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Air volume measurement error in pumps with rotameters and high range "constant flow" pumps

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The inherent variability of three types of sampling trains commonly used in industrial hygiene field work were compared to that of a "control" sampling train in a laboratory setting. Eight quartets of samples were taken for each sampling train inside a cubic meter aerosol chamber in which Portland cement dust was generated. Side one, used as a control, had each of four sampling cassettes connected to a 2 Lpm critical orifice. Each orifice was connected by manifold to a Little Giant® pump. Side two had four sampling cassettes, each attached to a MSA Model G pump, and the ball setting of each rotameter was adjusted every half hour during sampling. Side three also had four sampling cassettes, each attached to an MSA Model G pump. The rotameters of these pumps were not adjusted during sampling. In the fourth side of the chamber four sampling cassettes were each connected to a DuPont "Constant Flow" Pump, Model P-2500. The variability in concentration among the four samples for each sampling train was calculated and compared to the other three sampling trains. The MSA Model G pumps in which the rotameter was adjusted every half hour during sampling had over twice as much variability as the other three sampling trains with a coefficient of variation of 5.80%. The MSA Model G pump with the unchanged rotameter had 2.48%, the DuPont, 2.21%, and the critical orifice, 2.20%.

Air volume measurement error in pumps with rotameters and high range "constant flow" pumps

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introduction

Air sampling is used to determine airborne pollutant concentrations most commonly by measuring the quantity of contaminant in a measured volume of air. The sampling flow rate of air must be known in order to determine total concentration of airborne contaminant per volume of air. Sources of sampling error which may affect the final determination of air contaminant concentration are effects of atmospheric co-contaminants on samples during collection, sample stability during sampling, storage and transport, efficiency of recovery from sampling substrate and interferences of sampling substrates, errors in sampling time and of course, error in air flow rate measurement.[1]

Air volume measurement is accomplished with flow meters built into the sampling train. Flow meters often used for field sampling can be divided into two types. One group operates with a fixed restriction and are known as fixed head meters. This group includes orifice meters, venturi meters and flow nozzles. The other type is known as variable-area meters and are best known as rotameters.

Rotameters are especially common on commercial, portable air samplers. Because of their small size, scale length is limited to usually no more than ten centimeters and often only five centimeters. If not individually calibrated, the accuracy is not believed to be better than ± 25%. It is estimated that individual calibration may be accurate to ± 5%, which is the NIOSH Engineering Branch estimate of typically calibrated pumps capable of air sampling flow rates in the range of 1.5 to 3.0 liters per minute (Lpm). This includes several brands of pumps which have varying capacities and accuracies. Charles McCammon related that in an unpublished study this was the maximum error found in the groups of pumps tested although some brands have a

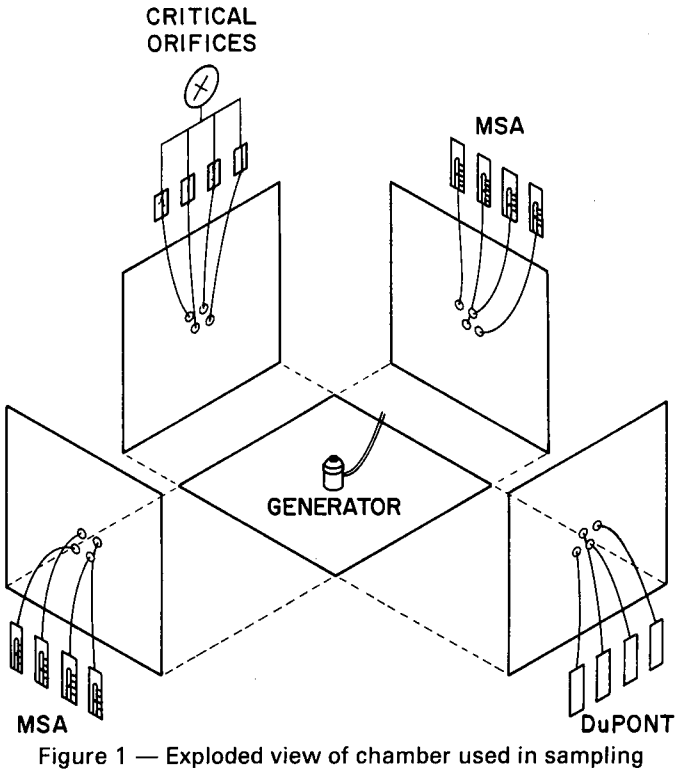

Figure 1 — Exploded view of chamber used in sampling

TABLE I
Average Total Aerosol Concentrations of Four Sampling Methods From Eight Four Hour Runs

	MSA-C[1]	MSA-U[2]	DuPont[3]	Critical Orifice
Mean Concentration (mg/m^3)	187.6	198.5	194.1	191.4
Standard Deviation	10.3	5.0	4.3	4.5
Coefficient of Variation (%)	5.8	2.5	2.2	2.2
Range (mg/m^3)	103.9-289.7	112.1-293.6	107.6-302.1	105.2-300.7
Number of Sample Quartets	8	8	8	8

[1]MSA-C - MSA pump, rotameter adjusted every half hour during sampling.
[2]MSA-U - MSA pump, rotameter not adjusted during sampling
[3]DuPont - DuPont "Constant Flow" pump, P-2500

much lower overall error.[(2)] Each brand of pump has its own degree of variation depending upon the type of flow metering device.

The "OSHA Field Operations Manual" maintains that as a minimum during sampling, the pump flow should be checked the first half hour, hour and thereafter every 2 hours.[(3)] If the pump rotameter setting has changed, it should be adjusted back to the initial position. Accurate adjustment of a five centimeter rotameter can be difficult. It requires exact placement of the ball setting each time. If the rotameter is adjusted, even slightly, every half-hour to hour, substantial error may occur. There may be a greater error associated with reading the rotameter in cases where personal sampling pumps are precalibrated by lab technicians and then adjusted out in the field by the industrial hygienist. It may be possible that the self-compensating flow control apparatuses, such as the DuPont "Constant Flow" samplers have an advantage over the rotameters since they are not manually adjusted during sampling.

It is common practice in industrial hygiene field work to continually be adjusting a rotameter setting with the intent to accurately define sampling flow rate of air. Therefore, a laboratory study was designed to examine the potential air volume measurement error due to reading rotameters and to compare these errors to those found in personal sampling pumps with other means of air volume measurement.

methods and materials

Those sampling trains in which air volume measurement was dependent on a 5 centimeter rotameter were of special concern because of the potential error in reading and adjusting the rotameter float. Four specific types of sampling trains were studied in this research. Eight sets of data for all four types of sampling trains together were collected. In each set, four samples of each sampling train type was taken. All sets of samples were collected in a 1.0 cubic meter (m^3) plexiglass chamber in which Portland cement aerosol was generated.

The sampling method consisted of collecting four "closed-face" cassette aerosol samples from each of the four sides of the chamber (Figure 1). The dust was collected on a membrane filter which was supported by a 37 millimeter (mm) plastic cassette. Air concentrations were determined by gravimetric analysis. Variation in concentration in each group of four was then compared using the coefficient of variation.

Samples were collected in two-peice, 37 mm filter cassettes which were sealed with cellulose shrinkable bands to avoid leakage of air. The Gelman, DM-800 membrane filter, supported by a Gelman absorbant pad, was used. It has the advantage of being fairly hydrophobic which makes it a more stable filter with less variability in weight.[(4)] All filters were disiccated for three hours before and after sampling.

Three brands of sampling pumps were used: MSA Model G Personal Samplers, DuPont P-2500 "Constant Flow" Samplers, and the Gelman "Little Giant" Pump which was attached by manifold to four critical orifices matched at a flow rate of 2.0 Lpm. These were used to make up four sampling trains - one using the critical orifices, one the DuPont and the other two consisting of the MSA Model G pumps.

All pumps were set to run at approximately two Lpm and were run for fifteen minutes before pre-calibration to allow for voltage drop of the battery. Each filter used in sampling was used to individually calibrate its sampling pump. It was thought that by calibrating a pump with its sampling filter rather than a standard calibration filter this amount of bias could be removed. Each sampler was pre- and post-calibrated using the primary standard bubble burette.

Four cassettes for each sample method were mounted on one of the four walls of the chamber. These were mounted so that the cassette inlets were horizontal and positioned in the shape of a parallelogram.

Once cassettes were mounted and were connected by Tygon® tubing to their respective pumps, the chamber was closed and a compressed air pump connected to a Mist-o-

gen® generator inside the chamber was started. The compressed air from the pump would go to the generator which contained bulk Portland cement and the dust would be blown into the air of the chamber. A slight positive pressure was created in the chamber. All pumps were activated and their times noted during the sampling period. Their sampling times were for four hours. Only one set of the sampling trains, an MSA Model G set, (denoted MSA-C) was adjusted for flow rate during sampling. The rotameter was adjusted every half hour during sampling (whether it was necessary or not). The other MSA Model G sampling train (denoted MSA-U) was not adjusted.

analytical procedures

Samples were weighed immediately after the three hour dessication period to within 0.01 milligrams (mg) on the Mettler® Electronic Analytic Balance. The balance was zeroed before each filter was weighed. Cahn® Calibrating Weights were used to calibrate the balance before each weighing so that error was no more than ±1%. The dust concentration was calculated by the following equation:

$$\text{Dust concentration } (\text{mg}/\text{m}^3) = \frac{\text{final weight (mg)} - \text{initial weight (mg)}}{\text{sampling time (min)} \times \text{rate of sampling (Lpm)}/(1000\ \text{L}/\text{m}^3)}$$

data analysis

After gravimetric determination was used to detect aerosol concentration for each sample, the mean ($\bar{x}$) and standard deviation (s) of each group of four samples was determined. The coefficient of variation (C.V.) was then determined by dividing the mean into the standard deviation ($s/\bar{x}$) and multiplying by 100 to give a percentage. The C.V. was chosenbecause it is a measure of relative variation.[5] In this way, the variation found in each method of sampling could be seen and compared.

results

Eight sets of quartets of samples for each of the four sampling methods was collected and total aerosol concentration was the environmental parameter measured. The overall mean concentration, standard deviation, range and coefficient of variation of each sampling method (32 total samples per method) are shown in Table I.

Table I shows that there is over twice as much error, as shown by the coefficient of variation (C.V.), in the MSA Model G sampling trains that had their rotameters adjusted (C.V. = 5.8%) than in any of the other three sampling methods. The critical orifice had the least amount of relative error with a 2.20% C.V. It was assumed from the start of this

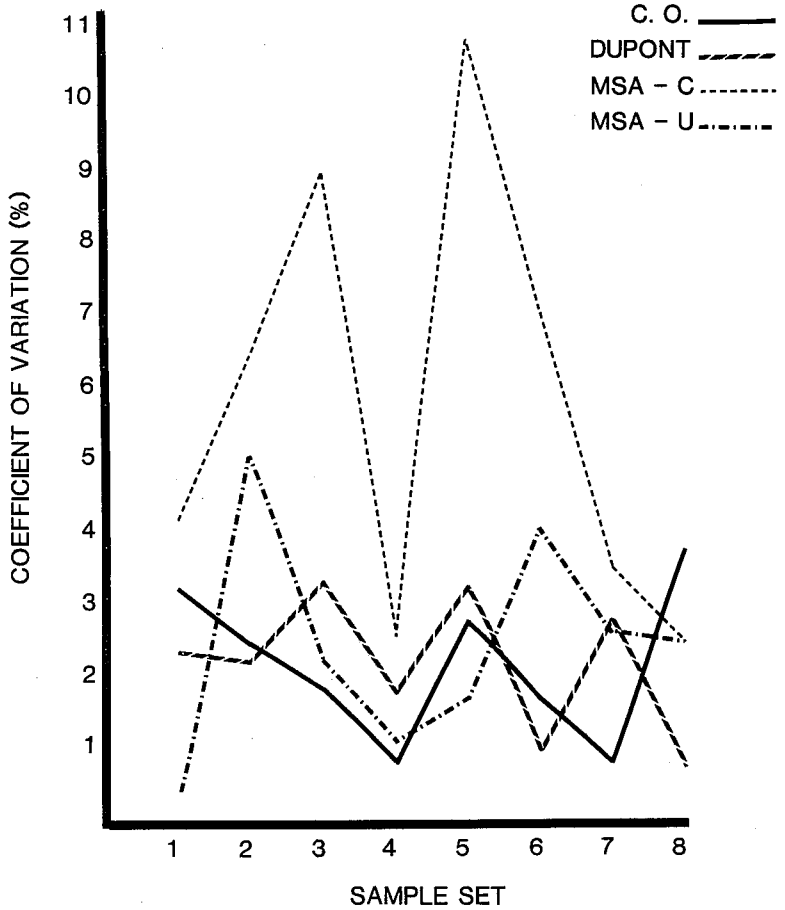

Figure 2 — Variation in each sampling set

TABLE II
Statistical Evaluation of Total Aerosol Sets

n	= 32
df	= 21
F	= 7.915
p	= 0.001

TABLE III
Difference Between Coefficients of Variation of Each of Four Sampling Methods

	Least Significant Difference		
Method	**MSA-U**	**DuPont**	**C.O.**
MSA-C	3.32*	3.58*	3.60*
MSA-U	----	0.27	0.28
DuPont	----	----	0.01
C.O.	----	----	----

*Greater than 2.50 LSD required for statistical significance ($p < 0.01$).

study that this type of sampling train would have the least amount of relative error, and this was used as a baseline sampling train. The DuPont "Constant Flow" pump had only a slightly higher relative error above the baseline with a 2.21% C.V. The MSA Model G pump that did not have the rotameter varied during sampling had the highest C.V. of the unadjusted pumps with 2.48%. Thus, by adjusting the rotameter on the MSA pump every one half hour, the relative error was increased approximately 2.5 times.

A more graphic representation of the variation in the sampling methods can be seen in Figure 2. This shows the C.V. of each sampling method for each day of sampling. In all but one case, the C.V. was highest in the MSA-C sampling method.

Analysis of variance was run to determine if there was significant variation among the four methods. Results of the Analysis of Variance are shown in Table II. There was a difference among the four sampling methods with F = 7.915 ($p < 0.001$). The Least Significant Difference (LSD) test was then performed to determine exactly where the difference occurred.[6] The LSD is determined using the following formula:

$$LSD = t_{f,\alpha}\sqrt{s^2\left(\frac{2}{n}\right)}$$

t = test statistic
f = degrees of freedom
α = level of significance
s^2 = variance
n = number of sample sets

In calculating the LSD for the four sampling methods, the test statistic t was determined to be 2.831 with 21 degrees of freedom at the 0.01 level of significance. Variance was 3.117 and 8 total sample sets were collected in all. Table III shows the LSD being performed on the coefficients of variation. The smallest difference between two C.V.'s that was needed to show a statistically significant difference at the 0.01 level was 2.50. The difference between MSA-C and MSA-U was 3.32. This showed that there was a 99% probability that the variation between the MSA-C and the other three sampling trains was statistically significant. There was no statistical significant difference, however, among the MSA-U, the DuPont and the critical orifice. The only difference was between the MSA-C and these three methods.

conclusions

This work demonstrated that the sampling pumps tested which were not adjusted during the sampling process tended to show less variation in the concentrations collected than those pumps which were adjusted during sampling. The pumps which used a critical orifice or had "constant flow" had the lowest deviation.

This raises the question of how much adjustment of the rotameters is necessary during sampling. Both OSHA and MSHA require that the rotameter be adjusted if the flow rate drops. Some industrial hygienists, however, constantly adjust the rotameter ball setting so that they believe that it is exactly the same as the precalibrated setting. These hygienists may add more error to flow determination than if they did not adjust the rotameter at all.

Sometimes there is a very real drop in the flow rate which is reflected by a drop of the rotameter ball setting during sampling, especially when there are heavy airborne concentrations. A heavily loaded filter would provide more resistance to air flow and would cause the rotameter to drop. Instead of adjusting the rotameter, however, the industrial hygienist could replace the "loaded" filter with a new one. The rotameter then, should go back to its preset flow rate setting.

Further studies should be performed on other sources of error that were indicated from this study but not explored. It is speculated that using the sampling media for pump calibration and voltage drop due to pump operation are possible sources. Another study could be performed to determine accuracy of pump calibration in the field using a mass flow sensor. All sources of error need to be decreased as much as possible. OSHA and MSHA need to reconsider their policies regarding rotameter adjustment.

acknowledgements

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