0.61</td>
<td>60.7</td>
<td>2.2</td>
<td>0.39</td>
<td>26.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Blast furnace</td>
<td>12</td>
<td>0.66</td>
<td>67.3</td>
<td>5.2</td>
<td>0.34</td>
<td>19.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Drossing area</td>
<td>8</td>
<td>0.73</td>
<td>71.4</td>
<td>2.8</td>
<td>0.27</td>
<td>21.7</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 2. Median and mean values (in parentheses) for five indices of particle size expressed in terms of the ACGIH/ISO/CEN particle size-selective criteria, for each of the four worksites studied.

<table>
<thead>
<tr>
<th>Worksite</th>
<th>n</th>
<th>% inhalable (59.5)</th>
<th>% thoracic (16.8)</th>
<th>% respirable (6.1)</th>
<th>% thoracic/inhalable</th>
<th>% respirable/inhalable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore storage/mill</td>
<td>10</td>
<td>59.8</td>
<td>15.7</td>
<td>5.1</td>
<td>25.6</td>
<td>8.5</td>
</tr>
<tr>
<td>Sinter plant</td>
<td>16</td>
<td>53.6</td>
<td>6.3</td>
<td>1.6</td>
<td>11.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Blast furnace</td>
<td>12</td>
<td>57.9</td>
<td>19.5</td>
<td>12.4</td>
<td>33.6</td>
<td>20.8</td>
</tr>
<tr>
<td>Drossing area</td>
<td>8</td>
<td>53.8</td>
<td>7.7</td>
<td>2.7</td>
<td>14.3</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Table 3. Results of ANOVA and pairwise comparison procedures for particle size indices obtained from analysis of the raw PIDS data. Note that only those pairs for which statistically significant differences were observed are shown.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variable</th>
<th>ANOVA F-ratio</th>
<th>ANOVA p-value</th>
<th>Tukey significant differences (z = 0.05)</th>
<th>Tukey p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>% thoracic</td>
<td>Worksite</td>
<td>2.943</td>
<td>0.044</td>
<td>Sinter plant</td>
<td>0.030</td>
</tr>
<tr>
<td>% respirable</td>
<td>Worksite</td>
<td>2.876</td>
<td>0.047</td>
<td>Sinter plant</td>
<td>0.041</td>
</tr>
<tr>
<td>% thoracic inhalable</td>
<td>Worksite</td>
<td>3.399</td>
<td>0.026</td>
<td>Sinter plant</td>
<td>0.018</td>
</tr>
<tr>
<td>% respirable inhalable</td>
<td>Worksite</td>
<td>3.316</td>
<td>0.029</td>
<td>Sinter plant</td>
<td>0.024</td>
</tr>
</tbody>
</table>

DISCUSSION

Interpretation of the results of this study is made in the light of what is known about the performance of the PIDS. As indicated earlier, this instrument was found to aspirate the inhalable fraction for particles with $d_{ae}$ up to at least 30 $\mu$m (Gibson et al., 1987). However it needs to be stated that evidence has recently emerged which suggests the possibility that, in fact, the PIDS oversamples with respect to the inhalable fraction (Liden and Melin, 1996), perhaps by oversampling very large particles (i.e.. with $d_m > 30 \mu$m). In the context of the current research, although this may bias somewhat the particle size distributions towards generally larger particles sizes.
and so in turn influence the numerical values of quantities like those given in Table 2, the broad findings of the research are expected to be unaltered. Meanwhile the tendency suggested by Lidén and Melin has not yet been confirmed, and deserves further study.

The results of this research provide a clear indication of the large amount of exposure-related information which may be extracted from a single sample, using an instrument like the PIDS. There are, however, a number of considerations to be borne in mind when interpreting these results. First, Table 1 shows MMAD-values which are unexpectedly large compared to previous occupational hygiene experience even for aerosols expected to be relatively coarse (e.g., Bullock and Laird, 1994 for dust in the wood and paper products industry). This is true even notwithstanding the qualification expressed in the preceding paragraph. But this observation is not surprising since, in general, the particle size distribution provided by PIDS is based on raw data which reflect the whole catch of particulate material entering the instrument. By contrast, for other cascade impactor-based instruments, the mass of aerosol deposited in the entry section is not explicitly included in the analysis. In addition, knowledge of the aspirated fraction (in relation to total aerosol) is not known for those other cascade impactors, but is likely—based on studies of the aspiration efficiencies of other types of aerosol sampler (Vincent, 1989 and Vincent, 1995)—to be less for larger particles than for the PIDS.

Table 2 shows clearly that the ambient aerosol is coarser in the sinter plant than in the blast furnace area. That the difference is statistically significant is borne out in Table 3. This is relevant to the interpretation of results of extensive sampler intercomparison studies for the same worksites which are being reported separately (Spear et al., 1997). In this regard, Table 4 contains a summary of the results of intersampler comparisons that were made in which side-by-side measurements were made of exposure to so-called 'total' aerosol using the widely-employed 37 mm plastic cassette (E_{37}) and to inhalable aerosol using the Institute of Occupational Medicine (IOM) personal inhalable aerosol sampler (E_{IOM}). Wind tunnel studies have previously shown that the IOM sampler, whose performance closely matches the inhalability curve in Equation (1) for particles with \( d_{50} \), up to as high as close to 100 \( \mu m \), is more efficient for collecting large particles than the 37 mm sampler (Mark et al., 1994; Kenny, 1995). So it is not surprising to see in Table 4 that the ratio, \( S = E_{IOM}/E_{37} \), obtained from weighted least-squares linear regression of the raw inter-sampler comparison data, is consistently greater than unity. This is what would be expected based on application of our understanding of the nature of the aspiration process to the samplers in question (e.g., Vincent, 1989 and Vincent, 1995; Tsai et al., 1996). Further, we would expect \( S \) to be greater for coarser aerosol, and this indeed is the case for the comparison between the sinter plant and blast furnace worksites where, as shown in Table 3, there are significant differences in particle size distribution which correlate strongly with the observed difference in \( S \). However, it must be said, the same trend is not found elsewhere where it might have been expected. For example, for the drossing area, which exhibits the smallest S-value, there is no real evidence that the aerosol there is finer than in the sinter plant (which has the largest S-value). But it is noted that the number of PIDS samples for the drossing area was less than for the other worksites.

**CONCLUSIONS**

This research has demonstrated that particle size distributions may differ significantly for workers' aerosol exposures at different worksites in the lead smelter studied. The primary tendency from the results supports the hypothesis that coarser aerosols are associated with larger values for the ratio \( S = E_{IOM}/E_{37} \) of exposures as measured using the IOM personal inhalable aerosol sampler (E_{IOM}) and the 37 mm sampler (E_{37}) respectively. Although there were some inconsistencies for data comparisons where fewer PIDS samples were collected, the hypothesis gains strong additional support from knowledge of the physics governing the performances of the samplers in question.

Such findings have important implications to practical occupational hygiene as the transition is made from occupational aerosol exposure limits (OELs) based on an ill-defined 'total' aerosol concept to new standards which reflect the particle size-selective nature of aerosol sampling and exposure (Werner et
al., 1996). Furthermore, this research has demonstrated the utility of the PIDS, and other such aerosol spectrometers, in the assessment of workplace aerosol exposures. Such measurement of particle size distributions in workers' aerosol exposures can be useful in the simultaneous assessment of exposure to inhalable, thoracic and respirable aerosol, and in turn to the modelling of the associated dose to the regions of the human respiratory tract.

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