**Case Study**

**Exposure to Lead and its Particles Size Distribution**

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**Key words:** Lead size distribution, Size-selective sampling, Small lead particle

It has been recognized that particle size is a primary determinant of the inhalation and deposition of particulate matter in the human respiratory tract. In this regard, most aerosols have dual Threshold Limit Values (TLV), such as total and respirable particulate mass, in order to consider the difference in absorption due to particle size¹. It is generally accepted that measurements of airborne lead, an aerosol that could have a diverse size distribution, are taken by means of total mass sampling without particle size selective criteria.

Although the Occupational Safety and Health Administration’s Permissible Exposure Limits (OSHA PEL), promulgated in 1978, have contributed to reductions of airborne lead concentrations since their adoption, workers’ exposure to lead in the workplace still remains a major occupational problem², ³. Froines et al. (1986) demonstrated that OSHA PEL did not adequately take into account the effects of the size distribution of the lead aerosol on the absorption of lead³. The OSHA model developed by Ashfold et al.⁴ was based on a theoretical particle size distribution of lead aerosols as predicted in lead-acid battery manufacturing.

Several previous studies had reported that the particle size distribution assumed in the OSHA model was likely to be incorrect for not only battery plants⁵ but also for primary smelter plants⁶, capacitors, and lead powder plants⁷. If the OSHA model was to be directly applied to the actual particle-size distributions, significantly lower levels of lead in the blood would be predicted for a given air lead exposure⁵, ⁶, ⁷, ⁸, ⁹.

It is known that fine lead particle fumes generated in high temperature operations are more easily absorbed into the body than coarse lead particles. Our previous work concluded that the contribution of respirable lead particles to lead absorption would be greater than that of PbA⁰.

The present study is designed to compare the size characteristics of lead particles generated in four major lead industries. Our ultimate aim is to suggest that measurement of the respirable fraction of lead is necessary. The specific objectives to obtain this were: 1) to evaluate the worker’s exposure to inhalable (PbI), thoracic (PbT), respirable (PbR) and fine lead particles smaller than 1 µm (Pb1µm), 2) to examine the difference between lead size fractions (PbI, PbT, PbR and Pb1µm) with respect to PbA by industry and 3) to compare the relationship between PbA and fractions of lead size (PbI, PbT, PbR and Pb1µm) in PbA by industry.

**Methods**

1) Industry selection

The secondary smelting, lead powder, and battery manufacturing industries were chosen for this study because workers’ exposure was known to be higher than in other industries¹⁰. In addition, the radiator manufacturing industry, in which lead size distribution has not been studied, was included because it has operations generating fine lead particles.

2) Air sampling and analysis

Not only operations and worker’s tasks, but also sampling and the analytical methods in these four industries were described in our previous study⁹.

3) Lead particle size distribution

One hundred-seventeen personal cascade impactor samples reported in a previous study were re-analyzed by focusing on the characterization of the lead particle size fraction by industry.

PbI, PbT, PbR and fine particle 1 ≤ µm (Pb1µm) fractions for each impactor stage size interval were estimated from the regression equation of respective mass collection efficiencies and AD as defined by ACGIH and Hind’s methods¹, ¹⁰.

Fine lead particles less than 1 ≤ µm (Pb1µm) in diameter are used in the OSHA model to determine the PEL for lead. It is assumed to be respirable and able to be deposited in the alveolar region with 37% deposition efficiency and 100% absorption efficiency⁹.

4) Statistical analysis

Size distribution and concentration of PbA, PbT and Pb1µm as reported in our previous paper⁹ as well as PbR and Pb1µm included in this study, were analyzed. Statistical testing was carried out with the standard version of SPSS. Scheftee’s pair-wise multiple comparison analysis was performed to identify industry groups with similar lead particle size characteristics. The t-test was performed to compare the average concentrations of PbR and Pb1µm by
industry. Simple linear regression analysis was constructed to compare the relationship between PbA and the fractions of lead size (PbI, PbT, PbR and Pb₁µ) by industry.

Results and Discussion

1) Exposure to Lead Concentration by Size (PbA, PbI, PbT, PbR and Pb₁µ)

In all industries, except for the radiator industry, worker’s exposure to concentrations of PbA as well as PbI and PbT greatly exceeded 50 µg/m³, the Korean PEL (Table 1). In particular, the secondary smelting industry showed that worker’s exposure to Pb₁µ was much higher than the PEL.

In the battery and lead powder manufacturing industry, worker’s exposure to PbI and PbT also considerably exceeded the PEL. Workers who ground lead plates in the battery plants were exposed to the highest level, 3467.4 µg/m³ of PbI, 1548.8 µg/m³ of PbT and 398.1 µg/m³ of PbR. Since the lead plate was pasted with a mixture composed of lead, lead oxide and sulfuric acid, most of the particles generated from the grinding operations such as polishing and buffing would be lead based, which caused exposure to high lead concentrations.

Secondary smelting, battery and pigment manufacturing were identified by OSHA as lead industries that had a significant proportion of workers exposed to airborne lead concentrations above 100 µg/m³, 11).

The geometric mean (GM) of PbA concentration (19.1 µg/m³) in the radiator plants was much lower than the PEL. Since lead particles in these plants were very fine with 1.3 µm of MMD, it could be estimated that PbA concentrations were low when compared to other industries. Therefore, workers who are exposed to fine lead particles could be excluded from monitoring and inspection 12).

2) Size fraction of lead particle

The fractions of each of Pb₁, Pb₁µ, Pb₂ and Pb₁µ relative to PbA in the battery and lead powder manufacturing industries were relatively small when compared with average fractions in the secondary smelting and radiator industry.
manufacturing industries (Fig 1). In particular, the average fractions of PbR and Pbµ were found to be much smaller.

The respirable fraction in the lead powder industry (18.9%) was a little higher than the 5–15% range that Tsai et al. reported for the same industry6). The average of 10.9% of PbR to PbA in battery plants was lower than the average of 34.6% (range; 28.1%–38.1%) as reported by Hwang et al., who investigated lead exposures of 96 lead battery assembly workers in Taiwan13).

Pbµ accounted for more than 50% of PbR in high temperature operations such as the secondary smelting and radiator manufacturing industries.

A T-test demonstrated that the concentrations of PbR and Pbµ were not significantly different in the secondary smelting (p=0.2720) and radiator manufacturing industries (p=0.2394). This result indicated that fine lead particles accounted for most of the PbR in high temperature operations such as the secondary smelting and radiator manufacturing industries.

Scheffe’s multiple comparison tests found that four industries were categorized into two groups with similar size characteristics, as to not only mass median diameter (MMD), but also the fractions of PbT, PbR, and Pbµ in PbA (Table 2).

One group included the secondary smelting and radiator manufacturing industries, which produced larger percentages of PbR, and Pbµ. The other group included the battery and lead powder manufacturing industries, which generated much coarser lead particles. Significant differences at the 95% confidence level were found between the two industry groups for five dependent variables related to lead particle size distribution. It would be very interesting to find the same classification for the 4 lead industries, in spite of the fact that MMD and size fractions indicate their own size characteristics.

Spear et al., found that the percentage of respirable fraction in terms of PbA in the blast furnace was 12.4% and in the other work sites was lower than 5.1%7). The authors demonstrated that lead particle size distribution (i.e. % thoracic, % respirable, % thoracic/inhalable and % respirable/inhalable) in the sinter plant and the blast furnace operations in the lead smelter was significantly different4).

These results demonstrated that the size characteristic of lead particles, such as MMD, and size fraction varied not only from operation to operation within the same industry, but also from industry to industry. Even in indoor environments of the seven households, the dust mass and lead mass distribution as functions of particle size differed significantly15).

Like the smelter and radiator manufacturing industries we studied, there are many high-risk activities associated with lead dust and fumes among bridge and structural steel workers: abrasive blasting, sanding, burning, and cutting or welding on steel structures coated with lead paint in construction16–20).

These operations typically produce fumes with very small particle sizes and are likely to lead to great alveolar particle deposition. Levin et al. suggested that to reduce exposures to lead in construction settings, blood lead determinations need to be utilized because current air monitoring does not offer sufficient information about exposure to lead16).

This suggestion is thought to be caused by the fact that workers’ exposure to fine lead particles might not be effectively monitored by the current PbA sampling without consideration of lead particle size.

3) Relationship between PbA and Lead size Fractions (PbR, PbT, Pbµ, and Pbµ) by industry

Lead size fractions such as PbR, PbT, Pbµ, and Pbµ were regressed against PbA respectively (Table 3). These relationships were all significant with high R² in the battery and lead powder industries. Thus, PbA significantly accounted for the variations in PbR, PbT, Pbµ, and Pbµ concentrations in the operations which generated coarse lead particles and similar size distribution. In particular, the variations in Pbµ concentrations significantly predicted by PbA were no less than 38% in the battery and 75% in the lead powder industries, respectively. These values were much higher than those of the other industries with fine lead particles.

Tsai et al. reported that the respirable lead concentration was correlated with the PbA concentration in battery and lead powder plants (R²=0.89)9). Hwang et al., who studied 96 personal exposures in the battery plant, found that the
The plot of respirable lead against PbA levels was significant with an $R^2$ of 0.98 for the regression line. These results were similar to our results indicated in Table 3. By contrast, in the other two industries that generated fine lead particles with distinctly different size distributions, PbA significantly reflected only the variations in PbI in the secondary smelting industry. In the radiator manufacturing industry, the variation in PbR, and Pb$_{1\mu}$ concentrations that were accounted for by PbA were 18% and 14%, which were much lower than those in the battery and lead powder industries. PbA significantly accounted for the variations in Pb$_1$ and Pb$_R$ concentrations in all industries.

These results indicated that controlling lead exposure according to total mass sampling methods will not necessarily provide adequate protection to workers exposed to lead with significant proportions of fine aerosol mass. Knowledge of the lead mass as a function of particle size could be critical in improving our ability

### Table 2. Results of ANOVA and multiple pair-wise comparison for lead particle characteristics

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variable</th>
<th>ANOVA F-ratio</th>
<th>ANOVA p-value</th>
<th>Similar industry group by Sheffe's significant differences ($\alpha=0.05$)</th>
<th>Sheffes p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMD</td>
<td>Industry</td>
<td>20.92</td>
<td>0.003</td>
<td>2ndary smelting Battery Lead powder</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb$_R$/PbA, %</td>
<td>Industry</td>
<td>11.23</td>
<td>0.010</td>
<td>2ndary smelting Battery Lead powder</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb$_T$/PbA, %</td>
<td>Industry</td>
<td>27.83</td>
<td>0.002</td>
<td>2ndary smelting Battery Lead powder</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb$_{1\mu}$/PbA, %</td>
<td>Industry</td>
<td>38.04</td>
<td>0.001</td>
<td>2ndary smelting Battery Lead powder</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb$_{1\mu}$/PbA, %</td>
<td>Industry</td>
<td>65.29</td>
<td>0.000</td>
<td>2ndary smelting Battery Lead powder</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Abbreviation: MMD=mass median diameter; Pb$_I$=Inhalable Particulate Mass; Pb$_T$=Thoracic Particulate Mass; Pb$_R$=Respirable Particulate Mass; Pb$_{1\mu}$=particles $\leq 1\ \mu$m.

### Table 3. Simple linear regression analysis for predicting Pb$_I$, Pb$_T$, Pb$_R$ and Pb$_{1\mu}$ concentration by industry (Independent variable=PbA)

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Coefficient ± SE</th>
<th>Intercept ± SE</th>
<th>$R^2$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary melting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb$_I$</td>
<td>0.76 ± 0.07</td>
<td>28.38 ± 53.45</td>
<td>0.96</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb$_T$</td>
<td>0.45 ± 0.18</td>
<td>65.65 ± 128.49</td>
<td>0.62</td>
<td>0.062</td>
</tr>
<tr>
<td>Pb$_R$</td>
<td>0.38 ± 0.19</td>
<td>42.51 ± 141.59</td>
<td>0.49</td>
<td>0.124</td>
</tr>
<tr>
<td>Pb$_{1\mu}$</td>
<td>0.37 ± 0.18</td>
<td>-61.18 ± 132.20</td>
<td>0.38</td>
<td>0.113</td>
</tr>
<tr>
<td>Battery</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb$_I$</td>
<td>0.69 ± 0.004</td>
<td>-4.04 ± 7.68</td>
<td>0.99</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb$_T$</td>
<td>0.28 ± 0.008</td>
<td>-1.12 ± 17.23</td>
<td>0.97</td>
<td>0.062</td>
</tr>
<tr>
<td>Pb$_R$</td>
<td>0.07 ± 0.003</td>
<td>6.43 ± 7.34</td>
<td>0.91</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb$_{1\mu}$</td>
<td>0.01 ± 0.002</td>
<td>13.9 ± 4.12</td>
<td>0.22</td>
<td>0.001</td>
</tr>
<tr>
<td>Radiator</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb$_I$</td>
<td>0.75 ± 0.049</td>
<td>2.62 ± 1.85</td>
<td>0.85</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb$_T$</td>
<td>0.38 ± 0.064</td>
<td>5.84 ± 2.40</td>
<td>0.46</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb$_R$</td>
<td>0.19 ± 0.063</td>
<td>6.84 ± 2.37</td>
<td>0.18</td>
<td>0.004</td>
</tr>
<tr>
<td>Pb$_{1\mu}$</td>
<td>0.13 ± 0.05</td>
<td>6.14 ± 1.76</td>
<td>0.14</td>
<td>0.007</td>
</tr>
<tr>
<td>Lead powder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb$_I$</td>
<td>0.76 ± 0.018</td>
<td>-17.51 ± 31.24</td>
<td>0.99</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb$_T$</td>
<td>0.44 ± 0.041</td>
<td>-24.45 ± 69.96</td>
<td>0.84</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb$_R$</td>
<td>0.19 ± 0.053</td>
<td>3.83 ± 91.46</td>
<td>0.37</td>
<td>0.001</td>
</tr>
<tr>
<td>Pb$_{1\mu}$</td>
<td>0.04 ± 0.005</td>
<td>-9.02 ± 7.87</td>
<td>0.75</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Abbreviation: Pb$_I$=Inhalable Particulate Mass; Pb$_T$=Thoracic Particulate Mass; Pb$_R$=Respirable Particulate Mass; Pb$_{1\mu}$=particles $\leq 1\ \mu$m.)
Conclusions

In summary, our study concluded that the fractions each of Pb<sub>1</sub>, Pb<sub>2</sub>, Pb<sub>3</sub>, and Pb<sub>4</sub> relative to PbA varied greatly among the four industries. In high temperature operations such as secondary smelting and radiator plants, the variations in fine lead particles such as Pb<sub>3</sub> and Pb<sub>4</sub> predicted by the PbA concentration were either not significant, or very low, while they were significant in other industries with coarse lead particles. These results indicated that workers’ exposure to fine lead particles might not be effectively monitored by the current PbA sampling without consideration of lead particle size. The importance of the measurement of respirable fractions should be discussed to protect workers from exposure to fine lead particles generated by numerous lead operations.

References

8) CJ Tsai, TS Shih and RN Sheu: Characteristics of lead aerosols in the different work environments. Am Ind Hyg Assoc J 58, 650–656 (1997)