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Effect of Aerosol Size on the Blood Lead Distribution of Industrial Workers

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The size distribution measurements of lead aerosol from a brass foundry and primary lead smelter are used to simulate blood lead distributions applying a pharmacokinetic model developed by Bernard. The predicted distribution of blood lead levels determined using the actual size distribution of lead aerosol are compared to the blood lead levels predicted according to the model assumptions adopted in setting the OSHA lead standard.

In the furnace area of the smelter and the pouring area of the foundry the predicted mean blood lead level is higher than that found in the standard whereas, in the smelter's sintering and mixing operation the blood lead level is less than that suggested by the standard. The data support the conclusion that size-selective sampling needs to be considered for incorporation into the OSHA lead standard.

Key words: lead, aerosol size distribution, blood lead, OSHA standard, respirable sampling

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INTRODUCTION

The health objective of the 1978 Occupational Safety and Health Administration (OSHA) standard for occupational exposure to lead is to limit workers' exposure to lead so that their blood lead (PbB) levels would not exceed 40 μg/100 g [OSHA, 1978a,b]. OSHA concluded that a standard that limited the concentration of airborne lead would be more satisfactory than a standard based on the monitoring of lead in blood. However, the available studies in the hearing record generally linked the adverse health effects associated with lead exposure to the blood lead value rather than air lead concentration. To determine the airborne lead concentration that was consistent with the PbB goal, OSHA needed to correlate air lead levels to resulting population-based blood lead distributions. The relationship between air lead and blood lead concentration can be established either through the use of empirical studies on the relationship between airborne lead concentration and blood lead levels or by identifying a model that predicts blood lead levels from environmental data. Given certain limitations in the empirical studies that limited their generalizability, OSHA elected to model the air lead–blood lead relationship [OSHA, 1978a].

The model adopted was a pharmacokinetic multicompartment mammillary model that had been originally proposed by Bernard [1977] and subsequently modified by

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Ashford et al [1977] of the MIT Center for Policy Alternatives (CPA) to include consideration of job tenure (see Methods for a discussion of job tenure) and particle size. CPA observed that previous empirical studies of air lead–blood lead correlations that use linear regression to correlate blood lead and total particulate exposure have assumed that all lead particulate exposure, no matter what the size distribution, is absorbed and metabolized with the same efficiency. To take particle size into consideration, CPA assumed that the first 12.5 $\mu g/m^3$ of lead in air is composed of small particles ($\leqslant$ 1 μm in diameter) and all additional air lead is present in large particles ($\geqslant$ 1 μm). The authors recognized this assumption (designated as assumption C) as ad hoc but considered it to be the best amalgam of theory and observation [Hattis, 1978; Ashford et al, 1977]. When the model with assumption C was applied to a permissible exposure limit (PEL) of 50 $\mu g/m^3$ it predicted that, at equilibrium, the population of blood lead levels in Table I would result.

This distribution came closest to approximating the desired health goal of $\leqslant$ 40 μg/100 g for all workers and was also considered to be feasible [OSHA, 1978a,b]. OSHA noted that the PbB distribution resulted in 70% of lead-exposed workers having blood lead levels below 40 μg/100 g and only 6% would be above 50 μg/100 g. The importance of the assumptions comprising assumption C to this prediction can thus be understood. Based on these considerations OSHA ultimately adopted 50 $\mu g/m^3$ as the PEL [OSHA, 1978a].

CPA's assumption C, however, has a limited experimental basis [Hattis, 1978], since there were very few studies in the scientific literature or the hearing record on the particle size distribution of aerosols encountered in the lead industry. There was general agreement that the particle size distribution would affect the concentration of lead in the blood of exposed workers, but the limited data available made it difficult to assess the magnitude of this effect quantitatively. OSHA relied on four studies in the hearing record (3 of which were unpublished) that appeared to support assumption C: an investigation that documented a strong inverse correlation between total exposure and small particulate exposure, a study of particle size distributions in a primary smelter, and a study of particle size distribution in a battery manufacturing plant, a pigment manufacturing plant, and a smelter [OSHA, 1978b; King et al, 1979]. These studies are difficult to interpret but provide some support for assumption C. Further investigation of the size distribution of airborne lead particulate in different work

TABLE I. Distribution of Blood Lead Concentrations Under Assumption C[a] Assuming a PEL of 50 $\mu g/m^3$

Blood lead concentration (μg/100 g)	Percent of exposed population
$\geqslant$60	0.5
51-60	5.5
41-50	23.3
$\leqslant$40	70.7

[a] Actual airborne lead concentration used for simulation is 25 $\mu g/m^3$. The simulation conditions used by CPA are given in Methods. The airborne lead concentration of 25 $\mu g/m^3$ represents the mean air lead level that needs to be maintained if no more than 5% of the air lead measurements are to be above 50 $\mu g/m^3$ assuming a log normal distribution of air lead levels [Hattis, 1978].

environments was necessary for 1) reconciling the theoretical input conditions to the model with empirical measures, 2) evaluating the likelihood that the stated objectives of the standard are being met, and 3) examining the health and cost implications of this assumption. In addition to these considerations, an evaluation of the actual size distribution is necessitated by the requirement that compliance with the PEL of 50 $\mu g/m^3$ be determined by total mass sampling. Although OSHA recognized the need to address aerosol size distribution in establishing the relationship between air blood levels, it did not incorporate similar considerations into its requirements for environmental monitoring and determination of compliance. Analysis of the variability of the size distribution of lead aerosol and its impact on the distribution of blood lead levels will enable a determination of whether particle size–selective sampling, such as respirable mass sampling, of the lead aerosol would be more appropriate than total mass sampling.

The research reported here investigates the particle size distribution of lead aerosols in a brass-bronze foundry and then combines these data with the results of a NIOSH study in a primary lead smelter to simulate the distributions of blood lead levels expected for each job site. The blood lead levels derived as a function of work site and aerosol size distribution are evaluated in the context of OSHA's predicted blood lead distribution when compliance with the 50 $\mu g/m^3$ PEL is achieved. The policy implications of our findings are discussed.

METHODS

Determination of Lead Aerosol Particle Size Distribution

Aerosol size distribution was determined for several operations in a primary lead smelter and a brass foundry. The measurements on the aerosol size distribution in a primary smelter were collected by the National Institute for Occupational Safety and Health (NIOSH) in 1982 and were provided to us for analysis [Lenhart and Campbell, 1984].

Sierra Series 290 Marple personal cascade impactors were used as area samplers in both studies. This impactor has a baffled inlet and multiple impactor stages followed by a built-in filter holder. Each stage has six radial slots with contoured inlets. The impactor cut points (particle size for 50% collection) range from 21 to 0.5 μm at a sampling flow rate of 2 L/min. Although the cut points for each stage are experimentally calibrated at a design flow rate of 2 L/min, sampling flow rates from 0.5 to 5 L/min may be used and cut points at these conditions can be determined by calculation. A flow rate of 3 L/min was used in the brass-bronze foundry measurements.

Cascade impactor measurements in the brass foundry were made with the cascade impactor using an oil-saturated Membrana 10-μm pore size Teflon membrane filters (Membrana Inc, Pleasanton, CA) as collection surfaces. The oil-saturated Membrana surfaces were prepared by cutting the filters to the desired dimensions including radial slits and adding about 0.1 ml of 20% oleic acid dissolved in cyclohexane to the membrane surface with a syringe. The filters were cut in our laboratory prior to visiting the foundry, and control filters were always used to ensure that there had been no contamination in the laboratory. This oil-saturated membrane impaction surface minimizes the problem of particle bounce during cascade impactor sampling [Hinds et al, 1985].

The brass foundry is fully automated. The brass alloy, containing 7% lead, is melted in an electric furnace, and the molten metal is poured automatically into molds passing the pouring station as a continuous train. The castings are shaken out on an enclosed vibrating transfer belt. Riser, flashing, and imperfections on the cast parts are removed by manual cutting and grinding operations. Cascade impactor samples were collected as area samples positioned as close as possible to the operation without interfering with operator movement. For sampling the pouring fume, impactors were positioned 1.5 m above the floor and 1.5 m away from the pouring station. For sampling the grinding dust, impactors were attached to a tripod positioned a distance of 1.5 m away from the grinding wheel. The height of the impactor in the grinding area was 1.25 m. The size distribution of lead particulates was determined by measuring the lead content of the particulate deposited on each stage of the impactor using a Varian 1475 atomic absorption spectrophotometer [Hinds et al, 1985].

Kinetic Model to Estimate Blood Lead

This study intends to compare the distribution of blood lead levels predicted by the Bernard model and assumption C with the blood lead distributions obtained using the same pharmacokinetic model but incorporating actual aerosol particle size distributions by job site. Since our intent was to compare assumption C with actual size distribution data, all other variables have been held constant. The five-compartment model (Fig. 1) developed by Bernard and the simulation conditions are the same as those used by CPA (see below).

The model is intended to describe the functional anatomy of the body lead burden and to provide an accurate representation of lead exchange to and from the slowly exchanging compartments and thus to predict more precisely the influence of

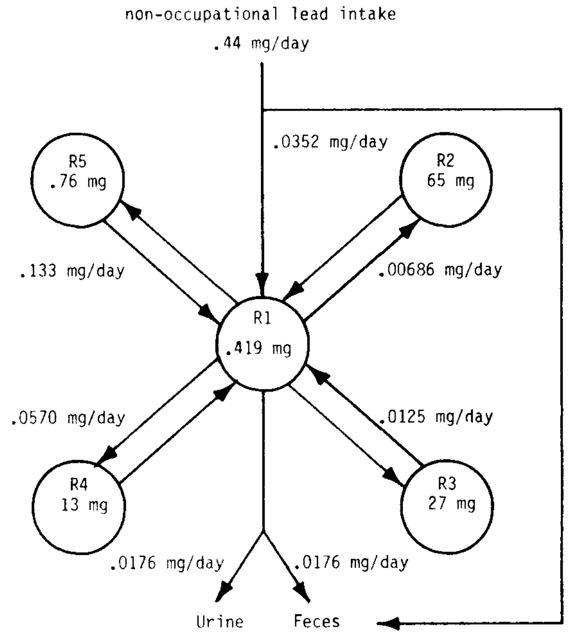

Fig. 1. Basic mammillary model of Bernard for lead in human.

skeletal lead stores on the blood lead level. In the Bernard model at steady state, compartment 1 (R1) contains approximately 1% of the body lead burden and comprises lead in blood. Compartment R2 represents primarily the lead in cortical bone, R3 the lead in trabecular bone, and R4 the bulk of slowly exchanging lead in soft tissue. The compartment R5 represents rapidly exchanging lead in soft tissue. Exchange of lead is postulated to occur between the central and peripheral compartments only. There is no exchange between the peripheral compartments. The advantage of this model over others with fewer compartments—eg, the Rabinowitz model [Rabinowitz et al, 1977]—is in the assumption that the rate of transfer of lead from bone varies depending on the type of bone. Bone biopsy experiments indicate that the uptake of isotopic lead is 2–3 times more rapid in spongy trabecular bone than in dense cortical bone [Hattis, 1978]. This suggests that a more rapid exchange of lead occurs in the trabecular bone. The model predicts that the exchange rates of the R3 and R4 compartments and the R1 compartment are sufficiently rapid that lead will be continually released from these compartments in amounts sufficient to elevate blood lead levels for prolonged periods after reduction of external lead exposure.

Before CPA could use the model to estimate blood lead arising as a result of occupational lead exposure, an assumption had to be made with respect to the efficiency of absorption from inhalation or ingestion of lead. Respiratory absorption of airborne lead is a function of site of deposition within the respiratory system, rate of dissolution, and rate of clearance. These depend on particle density, size, and shape as well as particle solubility and the rate and depth of respiration [National Academy of Sciences, 1972]. It has been estimated that for most common lead aerosols of mixed particle size between 30% and 50% of the total inhaled lead mass will be retained in the alveolar region and completely absorbed [Kehoe, 1961; Task Group on Lung Dynamics, 1966; National Academy of Sciences, 1972; Chamberlain et al, 1975; Ratcliffe, 1981]. The larger particles deposit in the nose, throat, and upper airways, where they are cleared to the gastrointestinal tract by ciliary action [Muir, 1972].

CPA assumed that all lead particulates not deposited and absorbed through the alveoli are ingested. The efficiency of absorption of ingested lead through the gastrointestinal tract was estimated to be 8%. They further assumed that 37% of all small particulate, which they defined as being $\leqslant 1\ \mu m$, is deposited with 100% absorption [National Academy of Sciences, 1972; Morrow et al, 1980]. The value of 37% was an amalgam of the empirical studies of Kehoe [1961], Mehani [1966], and Nozaki [1966]. Mehani did not measure the aerosol size, whereas Kehoe studied lead sesquioxide particulate generated by burning tetraethyl lead. Two size groups were used: the first had an average diameter of 0.05 μm with 90% between 0.02 and 0.09 μm, and the second a median diameter of 0.9 μm with 90% less than 2 μm. Particle size in Nozaki's study was carefully controlled and varied between 0.5 and 1 μm.

CPA assumed that there was no deposition in the alveolar region for particles greater than 1 μm in diameter. It is known, however, that there is deposition of particles with aerodynamic diameters in the range of 1–10 μm. CPA did not separately account for the 1- to 10-μm particulate, assuming instead that 1- to 10-μm particles are ingested and absorbed at 8% efficiency. In addition, although their use of the empirical data was appropriate, it should be understood that they did not adjust for the fact that the empirical data were limited by the size distributions selected by Kehoe and Nozaki. Therefore, the assumption that the efficiency of absorption is

37% for the lead particulate has a limited experimental basis. No attempt has been made to compare the results of these earlier experimental studies with those predicted by appropriate models, such as the ICRP model. In another study we shall report the results of calculations that address the issue of the deposition of lead particulate and analyze the impact on the resulting blood lead distribution. However, since the goal is to compare predicted blood concentrations using the size distributions of assumption C with that obtained using experimentally derived size distribution data, we have adopted the CPA assumption of 37% absorption of particulate less than 1 μm. Any inaccuracies in the percentage of particulate deposited will similarly affect both assumption C and the empirical data developed here. Although the absolute blood lead values will vary depending on assumptions made with respect to the efficiency of deposition, the relative blood lead distributions will remain the same.

The only CPA assumption modified in this study is assumption C. The modifications are that rather than assume that the percent of small aerosol decreases as the total lead concentration increases, we assume a constant size distribution for each operation throughout the range of air lead concentrations of interest, 50–200 $\mu g/m^3$. Additionally, no assumption is made regarding the form of the size distribution. Actual size distribution data are used in the blood lead simulations.

The occupational lead intake per day to the central pool (R1) of the model can be estimated by assuming the intake volume of air was 9.6 m^3 per 8-h workshift and specifying the initial blood lead level and job tenure distribution. The logical choice of the initial blood lead level would be the average blood lead level of people who have never been exposed occupationally to lead. The level selected by CPA and this study was 19 μg/100 g with a standard deviation of 9.5 μg/100 g.

The 1973 job tenure distribution for all lead industries was selected by CPA for simulation in order to generate a blood lead distribution that was reasonably accurate with respect to the actual distribution. The same job tenure distribution is used in this study. In 1973, 19.6% of the workers in the lead industries had worked for less than a year, 28.4% for 1–5 years, 18.9% for 5–10 years, 17.6% for 10–20 years, and 15.5% for more than 20 years. For ease of simulation, a weighted point average of each job tenure category was used: 0.95, 3.4, 9.0, 16.0, and 28.5 years, respectively. The blood lead levels estimated from the simulations for each operation for these five simulation periods were then multiplied by the corresponding percentages of workers in that job tenure category to obtain an estimate of the average blood lead levels. The blood lead simulation was carried out on a PDP-11 minicomputer using a computer code produced by CPA.

To summarize, the following simulation conditions were adopted for this study: 1) an initial blood lead level of 19 μg/100 g; 2) three air lead concentrations—50, 100, and 200 $\mu g/m^3$; 3) job tenure-weighted point average categories 0.95, 3.4, 9.0, 16.0, and 28.5 years; 4) air intake per workshift 9.6 m^3; 5) total absorption efficiency for "small" (< 1 μm) particles of 37%; 6) gastrointestinal absorption efficiency of 8%; and 7) normal distribution of blood lead with a standard deviation of 9.5 μg/100g [Hattis, 1978].

RESULTS AND DISCUSSION

Figure 2 shows the aerosol size distributions for selected operations in primary lead smelting and the brass foundry. In the primary smelter, the mixing operation in

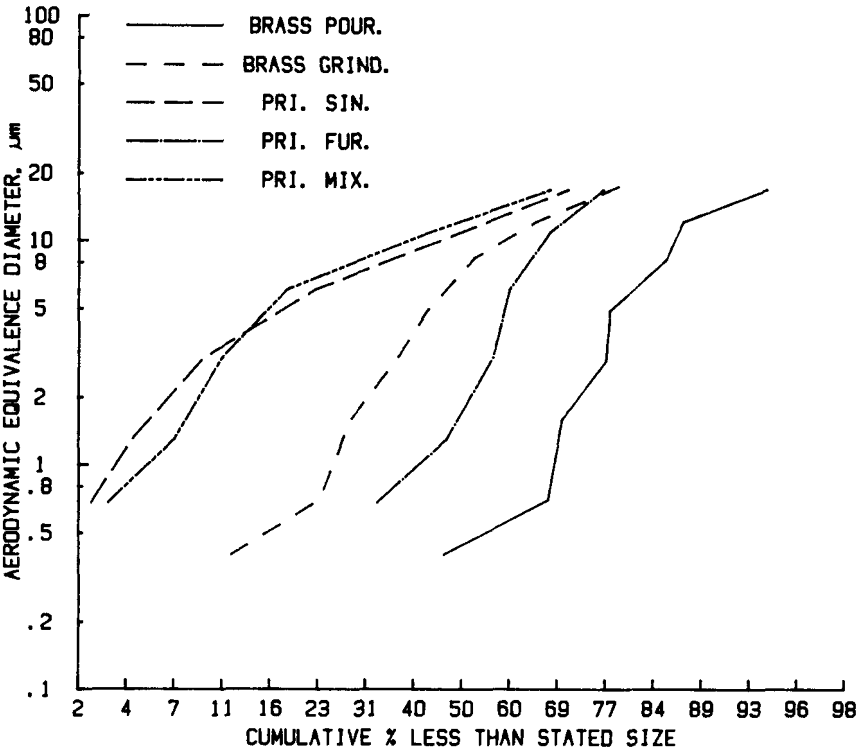

Fig. 2. Aerosol size distributions for specific job sites in a primary smelter and brass foundry.

TABLE II. Mass Median Diameters of Aerosols Generated Under Different Operations

Operations[a]	No. samples	MMD (µm)	GSD[b]	% ≤1 µm
Pri, Sin	7	11.0 ± 1.7	2.4 ± 0.7	3.6 ± 3.6
Pri, Mix	4	12.5 ± 1.2	2.4 ± 0.2	5.0 ± 2.9
Pri, Fur	8	3.3 ± 3.4	15.7 ± 4.8	41.8 ± 13.0
Brass, Pour	4	2.1 ± 1.2	10.3 ± 4.8	46.0 ± 16.3
Brass, Grind	3	7.2 ± 1.9	12.9 ± 2.7	25.0 ± 4.0

[a] Site of measurement.

[b] Geometric standard deviation.

Key: Pri, primary smelter; Sin, sinter plant; Mix, mixing room; Fur, furnace; Brass, brass foundry; Pour, pouring; Grind, grinding.

the sinter plant and the sintering operation itself generate aerosols of similar size distributions, whereas the lead aerosol generated in the smelter furnace area, the grinding operation in the brass foundry, and the pouring area of the foundry have distinctly different size distributions.

The mass median diameters (MMDs) of aerosols generated in different operations and industries and the percentages of particulate less than 1 µm are shown in Table II. There are large differences between the MMD determined in this study, with the mixing operation in primary smelting having the largest MMD of 12.5 µm and, at the other extreme, 2.1 µm in the foundry's brass pouring operation. The data collected here on size distribution, although taken from only two work sites, do illustrate the wide range found in actual work settings.

The results of the airborne lead-blood lead simulation using the Bernard model with the CPA simulation conditions and the data from the primary smelter and brass-bronze foundry are found in Table III. It is possible to categorize the information as to whether the simulation using measured size distributions predicts the blood lead distribution would be higher than, lower than, or the same as that obtained from assumption C. The distribution of blood lead concentrations predicted by the simulations using measured size distributions for the pouring operation in the brass foundry and the furnace area in the primary smelter exceeds that predicted by the model. The simulation that uses assumption C predicts that 50.3% of workers would have blood lead concentrations above 40 μg/100 g, the stated goal of the standard, and 16.8% above 50 μg/100 g, whereas our predicted proportion of blood lead values above 40 and 50 μg/100 g in the pouring area would be 78.0% and 45.4%, respectively. Similarly, in the furnace area 73.6% of the blood leads would exceed 40 μg/100 g, and 39.2% would exceed 50 μg/100 g.

In the furnace and pouring areas, use of assumption C yields predicted blood lead distributions that are significantly lower than those predicted using the actual particle size distribution. The higher blood lead distribution arises when actual size distribution is used as a result of greater deposition of lead in the alveolar region and subsequent absorption. The results of this distribution would be higher, but unexpected medical removal protection costs to an employer who believed that he was in compliance with the standard. Depending on the employer's compliance with the biological monitoring requirements of the standard, there is also the potential for the worker to be significantly underprotected.

TABLE III. Estimated Percentages of Workers Having Blood Lead Levels Exceeding 40, 50, and 60 μg/100 g to Two Assumed Permissible Exposure Levels

Locations[a]	PbA μg/m^3[b]	MPbB[c]	>40[d]	>50[d]	>60[d]
Pri, Sin	50	31.5	19.2	2.9	0.2
	100	44.1	65.0	29.2	6.6
Pri, Mix	50	32.1	21.0	3.4	0.2
	100	45.3	68.9	33.4	8.5
Pri, Fur	50	46.9	73.6	39.2	11.4
	100	74.9	99.3	95.2	83.8
Brass, Pour	50	48.6	78.0	45.4	15.2
	100	78.3	99.6	96.7	87.6
Brass, Grind	50	40.1	50.6	16.8	2.6
	100	61.3	95.1	81.2	55.3
Assumption C	50	40.0	50.3	16.8	2.6
	100	51.3	83.7	54.9	22.4

[a] Site of measurement.

Pri, primary smelter; Sin, sinter plant; Mix, mixing room; Fur, furnace; Brass, brass foundry; Pour, pouring; Grind, grinding.

[b] PbA (air lead concentration in μg/m^3).

[c] MPbB (mean blood lead level in μg/100 g).

[d] Percentages of working population having blood lead exceeding 40, 50, and 60 μg/100 g.

For the brass foundry grinding area, the simulation predicts that 16.8% of the workers will have blood lead levels greater than 50 μg/100 g because 25.0% of the lead aerosol in this area is less than 1 μm. In this case, the simulation predicts blood lead levels essentially the same as that predicted by assumption C. Although this size distribution would not have been anticipated given that grinding was the source of aerosol generation, we believe that there may have been mixing of lead aerosol from the pouring area with that from grinding resulting in a higher percentage of less than 1 μm particulate. The possibility that there was mixing of fume with aerosol from grinding is supported by the fact that both processes are in one open room with a high ceiling and are only about 12 m apart.

The distribution of blood lead levels would be less than that predicted using assumption C for the sintering operation and mixing room in the primary smelter. The percentage of workers with blood leads greater than 40 μg/100 g would be 19.2 and 21.0% in those areas, whereas the percentages with blood leads greater than 50 μg/100 g would be 2.9 an 3.4%, respectively. Under these circumstances the costs of medical removal protection would be lower than predicted using assumption C, and the overall protection of workers in these areas would be enhanced. This results from the mean blood lead being lower and the resulting distribution of blood leads for the workers at these sites being reduced over that predicted. If an employer installed controls at these sites to meet the 50 $\mu g/ms^3$ standard, he would provide protection to the employee population greater than that anticipated by the standard. Since the goal of the standard was a 40 μg/100 g blood lead for every worker, the fact that the standard underpredicted blood leads for sintering and mixing by not taking particle size distribution into account may simply result in greater protection. However, the complex problems of cost and feasibility cannot be ignored and need to be considered in the ultimate decision of how an overprediction of the blood lead distribution for a particular site should be addressed. A full discussion of the policy issues associated with this issue is beyond the scope of the paper, but further consideration is clearly required.

In circumstances where the air lead levels are very high, greater than 200 $\mu g/m^3$, the issues raised by this study are irrelevant, since the resulting blood lead levels are going to be excessive under any conditions. The issues raised are germane for conditions closer to the standard's PEL as evidenced by the values in the tables.

This investigation demonstrates that there are significant differences in the size distribution of the aerosol generated in different processes—eg, fume from a blast furnace or pouring area vs dust generated in the process of mixing and grinding. These principles have been discussed, if not extensively measured, in the lead industry for some time. Earlier data used in the development of the OSHA lead standard have been cited [OSHA, 1978b]. The results of three recent studies [Muskett and Caswell, 1980; Jacko and Overmeyer, 1981; Harrison, 1981] on the size distribution of lead aerosol are consistent with the data developed and used in this study; none of these studies, however, studied the impact of particle size distribution on blood lead distribution.

Our data suggest that, because of air currents in the plant, most workers have a mixed exposure that is predominantly from one source in the brass foundry. The mixing of airborne lead occurs as a result of different generating sources being in reasonably close proximity to one another in the brass foundry. We recognize that this may be the case in other industrial settings. The workplace size, configuration, and ventilation will also affect the mixing of particulate. Thus, it is problematical to predict the actual aerosol size distribution in a particular job setting from a knowledge of the type of particulate typically generated by a source.

These results confirm that the nature and size of the lead aerosol workers are exposed to will have significant implications for the distribution of blood lead values found in an exposed population. Although there has been widespread appreciation of the impact that different particle size distributions have on blood lead levels, there have been no attempts to determine how varying size distribution will quantitatively affect blood lead distribution. Use of the Bernard model in this study demonstrates that there are marked differences in the blood lead distribution over that predicted by the OSHA lead standard when actual size distributions are taken into consideration. It is apparent that controlling lead exposure according to the OSHA standard will not necessarily provide adequate protection to workers exposed to certain size distributions—eg, those with significant proportions of the aerosol mass below 1 μm. Conversely, there are work areas where the proportion of lead aerosol is greater than that predicted by assumption C, which suggests that the costs associated with compliance with the standard may exceed what is needed for adequate protection. The section of the OSHA lead standard on environmental monitoring and the agency's approach to compliance do not adequately take into account the effect of size distribution of the lead aerosol on the absorption of lead. An occupational standard for lead should not be based on an assessment of total lead but on one that incorporates the measurement of respirable lead fraction as well as the total dust concentration. The need to consider both measures is based on the recognition that there are two routes of absorption with markedly differing efficiencies.

The data on size distribution presented here represent preliminary findings. In addition to the measurement of size distribution, the effects of chemical composition and whether size distribution changes as a function of the airborne concentration of lead need to be further investigated. For the purposes of this report we have assumed the validity of the CPA adaptation of the Bernard model with the exception of the size distribution issue. Additional work is under way in our laboratory to evaluate the model in the hope of addressing some of the unresolved issues concerning its efficacy [Hattis, 1981; Landrigan et al, 1985] and will be reported elsewhere.

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