American Industrial Hygiene Association Journal

ISSN: 0002-8894 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/aiha20

Particle Bounce in a Personal Cascade Impactor: A Field Evaluation

WILLIAM C. HINDS , WEN-CHEN V. LIU & JOHN R. FROINES

Am. Ind. Hyg. Assoc. J. 46(9):517-523 (1985)

Particle Bounce in a Personal Cascade Impactor: A Field Evaluation

WILLIAM C. HINDS, WEN-CHEN V. LIU and JOHN R. FROINES
University of California Southern Occupational Health Center, Division of Environmental and Occupational Health Sciences, UCLA School of Public Health, Los Angeles, CA 90024

The collection characteristics of five types of substrates (collection surfaces) used in personal cascade impactors were evaluated for particle bounce in the laboratory with lead dioxide dust, and in the field with brass pouring fume and brass grinding dust. The substrates tested were uncoated stainless steel, silicon grease-coated stainless steel, oil-saturated Millipore membrane filter, oil-saturated Teflon membrane filter and oil-saturated sintered stainless steel. The use of coated and uncoated stainless steel plates to collect lead dioxide dust produced no difference in measured mass median diameter (MMD); however, with brass grinding dust, there was a 50% decrease in measured MMD when uncoated stainless steel substrates were used, as compared with coated stainless steel substrates. Oil-saturated Millipore membrane surfaces gave consistently lower MMDs than coated stainless steel surfaces. Coated and uncoated stainless steel gave similar MMDs when used to sample brass pouring fume. Oil-saturated Teflon® membrane and oil-saturated sintered metal, surfaces for which the collection efficiency is presumed to be independent of the particle loading, gave MMDs similar to those measured for grease-coated stainless steel. The implications of these comparisons are discussed. It is concluded that bounce characteristics are strongly dependent on aerosol material and the suitability of collection surfaces needs to be determined by field evaluation.

Introduction

The Occupational Safety and Health Administration (OSHA) promulgated a lead standard in 1978.[1] In setting the permissible exposure limit (PEL) for lead, OSHA made the assumption that the first 12.5 $\mu g/m^3$ of particulate encountered by a worker will be small (less than 1 μm) and will be absorbed with an efficiency of 37%; the remainder will be larger than one micrometer and absorbed with an efficiency of 8%.[2] This assumption is critical to estimating occupational lead intake and excretion. It is an important factor in estimating the percentage of workers who will have blood lead levels above 40 $\mu g/100\ g$ (OSHA's regulated limit) when exposed at the environmental standard of 50 $\mu g/m^3$ for 8 hours per day. To evaluate the assumption that the first 12.5 $\mu g/m^3$ consists of particles less than 1 μm requires personal sampling that yields accurate aerosol mass size distributions. The Sierra personal cascade impactor is well-suited to this application. One problem that interferes with accurate measurement of particle size is particle bounce, *i.e.*, the bouncing of a particle from one impactor stage to subsequent stages.[3] The present study is a field and laboratory evaluation of the Sierra personal cascade impactor to determine the effect of particle bounce as a function of impactor collection surface.

There have been several studies characterizing the size distribution of aerosols in the lead industry using cascade impactors.[4,5] In 1976, King *et al.* sampled lead aerosol in a battery plant, a pigment factory and a primary smelter with a Casella cascade impactor.[4] The National Institute for Occupational Safety and Health (NIOSH) collected aerosol size distribution information in a smelter with personal cascade impactors in 1982.[5] The particle bounce problem associated with the cascade impactors was not evaluated in either of these studies, however. Consequently, the effect of particle bounce on the accuracy of the size distributions given is unknown.

The problem of particle bounce derives from the fact that hard, solid particles with sufficient kinetic energy are likely to bounce from collection surfaces of impactors and be carried to subsequent stages, where their velocity is greater and bounce more likely. Because these bouncing particles are captured by subsequent stages or the back-up filter, the measured size distribution is distorted toward smaller sizes.

The existence of particle bounce in cascade impactors has been demonstrated in numerous studies both in the laboratory with laboratory generated dusts and in the general environment.[6-12] Rao and Whitby compared the collection characteristics of oil-coated and uncoated steel plates, glass fiber filters and Whatman filters using an Andersen cascade impactor with monodisperse polystyrene latex and methylene blue aerosol particles.[6] They found that uncoated steel substrates have collection efficiency curves that differ markedly from theoretical collection curves. In another study, Rao and Whitby found similar results with impactors of different design,[7] indicating that bounce may be an inherent problem with cascade impactors. Hering showed that bare glass surfaces have poor collection efficiency for solid particles.[8] Wesolowski *et al.* evaluated uncoated and coated Mylar surfaces in a Lungren cascade impactor with methylene blue particles and ambient aerosol and showed that a bare Mylar surface is only 5 to 9% as effective as an Apiezon coated Mylar surface in collecting non-hygroscopic particles.[9] Dzubay sampled ambient aerosol with an Andersen 2000 impactor using uncoated and grease-coated aluminum foil surfaces and found that the mass median diameters (MMDs) measured using uncoated aluminum

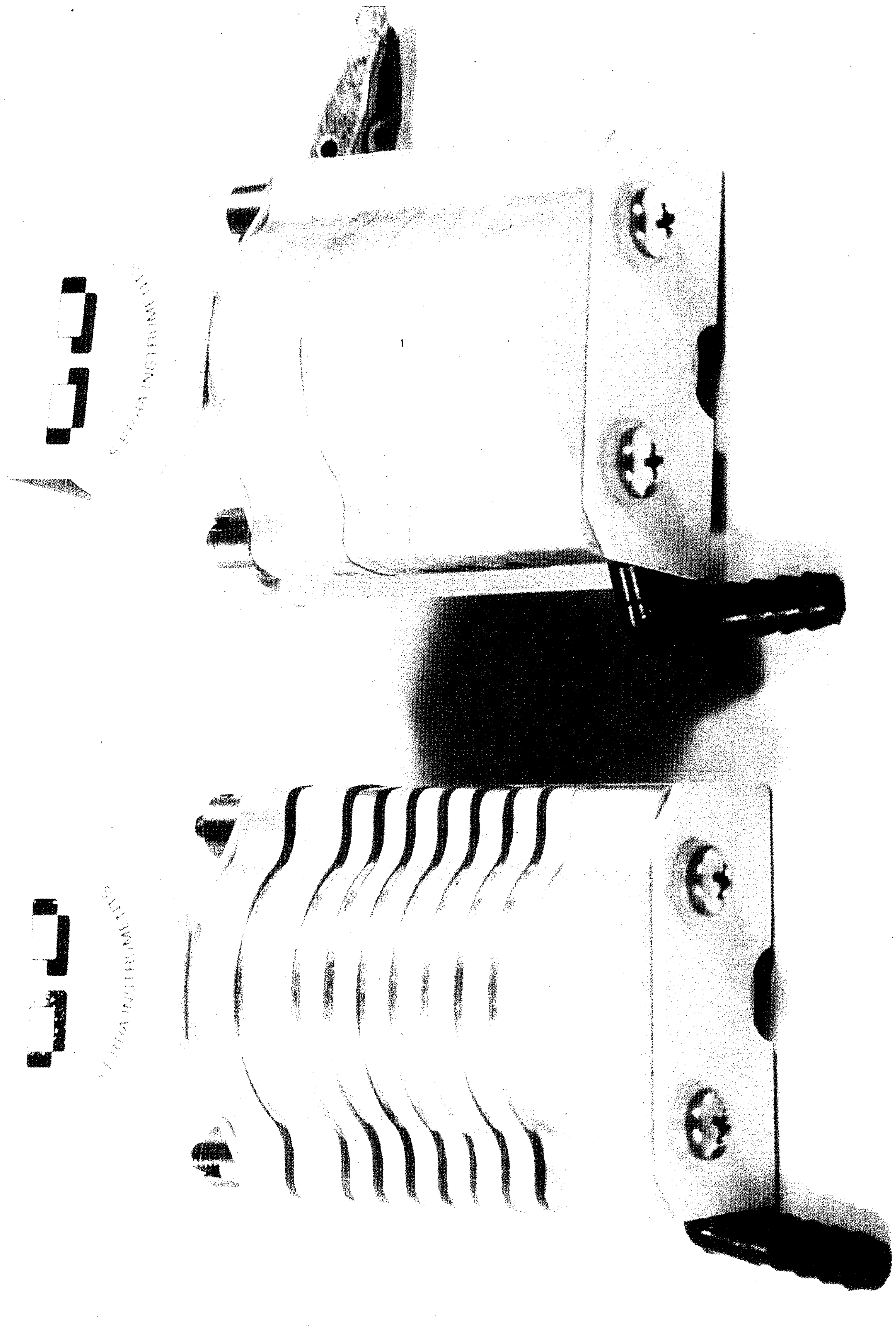

Figure 1 — Sierra 298 cascade impactor with and without the sintered metal discs and spacers.

TABLE I
Mass Median Diameter Ratios (MMD) Derived from Laboratory Test

Collection Surfaces Compared	MMD Ratio
Uncoated stainless steel	1.0
vs.	0.98
Coated stainless steel	1.0
Oiled Millipore membrane	1.02
vs.	1.03
Coated stainless steel	1.11

surfaces are lower than the values obtained using grease-coated surfaces by a factor ranging from 2 to 5.[10] Chan and Lawson evaluated uncoated and Vaseline-coated Mylar in both the Battelle and Mercer cascade impactors with gamma tagged diesel particles and showed a 41% decrease in the measured MMD when using uncoated Mylar.[11] Lawson collected ambient aerosol with coated and uncoated surfaces in the Battelle cascade impactor and showed that uncoated surfaces were only 25-45% as effective in particle retention as Apiezon L grease- and Vaseline-coated surfaces.[12] One can conclude from these studies that Apiezon, Vaseline, silicon grease or other adhesives with similar properties should be used in cascade impactor sampling, as had been suggested by May in 1945 in developing the first cascade impactor.[3]

Grease-coated surfaces have the limitation of being good for particle retention only when there is less than one monolayer of impacted particles. As particle loading increases on grease-coated impaction surfaces, the incoming particles no longer strike the grease layer, but impact on the already collected particulate matter and may bounce. For example, Lundgren observed a decreased collection efficiency when an adhesive coating of an impactor surface became loaded with a layer of either polystyrene or glass spheres.[13] Using silicon grease-coated stages in a modified Detron impactor, Reischl and John showed that the sticking efficiency decreased markedly as the surface became covered with potassium biphthalate particles.[14] To eliminate this loading effect, an oil reservoir impaction surface was developed, consisting of a sintered stainless steel plate saturated with a low viscosity oil. With this surface, particle bounce was eliminated, and the MMD was not affected by particle loading. Herring developed an oil reservoir surface using a Teflon membrane filter that gave the same collection efficiency as an oil-saturated sintered metal surface.[8] These newly developed oil reservoir surfaces have been tested only in laboratory settings using particles likely to bounce, such as polystyrene spheres or potassium biphthalate.

Based on the articles cited, we deemed it necessary to evaluate particle bounce with the Sierra cascade impactor since this was intended to be used to measure the size distribution of lead aerosol in industry. The objective of the present study was to evaluate grease-coated and oil reservoir surfaces for collection of lead particulate by the Sierra cascade impactor in a brass foundry.

Experimental Method

The Sierra Series 290 Marple personal cascade impactor was used in this study because of its compactness, light weight

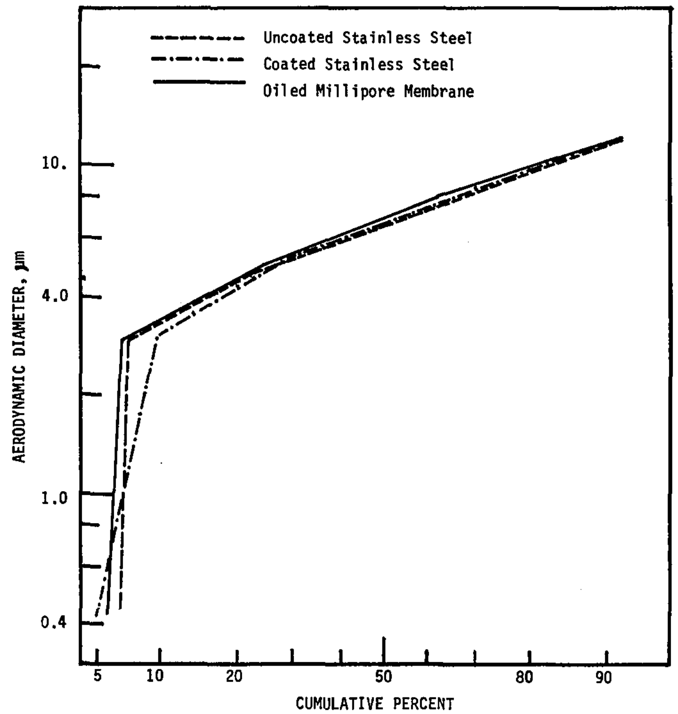

Figure 2 — Size distributions of laboratory generated lead dioxide dust estimated with CSS, USS and OMM.

and intended use as a personal sampling collection device in other related studies. This impactor consists of a baffled inlet and 8, 6 or 4 impactor stages followed by a built-in filter holder.[15,16] Each stage has six radial slots with beveled inlets. The impactor cut-points (particle size for 50% collection) range from 21 to 0.5 µm, for a sampling flow rate of 2 L/min. The cut-points for each stage have been experimentally calibrated at a design flow rate of 2 L/min. Sampling flow rates range from 0.5 to 5 L/min; however, the manufacturer points out that if the flow rate is too high, particle bounce and internal losses can be significant, and recommends flow rates from 1 to 3 L/min. Cut-points at other flow rates can be either calculated or read from the material provided by the manufacturer.[15]

In order to obtain a sufficient amount of lead for chemical analysis, the upper limit of the manufacturer's suggested flow rate range, 3 L/min, was chosen as the sampling flow rate. DuPont P-4000 constant flow pumps were used to provide a constant sampling flow. Simultaneous parallel samples were taken with as many as five impactors fitted with different collection surfaces. Plain, uncoated stainless steel (USS), grease-coated stainless steel (CSS), oil reservoir Millipore membrane filter (OMM), oil reservoir Teflon membrane filter (OTM) and oil reservoir sintered metal (OSM) were used as impaction surfaces. Plain stainless steel substrates were obtained from Andersen Inc. (Atlanta, Ga.). Grease-coated stainless steel substrates were prepared by spraying the plain stainless steel plate with silicon grease (viscosity = 23,600 centistoke at 38° C), obtained also from Andersen Inc. The solvent was allowed to evaporate overnight before the substrates were used. An 8 µm pore size Millipore filter (Millipore Inc. Bedford, MA) and a

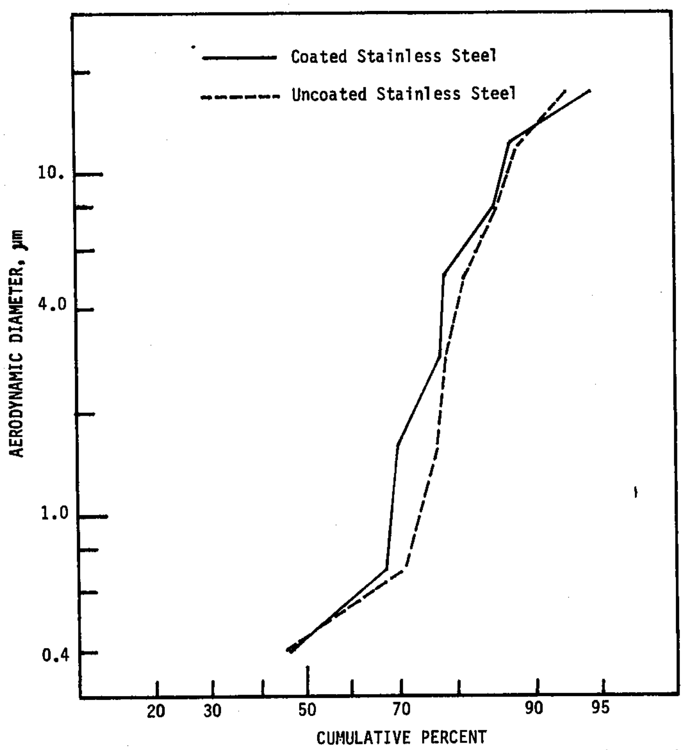

Figure 3 — Size distributions of brass pouring fume estimated with USS and CSS.

Membrana 10 μm pore size Teflon membrane filter (Membrana Inc., Pleasanton, Calif.) were used for membrane oil reservoir substrates. The Millipore and Membrana surfaces were prepared by cutting filters to the proper dimensions, including radial slits, and adding to the membrane surface with a syringe, approximately 0.1 mL of 20% oleic acid dissolved in cyclohexane.

Sintered metal discs, 10 μm grade and 0.15 cm thickness, were machined to match the shape of the manufacturer's substrates. Since each sintered metal disc adds 1.5 mm to the height of each stage, additional 1.5 mm ring spacers made of aluminum were placed between the stages and sealed with the original neoprene O-ring on the top and Dow Corning vacuum grease on the bottom. Figure 1 shows the Sierra 298 Marple cascade impactor with and without the sintered metal discs and spacers in place. The oil reservoir sintered metal surface is prepared by applying oleic acid with a transfer pipet onto the surface of the metal disc until it is fully saturated. Saturation is determined by observing the oil leaking through the opposite surface of the metal disc.

Three aerosols — lead dioxide, brass pouring fume and brass grinding dust — were used as test aerosols to evaluate the collection characteristics of the impaction surfaces. Lead dioxide dust was generated in the laboratory using a BGI Wright Dust Feeder (Waltham, Mass.). Lead dioxide powder was packed in the 37.4 mm diameter dust can at 9.7 MPa (1,400 psi) by a hydraulic press. The lead dioxide dust was carried by compressed air through a Kr-85 neutralizer to the mixing section of the sampling duct (19.5 cm diameter) and sampled by cascade impactors placed at the outlet end of the sampling duct. The sampling location was 1.9 m downstream from the mixing section.

The field evaluation of impaction surfaces was conducted in an automated brass foundry. The brass alloy used contained 7% lead. Raw materials are melted in an electric furnace and the molten metal is poured automatically into molds passing continuously through a pouring station. The castings are shaken out on an enclosed vibrating transfer belt. Risers, flashings and imperfections on the cast parts are removed by cutting and grinding operations. Parallel cascade impactor samples were collected as area samples from positions as close as possible to the operation without interfering with operator movement. For sampling the pouring fume, impactors were positioned on a beam which was 1.5 m above the ground and 1.5 m away from the pouring station. To sample the grinding dust, impactors were attached to a tripod positioned at about 1.5 m away from the grinding wheel. The relative humidity in the foundry was measured during each sampling session and ranged from 50% to 65%.

The lead content of the particulate deposited on each stage was determined using a Varian 1475 atomic absorption spectrophotometer. Two extraction methods were used in this study. One method was similar to the NIOSH suggested method,[16] which involves multiple digestions of the substrate with concentrated hot nitric acid. This method was used with uncoated and grease-coated steel substrates and Millipore and Membrana oil impregnated substrates. Other than the Millipore oil impregnated substrates, the ashing procedure as suggested in the NIOSH method was not used with these substrates. After the placement of known quantities of lead on the collection surfaces, lead recoveries were of the order of 90%. The second analytical method used employed multiple sonication of the impaction surface in nitric acid. It was used only with greased-coated stainless steel and sintered metal oil reservoir substrates. The recovery of lead was greater than 95%. The lead content on each cascade impactor stage was used to estimate the MMD by

TABLE II
Mass Median Diameter Ratios (MMD) Derived from Grinding Area Sampling Data

Collection Surfaces Compared	MMD Ratio
Uncoated stainless steel	0.5
vs.	0.72
Coated stainless steel	0.42
	0.33
	0.41
Oiled Millipore Membrane	0.69
vs.	0.50
Coated stainless steel	0.65
Oiled Membrana Membrane	0.92
vs.	0.85
Coated stainless steel	0.90
Oiled sintered metal	1.02
vs.	1.11
Coated stainless steel	0.82

plotting cumulative percentage vs. aerodynamic diameter on a logarithmic probability graph.

Results and Discussion

Laboratory data using a lead dioxide aerosol demonstrate that there is no difference between the MMDs estimated from the use of uncoated stainless, grease-coated stainless or oil reservoir Millipore membrane surfaces. The ratios of MMDs for uncoated stainless and oil-impregnated Millipore to that of the coated stainless steel are listed in Table I. The ratios, ranging from 0.98 to 1 for USS and from 1.02 to 1.11 for OMM, indicate that these surfaces work equally well in sampling of lead dioxide. The size distributions of a typical set of data are shown in Figure 2.

A similar trend was observed with data obtained from sampling the pouring fume. The USS and CSS collection surfaces gave the same MMDs. The size distributions from this set of samples are shown in Figure 3. MMDs of 0.4 to 0.5 μm are consistent with the aerosol size distributions expected from a pouring operation.

The aerosol bounce characteristics for samples collected in the laboratory, pouring and grinding areas were different. Five surfaces were tested. They were USS, CSS, OMM, OTM and OSM. The ratios of MMDs estimated from the use of USS, OMM, OTM and OSM to that from CSS are listed in Table II. CSS substrates yielded a higher average MMD than that obtained using USS and OMM substrates. Thus the use of USS would underestimate the MMD by an average of 53% for the grinding dust, and OMM would give an average 39% decrease in MMD. With OTM and OSM, the MMD ratios — 0.85 to 0.92 for OTM and 0.82 to 1.11 for OSM — indicate that for grinding dust the grease-coated surface works as well as the oil reservoir Teflon membrane surface and the oil reservoir sintered metal surface. Typical grinding dust size distributions obtained from USS, CSS, OMM, OTM and OSM are shown in Figures 4 and 5. Bounce occurs with brass grinding dusts on a bare metal surface. Grease-coating prevents bounce. Oil reservoir surfaces, except OMM, also reduce bounce, but they are equivalent to the CSS and give similar MMDs and size distributions. The sampling time intentionally was doubled for one group of samples resulting in a doubling of the loading. There was no effect of loading on the size distributions obtained using the three different surfaces. The number of monolayers of deposited particles on the CSS was estimated to range from less than one to more than 30 layers. Since the collection efficiencies of OTM and OSM have been shown to be independent of the loading,[8,14] it is reasonable to conclude that bounce did not occur when CSS was used for sampling brass grinding dust.

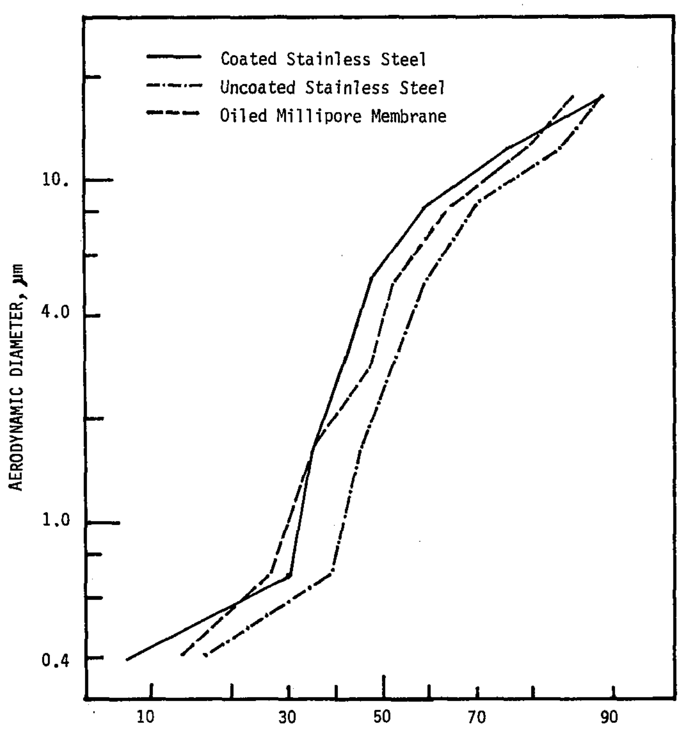

Figure 4 — Size distributions of brass grinding dust estimated with CSS, USS and OMM.

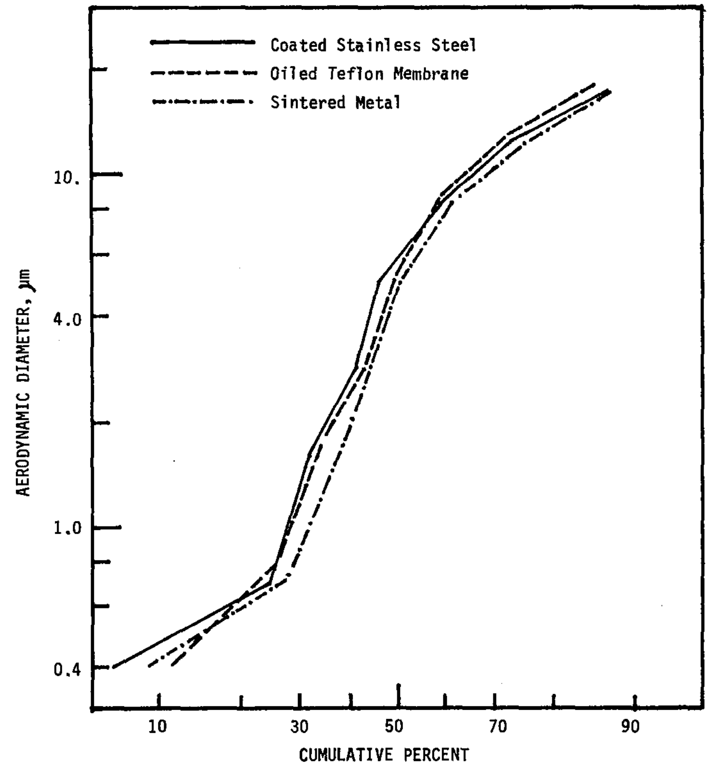

Figure 5 — Size distributions of brass grinding dust estimated with CSS, OTM and OSM.

The hardness of collected particles appears to be a significant factor influencing the collection characteristics of surfaces. Table III shows the hardness of the materials involved in this study.[17-19] Soft materials deform more readily on impact than hard material; consequently, it is expected that bouncing is minimized for soft materials. The softest aerosol sampled in this study was lead. Pouring fume may resemble lead in bounce characteristics because the fume is composed of particles formed from the condensation of lead, copper and zinc with the outer layers being primarily lead. This structure can be deduced from a knowledge of the vapor

TABLE III
Hardness of Elements Involved in Sampling

	Hardness	
Materials	**Mohs**	**Brinell**
Pb	0.3	4.3
PbO	2	
Pb_3O_4	2.5	
Cu	3.0	96
Stainless Steel (316)		150
Zn	2.5-3.0	31
Brass		55 - 65

pressures of the materials at the furnace temperature (1,177° C). The major component of the fume is zinc, with a small amount of lead and a minimal amount of copper. The copper vapor will condense first, followed by zinc and finally lead, which forms a soft outer coating. Thus condensation-formed "brass" particles would be less likely to bounce than the harder brass grinding dust.

With the grease-coated surfaces, the layer of grease absorbs the impaction energy and enhances adhesion to the surface. After a monolayer of particles have coated the surface the incoming particles will strike other brass particles rather than the grease surface. Bounce was not observed for heavy deposits of brass grinding dust on grease-coated stainless steel, suggesting that brass particles may not bounce on a brass collection surface. It is also possible that a component of the grease was drawn up by capillary force to coat the surface of adhered particles, thereby providing a "fresh" greased surface for incoming particles to adhere to. Grease migration has been observed microscopically in another study.[10] If this process is slow, compared to the rate of particle impaction, it is unlikely to be a significant factor in reducing bounce.

The size distributions obtained with OMM substrates were smaller than those for CSS, suggesting that bounce occurred for OMM. The oleic acid used may have changed the Millipore filter's physical properties to make it more elastic, but this possibility was not evaluated in this study. The ability of OMM, OTM and OSM to release the oleic acid was determined qualitatively by leaving a small disk of filter material on the surfaces of OMM, OTM and OSM and measuring their weight gain after one minute. It was determined that OSM releases oleic acid to the filter disk much faster than does OTM and OMM. This may account for OSM's bounce reducing property. However, the OTM is only slightly better than the OMM in releasing the oleic acid, and is thus unlikely to cause a significant difference in particle collection. Microscopically, the surface of OTM appears to be more "open" than OMM.[20] According to Daheneke's theory of particle adhesion, the bounce phenomenon is related to the interaction energy,[21] which is a function of particle-substrate surface deformation. Thus, there may be other important aspects of particle-substrate deformation of OMM and OTM not observed in this study. The unexpected bounce characteristic of OMM has been observed in other studies[22] and remains a topic for further study.

By the nature of this field study, it is impossible to distinguish between bounce of a whole particle and bounce of fragments of the original particle. For the relatively soft materials involved here, fracture seems unlikely except in the case of agglomerates. No evidence of particle fracture has been reported in several studies of impactor bounce.[6-8,15] Since the effect of fracture and its prevention is the same as for bounce, it matters little whether fracture occurs or not.

Conclusions

Whether or not a particle will bounce depends on the nature of the particle and the type of collection surface. When pouring fume from a brass foundry and laboratory generated lead dioxide dust were sampled, there was no bounce even with a bare metal surface. With foundry grinding dust there is particle bounce with uncoated surfaces. The use of laboratory generated dust to simulate an aerosol encountered in the field is an unreliable indicator of bounce unless physical and chemical properties can be matched exactly.

The use of a bare metal surface underestimated the MMD by 50% when sampling grinding dust. The use of silicon grease-coating on metal surface reduced bounce and yielded MMD and size distribution similar to those obtained with bounce-free oil reservoir Teflon membrane and sintered metal surfaces. We conclude that accurate estimates of the size distribution of lead aerosol in brass foundries may be determined using grease-coated impaction surfaces.

Although limited to brass foundry generated aerosols, the results presented here identify the apparent lack of bounce of relatively soft solid particles and serve to underscore the need for field evaluation of impaction surfaces.

Acknowledgements

This project was supported in part by USPHS/NIOSH Grant Number R03 OH02044-01, the University of California Southern Occupational Health Center, and the Foundation for Advancements in Science and Education award number P850104.

References

1. **Occupational Safety and Health Administration (OSHA):** Occupational Exposure to Lead, Attachments to the Preamble for the Final Standard — II. *Federal Register 43*:225 (21 Nov. 1978) 54353-54616.
2. **Ashford, N.A., W. Mendez and D. Hattis:** *Analysis of Available Evidence on Blood Lead-Air Lead Relationships Relevant to the Selection of a Permissible Exposure Limit for Lead in Air.* Center for Policy Alternatives, CPA-78-13. Massachusetts Institute of Technology, Cambridge, Mass. (1978). pp. 4-1 to 4-6.
3. **May, K.R.:** The Cascade Impactor: An Instrument for Sampling Coarse Aerosols. *J. Sci. Instrum. 22*:187-195 (1945).
4. **King, E., A. Conchie, D. Hiett and B. Milligan:** Industrial Lead Absorption. *Ann. Occup. Hyg. 22*:213-239 (1979).
5. **Lenhart, S.:** Telephone conversation with author, March 1983.
6. **Rao, A.K. and K.T. Whitby:** Non-ideal Collection Character-

istics of Inertial Impactors—II. Cascade Impactors. *J. Aerosol Sci.* 9:87-100 (1978).
7. **Rao, A.K. and K.T. Whitby:** Non-ideal Collection Characteristics of Inertial Impactors and Solid Particles. *J. Aerosol Sci.* 9:77-86 (1978).
8. **Hering, S.V.:** Developments in Bounce Free Impaction Surfaces, Draft Final Report, Chemical Engineering. University of California, Los Angeles, CA (1983).
9. **Wesolowski, J.J., W. John, W. Devor, T.A. Cahill, P.J. Feeney, G. Wolfe and R. Flocchini:** Collection Surfaces of Cascade Impactors. In *X-ray Fluorescence Analysis of Environmental Samples.* T.G. Dzubay, ed. Ann Arbor Science, Ann Arbor, MI (1980).
10. **Dzubay, T.G., L.E. Hines and R.K. Stevens:** Particle Bounce Errors in Cascade Impactor. *Atmos. Environ.* 10:229-234 (1976).
11. **Chan, T.L. and D.R. Lawson:** Characteristics of Cascade Impactors in Size Determination of Diesel Particles. *Atmos. Environ.* 15:1273-1279 (1981).
12. **Lawson, D.R.:** Impaction Surface Coatings Intercomparison and Measurements with Cascade Impactors. *Atmos. Environ.* 14:195-199 (1980).
13. **Lungren, D.A.:** An Aerosol Sampler for Determination of Particle Concentration as a Function of Size and Time. *J. Air Pollut. Control Assoc.* 17:225-229 (1967).
14. **Reischl, G.P. and W. John:** The Collection Efficiency of Impaction Surfaces: A New Impaction Surface. *Staub Reinhalt. Luft* 38:55 (1978).
15. **Sierra Instruments Inc.:** Series 290 Marple Personal Cascade Impactors Instruction Manual. Carmel Valley, Calif.
16. **National Institute for Occupational Safety and Health:** *NIOSH Manual of Analytical Methods.* 2nd ed., Vol. 3. pp. 1-7 (Method. S-341). Washington, D.C. (1977).
17. **Everhart, J.L., W.E. Lindlief, J. Kanegis, P.G. Weissler and F. Siegel:** *Mechanical Properties of Metals and Alloys.* pp. 74-393. United States Department of Commerce, National Bureau of Standards. U.S. Govt. Printing Office: Washington, D.C. (December 1943).
18. **Lyman, T., ed.:** *Metals Handbook.* American Society for Metals, Cleveland, Ohio (1961).
19. **Samsonov, G.V.:** *Handbook of Hardness Data.* U.S. Department of Commerce, National Technical Information Service, Springfield, Va. (1971).
20. **Liu, B.Y.H., Y.H. Pui and K.L. Rubow:** Characteristic of Air Sampling Filter Media in Aerosols. In *Mining and Industrial Work Environment.* pp. 989-1038. Ann Arbor Science, Ann Arbor, Mich. (1983).
21. **Dahneke, B.:** The Capture of Aerosol Particles by Surfaces. *J. Colloid Interface Sci.* 37:342-353 (1971).
22. **Herring, S.:** Telephone conversations with author, March 1983.

2 November 1984; Revised 1 April 1985