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Accepted practice by most professional industrial hygienists in government and industry is to use "closed-face" filter cassette techniques as standard sampling procedures for the majority of aerosols. A two-phase, field study was conducted to determine whether a gravimetric bias exists between "open" and "closed-face" sampling methods. Phase I involved an in-depth analysis of the potential gravimetric viability as it applies to an industrial paint spray mist, and Phase II was a series of pilot studies, of small sample base, to determine if this phenomena exists over a range of aerosol types. Dusts of wood, grain, cellulose, Portland cement and perlite, welding fumes, and chromic acid mist were sampled in Phase II. Paired breathing zone samples, "open" and "closed-face", 37 mm, 3-piece filter cassettes were utilized in both phases of the study. In both phases of the study, "open-face" concentrations were consistently higher than "closed-face" concentrations, with the exception of cellulose dust. Based on the concentration for both sampling techniques, the data suggests that "closed-face" sampling techniques (4.0 mm inlet diameter) might be size selective against large particles. This could lead to an underestimation of a worker's total aerosol exposure.

A comparison of aerosol sampling techniques: "open" versus "closed-face" filter cassettes

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Introduction

The "total" aerosol should always be sampled in industrial hygiene work when the air contaminant is a material capable of affecting body systems other than the lung. For example, when lead (Pb) pigments are inhaled, the lead might be soluble in lung tissue, and thus carried throughout the body or the lead may also be moved out of lungs by pulmonary clearance mechanisms, and subsequently ingested. Professional industrial hygienists and governmental agencies have used "closed-face" cassette sampling techniques for the majority of aerosols in "total dust" sampling, since the "closed-face" cassette lends protection to the filter and its accumulated contaminant. However, the structure of the "closed-face" cassette and the associated aerodynamic flow through the small orifice of the "closed-face" cassette may select against, or for, specific aerosol particles on the basis of their density, size, shape, or structure.

"Open-face" filter cassettes with a diameter of 33 mm (1.65 cm radius) and a 3 Lpm flowrate in a horizontal orientation will sample particles up to 20 μm with 100% efficiency. However, a "closed-face" filter cassette with 4 mm diameter (0.2 cm radius) inlet and a 3 Lpm flowrate in a horizontal direction will only be able to sample particles up to 20 μm with 95% efficiency.⁽¹⁾ It has been recommended that the sampling inlet radius be at least five times greater than the stop distance of the particles sampled:⁽²⁾

$$\frac{r_o}{d_s} > 5 \quad (1)$$

where:

- r_o = radius of the sampler inlet (cm);
- d_s = particle stop distance (cm).

If this condition is satisfied, the sampling error should be less than 1.6%. However, other work⁽¹⁾ showed that sampling inlet losses were less than 5% as long as:

$$\frac{r_o}{d_s} > 1.5 \quad (2)$$

Values of r_o/d_s were calculated for "open-face" (1.65 cm radius inlets) and "closed-face" filter cassettes (0.2 cm radius inlets) and are recorded in Table I. These calculations were done for spheres of unit density (1.0) ranging in diameter from 0.1 to 100 μm AED. Stop distances for the various sized particles were calculated from:

$$d_s = \left[\frac{Q\tau}{4\pi} \right]^{1/3} \quad (3)$$

where:

- d_s = particle stop distance (cm);
- Q = sampling rate (cm^3/s);
- τ = particle relaxation time (s).

The sampling flowrate (Q) was assumed to be 2 Lpm, and the particle relaxation times were determined from work by Davies.⁽³⁾

It can be noted from Table I, using the conservative criteria⁽²⁾ of $r_o/d_s > 5$, that "open-face" filter cassettes can sample particles up to 77.2 μm AED with less than 1.6% error, and "closed-face" filter cassettes can only sample particles up to 2.8 μm AED with less than 1.6% error. Also, experimental work that supports the need for use of large diameter inlets for "total" aerosol sampling documented minimum permissible diameters of sampler entries. In the 2.0 Lpm sampling range, it was determined that a 4 mm diameter sampling inlet (midget impinger) would collect an

TABLE I
 r_o/d_s Values for Spheres of Unit Density in Air
at One Torr and 20 °C

Particle Diameter μm AED	Relaxation Times τ (sec) ^A	Stop Distance at 33.33 cm ³ /s d. (cm)	r_o/d_s Values	
			1.65 cm Radius Inlet ^B	0.2 cm Radius Inlets ^C
0.1	8.67×10^{-8}	0.006127	269.30	32.64
0.2	2.295×10^{-7}	0.008475	194.69	23.60
0.3	4.28×10^{-7}	0.010432	158.17	19.17
0.5	1.02×10^{-6}	0.013934	118.42	14.35
1.0	3.57×10^{-6}	0.021157	77.99	9.45
2.0	1.305×10^{-5}	0.032591	50.63	6.14
3.0	2.802×10^{-5}	0.042045	39.24	4.76
5.0	7.95×10^{-5}	0.059522	27.72	3.36
10.0	3.057×10^{-4}	0.093251	17.69	2.14
15.0	6.93×10^{-4}	0.122499	13.47	1.63
20.0	1.223×10^{-3}	0.148035	11.15	1.35
25.0	1.938×10^{-3}	0.172587	9.56	1.16
30.0	2.752×10^{-3}	0.193987	8.51	1.03
50.0	7.34×10^{-3}	0.269022	6.13	0.74
100.0	2.548×10^{-2}	0.407339	4.05	0.49

^Afrom Davies⁽³⁾

^B33 mm diameter inlet.

^C4.0 mm diameter inlet.

aerosol sample without distortion for particles less than about 2.7 μm AED.⁽⁴⁾ However, when using the more liberal criteria⁽¹⁾ of $r_o/d_s > 1.5$, "open-face" filter cassettes can sample particles larger than 100 μm AED with less than 5% error, and "closed-face" filter cassettes can sample particles up to 17.3 μm AED with less than 5% error. These differences in sampling efficiencies, which depend on particle size and density, sampling flowrate, and inlet radii may explain differences between "open-face" and "closed-face" filter cassette concentrations.

From the published literature, it seems reasonable that small diameter inlets of samplers would probably exhibit a mass bias against large particles, underestimating a worker's exposure and thus the potential health hazard. Consequently, the objective of these field investigations was

to determine if a significant gravimetric bias existed between "open" versus "closed-face" aerosol sampling techniques.

experimental procedures

This research was carried out in two phases including a detailed analysis of paint spray mist (Phase I), and a series of small sample base studies over a range of aerosol types (Phase II). Phase I consisted of collecting thirty (30), breathing zone pairs of "open" versus "closed-face" filter samples in two industrial paint spraying operations. Similarly, Phase II consisted of collecting ten (10), breathing zone (with exceptions) pairs of "open" versus "closed-face" filter samples each of aerosols intended to be representative of the dusts, mists, and fumes often encountered in the industrial environment, excluding aerosols which require respirable mass sampling. Paired, "total" aerosol samples were taken of four inorganic and three organic air contaminants. The inorganic aerosols were chromic acid mist, welding fumes, perlite dust, and Portland cement dust. The organic aerosols were grain dust, wood dust, and cellulose insulation dust.

The paired samples were collected in 3-piece, 37 millimeter (mm) filter cassettes, which were sealed with

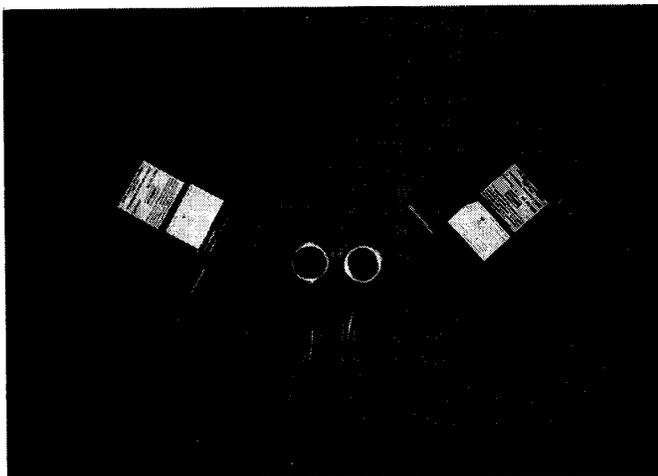


Figure 1 - Aerosol sampling cassette holder, neck strap and sampling pumps with side by side "closed-face" and "open-face" filter cassettes.

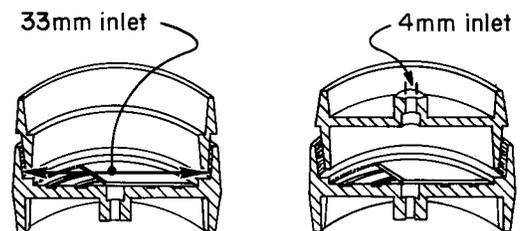


Figure 2 - Cross-sectional sketches of the 37 mm filter cassette holders; "open-face" (left) and "closed-face" (right).

cellulose, shrinkable bands to avoid short circuiting of air from the cassette inlet. Both cassettes were held in place by a "paired-sample" cassette holder which was hung around the monitored worker's neck in the lower portion of his breathing zone (Figure 1). Chest level, breathing zone samples were used for all aerosols collected except chromic acid mist. Stationary stands were used to hold the chromic acid sampling cassettes over a chrome plating tank. The "effective filtration diameter" of the "open face" cassette inlet was 33 mm, and the inlet of the "closed-face" cassette was 4 mm in diameter for both Millipore and Gelman products (Figure 2).

The cassette holder was designed to position the sampling inlets approximately horizontal to the work being performed and designed so as to not restrict air flow to the cassettes. The system was lightweight, durable, and had minimal interference with the worker's normal activities.

In order to ensure that a valid comparison was made between "open" and "closed-face" aerosol concentration, an attempt was made to minimize four documented sources of sampling error which may have had an effect on sampling accuracy. These sampling errors included; deposition by sedimentation, geometric orientation of cassettes, air flowrate variation associated with personal pumps and ambient wind speed and direction.

Deposition by sedimentation was minimized by horizontal placement of the cassettes in the cassette holder. When the cassette holder was hung around the monitored worker's neck, inlets of both field monitors were in horizontal position with respect to the job task. Naturally, the sampling angle changed as the worker moved his upper torso. The geometric orientation due to design of the sample holder for both "open" and "closed-face" cassettes remained reasonably constant for both cassettes with respect to the job task being performed.

It has been documented that a separation distance of 30.5 cm between sampling devices produces results that differed by a factor of up to 3 times.⁽⁵⁾ To minimize this sampling error, the physical separation between inlets of both cassettes was reduced to 2.4 cm.

Sampling in the field made it very difficult to minimize the error that ambient wind speed and direction impart on sample accuracy. A simple sampling technique was employed which would, over a number of sample runs, minimize and average out this error. The filter cassettes and pumps in this investigation were systematically rotated on alternating sample runs. For example, if on the first sample run, the "closed" filter was on the left side of the cassette holder and attached to pump number one, then on the second sample run it would be on the right side attached to pump number two. In addition, control samples were collected for each aerosol with paired "open-face" and paired "closed-face" filter cassettes. In Phase I, for every 6 pairs of "open" and "closed-face" samples, one pair of "open-face" filter controls and one pair of "closed-face" filter controls were collected. In Phase II, only one set of "control pairs" was taken per aerosol type.

MSA, model "G" personal pumps were used for sampling and the rotometers were calibrated using the bubble burette

before and after each sample collection and set to operate at a flowrate of 2.0 Lpm. The sample collection period ranged from 5 minutes to 40 minutes, and most of the sample volumes consisted of approximately 40 liters of air.

The membrane filter used in this investigation was a Gelman DM-800, 0.8 μm pore size filter, supported by a Gelman absorbant pad. The filter was composed of copolymers of polyvinyl chloride which rendered the filter chemically stable to attack from aromatic hydrocarbons often used as vehicles in industrial paints. This filter also had the added advantage of low ashing content which was important with respect to the analysis for heavy metals.

All filters were desiccated for a period of 24 hours before and after sampling to eliminate atmospheric moisture effects on the weight of the filter. The samples were weighed to the nearest 0.001 milligram (mg) on a Cahn G-2 electrobalance immediately following the 24 hour desiccation period. The weighing procedure was established to result in an error of no more than $\pm 1\%$. The aerosol concentration was calculated by dividing the change in filter weight in milligrams by the volume of air sampled in cubic meters. Since the "open-face" filter satisfied Davies sampling criteria,⁽²⁾ the measured concentration was assumed to be correct and thus a best indicator of a worker's overall exposure.

In addition to gravimetric analysis, 24 of the 30 pairs of samples of paint mist from Phase I were coded and submitted to a laboratory for lead (Pb) analysis. Six of the 30 pairs were samples of paints which contained pigments other than lead and thus were not submitted for analysis. Chromic acid concentrations (Phase II) were also determined by the same laboratory. The general procedure for "metals" from the NIOSH manual of analytical methods was utilized for determining the lead concentration.⁽⁶⁾ The analysis was performed on a Perkin-Elmer, flame, atomic absorption spectrophotometer (AAS).

The data obtained from the lead (Pb) determinations of the paint mist samples were used primarily as supportive data for gravimetric analysis. If similar trends were observed between two different analytical techniques, greater validity could be given to the comparison of "open" and "closed-face" aerosol sampling techniques. Due to the wide degree of variation between lead concentration for each sample pair, and the fact that the concentrations followed a log normal distribution, the log of the concentration was calculated and used in the statistic. This reduced variation and allowed for use of the statistic.

The concentration data were divided into 3 different groups and tested separately:

Group 1: This group constituted all pairs of samples analyzed for total aerosol and lead (Pb) concentration independent of pigment formulation and sample duration.

Group 2: A subset of Group 1 was the largest group of sample pairs with the same pigment formulation (lead chromate and inorganic copper complex) but disregarded sample duration. This was done to eliminate

TABLE II
Average "Open-Faced" and "Closed-Face" Filter Cassette Concentrations for Total Aerosol and Lead

	Total Aerosol		Lead	
	Open ^A	Closed ^B	Open ^A	Closed ^B
Mean Concentration (mg/M ³)	55.88	29.67	1.48	0.864
Range (mg/M ³)	5.90-140.25	5.10-90.97	0.01-28.00	0.01-15.00
Standard Deviation	31.63	24.46	5.67	3.04
Number of Samples	30	30	24	24

^AOpen – Open-faced filter cassette (33 mm diameter inlet)

^BClosed – Closed-faced filter cassette (4 mm diameter inlet)

possible biases which may have been present due to differences in aerosol generation as a function of two different application methods and possible bias as a result of different settling velocities imparted on the aerosol (droplet) by different pigment densities and viscosities between paints.

Group 3: This was also a subset of Group 1. This was the largest group of sample pairs with the same pigment formulation and sample volumes of 40 liters (flowrate of 2.0 Lpm). This group was used as a reference set.

data analysis

paint mist

To determine if there was a significant difference between "open" and "closed-face" aerosol sampling techniques, concentration data obtained from gravimetric analysis and lead concentration from atomic absorption spectrophotometry was subjected to the analysis of variance (AOV) procedure appropriate to a cross-over design statistic and tested at the standard significance level of 0.05.⁽⁷⁾ The AOV

procedure was used because the data was based on the use of two pumps being alternated between "open" and "closed-face" cassettes on successive sampling days.

After total aerosol and lead concentrations were determined for each sample pair, the difference between "open" and "closed-face" concentration for that sample pair was expressed as a ratio of "open-face" concentration divided by "closed-face" concentration. Due to the wide variation in concentrations between sample pairs, presenting the results in ratio form gave a better indication of the real difference between "open" and "closed-face" sampling techniques. Ratios tend to reduce the effect that outlying concentration values have on concentration values around the mean. Ratios were then verified relative to variability by calculating the standard error for each set of independent ratios. The following formula was used to determine the "approximate standard error"⁽⁸⁾ of the paired "open" and "closed-face" filter cassette concentration ratios:

$$S_R \cong \sqrt{\left(\frac{\bar{x}}{\bar{y}}\right)^2 \frac{1}{n} \left(\frac{S_x^2}{\bar{x}^2} + \frac{S_y^2}{\bar{y}^2} - \frac{2S_{xy}}{\bar{x}\bar{y}} \right)} \quad (4)$$

TABLE III
Paired Open-Face and Closed-Face Filter Cassette Concentration Ratios and Approximate Standard Error of the Ratios

Parameter	Total Aerosol		Lead
	Open	Closed	
Mean Ratio Open/Closed ^A	1.3	1.3	
Median Ratio Open/Closed ^A	1.3	1.25	
Approximate Standard Error of Ratios ⁽⁸⁾	0.0499	0.0461	
Range	1.0-2.6	0.2-2.2	
Number of Sample Pairs	30	24	

^AOpen-face filter concentrations divided by the closed-face filter concentration.

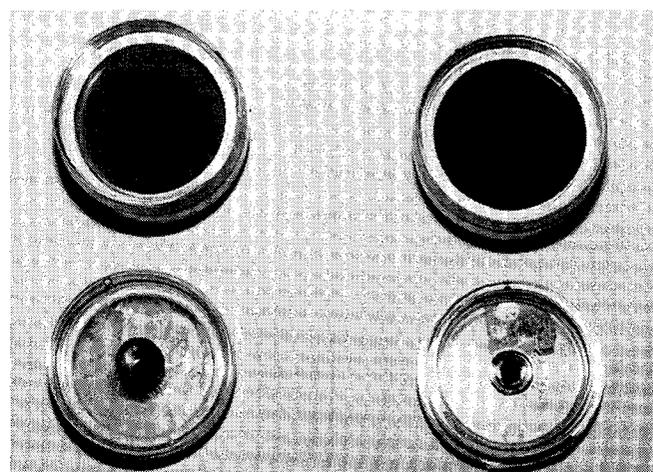


Figure 3 – Typical aerosol deposition characteristics on the surface of membrane filters: "closed-faced" cassette (left) and "open-faced" cassette (right).

TABLE IV
Mean Aerosol Concentration Ratios of Paired Filter Cassette Control Samples by Gravimetric Analysis

Total Aerosol Determination		
	Open Versus Open	Closed Versus Closed
Mean Ratio	1.0	1.1
Range	1.0-1.1	1.0-1.3
Number of Sample Pairs	5	5
"t" Value	0.39	0.04

^ANo significant difference in the paired values at 0.05.

where:

\bar{x} = the mean aerosol open-face filter cassette concentration;

\bar{y} = the mean aerosol closed-face filter cassette concentration;

n = the number of paired filter cassette samples;

S_x^2 = the sample variance of the open-face filter cassette concentrations;

S_y^2 = the sample variance of the closed-face filter cassette concentrations;

S_{xy} = the sample covariance of the paired open and closed-face filter cassette concentrations.

The concentration data obtained from the control pairs for total aerosol determination were tested for significance by the paired "t" test at the 0.05 probability level. Due to the small number of control pairs containing lead, the samples were not analyzed for lead content.

TABLE V
Statistical Evaluation of Total Aerosol and Lead Sample Pairs

	Group 1 ^A	Group 2 ^B	Group 3 ^C
Total Aerosol Analysis			
Number of Samples	30	16	12
F	12.93	7.21	5.52
p	0.001	0.018	0.010
Lead Analysis			
Number of Samples	24	16	12
F	4.09	13.40	10.23
p	0.055 ^D	0.003	0.041

^AAll pairs of samples.

^BThe largest group of sample pairs with the same pigment formulation (a subset of group 1).

^CThe largest group of sample pairs with the same pigment formulation and the same sample volumes (a subset of group 1).

^DGroup 1, lead analysis was the only group not to show a significant difference between the "open-face" and "closed-face" sampling techniques at the 0.05 level.

common industrial aerosols

As in Phase I, the ratios of the paired "open" to "closed-face" concentrations determined in Phase II were also calculated. "Open" and "closed-face" concentrations were statistically analyzed by a paired "t" test. Also, the "approximate standard error" of the paired "open" and "closed-face" filter cassette concentration ratios was determined.

results and discussion

paint mist

The average total aerosol and lead concentration for "open" and "closed-face" sampling techniques are shown in Table II. However, this data tends to be misleading relative to the actual difference between "open" and "closed-face"

TABLE VI
Mean Concentrations, Standard Deviations, and Probability Values for the Paired Open and Closed-Faced Filter Cassette Samples

Aerosols Sampled	Number of Paired Samples (n)	Open-Face Concentrations (mg/M ³)		Closed-Face Concentrations (mg/M ³)		Probability Values (p) Values
		Mean	S.D. ^A	Mean	S.D.	
Chromic acid mist	8	0.13	0.08	0.06	0.10	0.0073
Welding fumes	10	25.45	16.50	23.90	12.98	0.9071
Perlite dust	12	27.11	9.49	23.32	13.65	0.0083
Portland cement dust	10	163.56	120.42	68.68	52.52	0.0002
Grain dust	12	103.40	100.32	51.44	54.53	0.0003
Wood dust	10	14.33	20.24	7.87	8.72	0.0002
Cellulose dust	11	84.34	75.35	97.05	62.42	0.2433

^AS.D. = Standard Deviation.

TABLE VII
Paired Open-Face and Closed-Face Filter Cassette Concentration Ratios and Approximate Standard Error of the Ratios

Aerosols Sampled	Number of Paired Samples (n)	Ratio Range Open/Closed ^A	Mean Ratio Open/Closed ^A	Approximate Standard Error of Ratios ⁽⁵⁾
1. Chromic acid mist	8	0.8-7.5	3.8	0.9335
2. Welding fumes	10	0.1-2.6	1.2	0.3140
3. Perlite dust	12	0.8-3.4	1.4	0.1481
4. Portland cement dust	10	1.3-4.4	2.6	0.4319
5. Grain dust	12	0.8-4.3	2.2	0.2691
6. Wood dust	10	1.0-2.3	1.6	0.1086
7. Cellulose dust	11	0.5-2.2	1.0	0.1842

^AOpen-face filter concentration divided by the closed face filter concentration.

sampling techniques due to the wide degree of variation on concentrations between sample pairs, which is obvious from the large standard deviations calculated for total aerosol concentrations and lead concentrations. The reason for the wide degree of variation between the pairs was most likely attributed to three uncontrollable factors: a) effectiveness of the ventilation system and where the spraying took place relative to the ventilation system; b) size of the item being painted; and c) the amount of pigment in the paint. Paint pigment formulation could have had a profound effect on

the sampling bias phenomenon. The percentage of pigment in the paints (pigment to carrier) varied from 0.2-8.92 percent lead by weight thus explaining wide degree of variation in lead concentrations.

A summary of all the ratios by gravimetric analysis for total aerosol determination is displayed in Table III. This data indicated that, on the average, "open-face" sampling techniques collected 1.3 times, or 30 percent more paint mist than "closed-face" sampling techniques. This could have been speculated from visual observation of the typical

TABLE VIII
Mean Aerosol Concentration Ratios of Paired, Subject Filter Cassette Samples, and Paired Filter Cassette "Control" Samples

Aerosols Sampled	Mean Comparative Ratios	Mean Control Ratios	
	Open/Closed ^A	Open/Open ^B	Closed/Closed ^C
1. Chromic acid mist	3.8	1.1	1.1
2. Welding fumes	1.2	1.1	1.2
3. Perlite dust	1.4	1.1	1.7
4. Portland cement dust	2.6	1.0	1.0
5. Grain dust	2.2	1.2	1.4
6. Wood dust	1.6	1.1	1.2
7. Cellulose dust	1.0	1.2	1.3

^AMean Ratio, Open/Closed = Mean ratio of the open-face cassette concentrations divided by the closed-face cassette concentrations for the pairs.

^BMean Ratio, Open/Open = Ratio of the greater open-face cassette concentration divided by the lower open-face cassette concentration divided by the lower open-face cassette concentration for the pairs.

^CMean Ratio, Closed/Closed = Ratio of the greater closed-face cassette concentration divided by the lower closed-face cassette concentration for the pairs.

"open" and "closed-face" particle deposition characteristics shown in Figure 3. With respect to the ratio of the difference by atomic absorption spectrophotometry for lead concentration (Table III), virtually the same trend was observed. On the average, "open-face" techniques collected approximately 30 percent more lead than "closed-face" sampling techniques.

Based on the sampling controls placed on this study to minimize errors associated with flowrate variation, deposition by sedimentation, geometric orientation of the cassettes and error associated with ambient windspeed and direction, the observed difference in concentration (mg/M^3) within each sample pair was primarily a function of inlet diameter. Furthermore, the fact that two different analytical procedures measured essentially the same mean difference between "open" and "closed-face" sampling techniques indicated consistent sampling methodology. Independent of the wide degree of variability in the ratios between sample pairs, the ratios within each sample pair for both analytical procedures were quite similar. Therefore, the bias associated with sampling methodology as well as analytical procedure on concentration would be small in comparison to bias imparted on the concentration values by the sampling device.

Statistical evaluation (paired "t" test) of the total aerosol concentrations for both paired "open-face" and paired "closed-face" control samples showed no significant difference existed at the 0.05 level. This is indicated by the ratios in Table IV. Thus, the only significant source of bias in the experimental comparison of one sampler versus the other was that of sampler inlet diameter.

With the exception of Group 1 lead analysis, the F-statistic showed the difference between "open" and "closed-face" sampling techniques for all three groups to be significant at the 0.05 level (Table V). With respect to Group 1 lead analysis, the difference between "open" and "closed-face" sampling was very close to being significant at the 0.05 level as indicated by the p value of 0.055. Therefore, the data indicated the "closed-face" sampling techniques exhibited a bias and thus potentially underestimated a worker's overall exposure.

common industrial aerosols

The mean concentrations, standard deviations, and probability values for the paired "open" and "closed-face" filter cassette samples are given in Table VI. The mean "open-face" filter cassette concentrations were generally greater than the mean "closed-face" filter cassette concentrations, with the exception of cellulose insulation dust. The mean concentration ratio of cellulose was equal to unity.

The mean concentration ratios and "approximate standard errors" of the ratios for the paired "open" and "closed-face" filter cassette samples are shown in Table VII. Although all the mean "open-face" concentrations were not greater than the mean "closed-face" concentrations, all the mean concentration ratios were equal to or greater than unity.

Concentration ratios were significantly ($p < 0.01$) greater than unity for all the aerosols in this study, except welding

fumes, cellulose dust, and perlite dust. Welding fume concentration ratios were not expected to be significantly greater than unity, because welding fumes are typically small spheres. Differences in sampling efficiencies between "open" and "closed-face" filter cassette sampling techniques would be expected to occur with particles larger than $2.8 \mu\text{m}$ aerodynamic equivalent diameter (AED), and welding fumes generally range in size from 0.001 to $1.0 \mu\text{m}$ in diameter.⁽⁹⁾ Differences in cellulose dust concentrations may have been due to the heavy cellulose dust concentrations under which the aerosol was sampled. Furthermore, cellulose dust may have been better retained in the "closed-face" filter cassette holders while dust may have fallen out of the "open-face" filter cassettes. Sampling for a shorter time period or at a lower flowrate may have prevented the loss of cellulose dust from the "open-face" filter cassette. Perlite dust concentration ratios were not significantly greater than unity.

Chromic acid mist samples were taken in front of a slot hood in this study. Although the "open" and "closed-face" filter cassette samples were taken at an average sampling flowrate of 2.0 Lpm, the average face velocity on the "open-face" filter cassettes was 0.04 m/s, and the average face velocity on the "closed-face" filter cassettes was 2.65 m/s. The average face velocity of the slot hood was 1.78 m/s. This meant that the face velocity of the "open-face" filter cassette was 0.02 times the face velocity of the slot hood, and the face velocity of the "closed-face" filter cassette was 1.5 times the face velocity of the slot hood. Oversampling will occur if the sampling velocity is lower than the hood airstream velocity (subisokinetic), and lowered sampling efficiencies will occur if the sampling velocity is greater than the hood airstream velocity (superisokinetic).⁽¹⁰⁾ Therefore, the "open-face" chromic acid mist filter cassette samples may have been oversampled, and the "closed-face" filter cassette samples for chromic acid mist may have been undersampled. This might be the reason for the large "open" to "closed-face" filter cassette concentration ratio of 3.8 for chromic acid mist.

The ratios of the paired "open-face" filter cassette "control" concentrations for the aerosols in this study ranged between 1.0 and 1.2 (Table VIII). The ratios of the paired "closed-face" filter cassette "control" concentrations for all the aerosols was 1.1 and the overall average ratio of the paired "closed-face" filter cassette "control" concentrations was 1.3.

conclusions

Differences in particle sizes, particle densities, sampling flowrates, inlet radii, and ambient airstream velocities may have caused the bias between "open" and "closed-face" cassette sampling techniques. Most of the aerosols in this study were sampled in calm air. Under these conditions, particle sedimentation and inertia effects on sampling efficiency are most noticeable with particles larger than $10 \mu\text{m}$ AED. Since large particles are primarily responsible for the weight of a sample, it is very evident that the "closed-face" cassette was inducing a bias by not efficiently sampling large particles. The following is a possible explanation for

this phenomenon. Although the sampling velocity at the face of the "closed-face" (4.0 mm diameter inlet) cassette is greater than the sampling velocity at the face of an "open-face" cassette, the diameter of the "flow contour" of the "closed-face" cassette is much smaller than that of the "open-face" cassette. Logically, this is a function of the inlet diameter. Therefore, when large particles interface with the flow contour of the "closed-face" cassette, their trajectory will probably change in the general direction of the flow contour, but not to the extent of that of smaller particles, because of larger particle inertia. Consequently, in the small diameter inlet of the "closed-face" cassette, a good percentage of the large particles would not become entrained in the flow contour and either impact on the cap or pass by the cassette and thus not be collected.

Results from this research infer that "closed-face" filter cassette sampling techniques are significantly less efficient than "open-face" filter cassette sampling techniques for paint spray mist, chromic acid mist, Portland cement dust, grain dust, and wood dust. Assuming a bias does exist between "open" and "closed-face" filter cassette sampling methods, workers' exposures are probably being underestimated when "closed-face" filter cassettes are used in "total" aerosol sampling. This is important when exposure near the Threshold Limit Value is considered, because working conditions which may have been thought to be not harmful, may in reality be hazardous to workers' health. Consequently, "open-face" filter cassettes should be used for all "total" aerosol sampling.

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