



Pump Fluctuations and Their Effect on Cyclone Performance

DAVID L. BARTLEY , GEORGE M. BREUER , PAUL A. BARON & JOSEPH D. BOWMAN

To cite this article: DAVID L. BARTLEY , GEORGE M. BREUER , PAUL A. BARON & JOSEPH D. BOWMAN (1984) Pump Fluctuations and Their Effect on Cyclone Performance, American Industrial Hygiene Association Journal, 45:1, 10-18, DOI: [10.1080/15298668491399280](https://doi.org/10.1080/15298668491399280)

To link to this article: <https://doi.org/10.1080/15298668491399280>



Published online: 04 Jun 2010.



Submit your article to this journal [↗](#)



Article views: 15



View related articles [↗](#)



Citing articles: 9 View citing articles [↗](#)

Pump Fluctuations and Their Effect on Cyclone Performance

DAVID L. BARTLEY, GEORGE M. BREUER, PAUL A. BARON and JOSEPH D. BOWMAN
National Institute for Occupational Safety and Health, 4676 Columbia Pkwy., Cincinnati, OH 45226

Research has been carried out to characterize personal sampling pump pulsations and their effect on the performance of the 10 mm nylon cyclone. The fluctuation about mean flows equal to 1.2 L/min and 2.0 L/min of four each of three commercially available pumps has been determined. Measurements were made both near the sampling head as well as at the sampling pump without load, since resonance of the air column between pump and sampler was found to alter the fluctuations significantly. The cyclone itself was characterized by measuring the aerodynamic diameter dependent penetration under purely harmonic flow conditions in terms of frequency and amplitude. This information is combined with Fourier analyzed pump data in determining the expected effect of given pump characteristics on cyclone sampling of dust of specific size distribution.

Introduction

For approximately a decade it has been known that fluctuations in sampled air flowing through the 10 mm nylon cyclone have a significant effect on the size-dependent penetration characteristics of the sampler. Measurements of shifts in estimated respirable coal dust concentrations induced by pump fluctuations are described in the literature⁽¹⁻³⁾. Also available⁽⁴⁾ are data giving the penetration shift for various mean flow rates and for anharmonic fluctuations of various amplitudes.

As a result of studies of this sort, pulsation dampeners^(5,6) have become standard equipment within personal dust sampling units. Furthermore, the allowable pump pulsation is controlled⁽⁷⁻⁹⁾ by coal mine dust personal sampling unit (CMDPSU) certification administered jointly by the National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA). Present pump pulsation test procedures are summarized as follows:

- (i) The irregularity in flow rate due to pulsation shall have a fundamental frequency of not less than 20 Hz.
- (ii) On and after July 1, 1974 the quantity of respirable dust collected with a sampler unit shall be within 5 percent of that collected with a sampling head assembly operated with nonpulsating flow."

30 CFR Part 74

Pump pulsations and their effects have found renewed interest for several reasons. At the present time NIOSH is considering updating the CMDPSU certification program, replacing instrument specification by rigorous testing for the adherence to strict performance standards. Therefore, it must be determined how to revise the fluctuation-related parts of the program. From the point of view of sampling unit design, recent availability of automatic flow-controlled personal sampling pumps raises the question of their suitability for use with the 10 mm cyclone.⁽¹⁰⁾ For these reasons research has been carried out by NIOSH into pump pulsations and their effects, and results are presented here.

The organization of this paper is as follows. Both experimental and theoretical descriptions are given which indicate correlation between fluctuations in the air flow measured at the pump with those at the cyclone aperture. Frequency dependent effects are interpreted as a resonance of the column of air in the flexible tubing between sampling pump and sampling head. The effect of the sampling head on the flow resonance is discussed. In the following section, the fluctuations induced by three types of personal sampling pumps operated at two mean flows are characterized at the cyclone inlet. Finally, measurements of the cyclone penetration shift effected by fluctuating flow of given amplitude and frequency are described. The measurements are presented in terms of a tentative empirical mathematical model, which, combined with Fourier component amplitudes of the measured sampling pump fluctuations, provides rough estimates of penetration shifts to be expected for each pump. The bias expected in dust concentration measurements, comparing fluctuating and constant flow, also is calculated for log-normally distributed dust corresponding to size distributions measured in coal mines.

Resonance Effects

The dust penetration characteristics of the cyclone are affected by the air flow fluctuations that can be present in the CMDPSU. Because of the filter, filter cassette and the air column in the plastic tubing between cyclone and pump, the magnitude and harmonic content of fluctuations present at the cyclone can differ considerably from those near their point of origin, the sampling pump. Since the length (3 ft) of the air column is approximately one quarter the wavelength of sound waves in the range of common pump frequencies, resonant amplification of the fluctuations is expected. In order to ascertain the magnitude of this effect, measurements of the flow were made at the cyclone inlet and at the pump which produces a mixture of sinusoidal fluctuations of various frequencies.

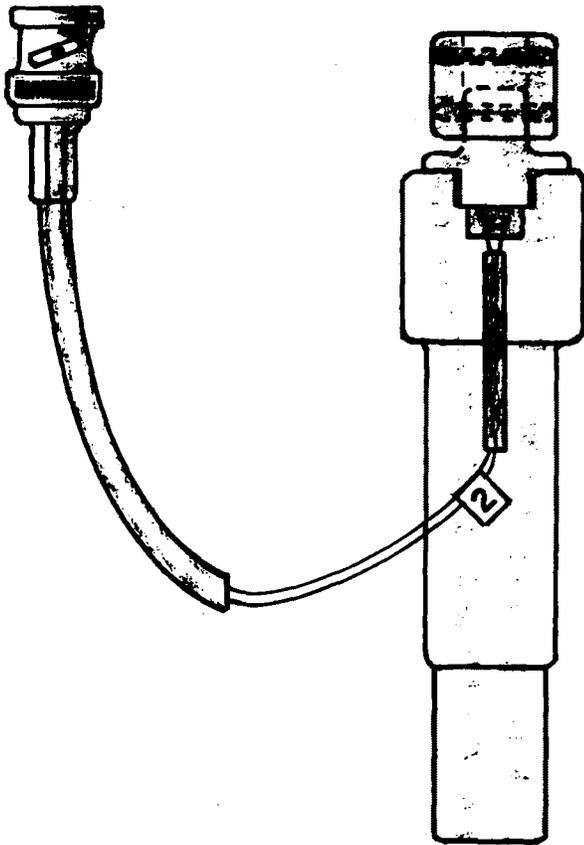


Figure 1 — Positioning of the anemometer probe near the cyclone aperture.

The determination of time dependent air flow was accomplished using a TSI-1051-2 anemometer and TSI-1054B linearizer with TSI-1276-10A hot film probes. Output of the linearizer was sent to a Tracor-Northern-1710 multichannel analyzer (MCA) for storage on magnetic tape and subsequent

analysis and plotting. For each probe, the anemometer, linearizer, MCA A/D converter (Tracor-Northern-1710-30) combination was calibrated to read air flow in units of L/min by comparison with a standard flow controlled by a critical orifice as a reference. Linearity and response time of this arrangement were tested by comparing it with the direct output of the anemometer with constant and sinusoidal flow and by measuring the harmonic distortion at a frequency of approximately 70 Hz. Because the flow was found to vary significantly with orientation of the probe near the cyclone inlet, the probe support was cemented directly to the body of the cyclone so that the hot film was located immediately in front of the cyclone inlet as shown in Figure 1. To measure the flow at the pump, an anemometer probe was cemented into a 8 cm length of 0.5 cm diameter copper tubing which was attached to the pump inlet.

With the CMDPSU assembled, the flow patterns at the pump and cyclone inlets were measured and recorded simultaneously for an assortment of pumps with mean flow equal to approximately 2.0 L/min. Amplitudes corresponding to the various harmonics of each pump flow were then computed using the Tracor-Northern 1710-52 fast fourier transform module. The amplitude ratios, cyclone/ pump, were then calculated for each pump harmonic. The results showing fluctuation amplification by the air column are given in Figure 2 as a function of the pump harmonic frequency.

Figure 2 shows that the amplification exhibits a resonant structure with peaks near odd multiples of the frequency of a sound wave with wavelength equal to four times the length of the air column. This resonant structure is similar to that of air oscillating within an organ pipe closed at one end and open at the other. The damping effect of the sampling filter, located just prior to the cyclone, is at least partially responsible for the finite amplitude of the peak responses. The observed variation in the peak response may be due to a

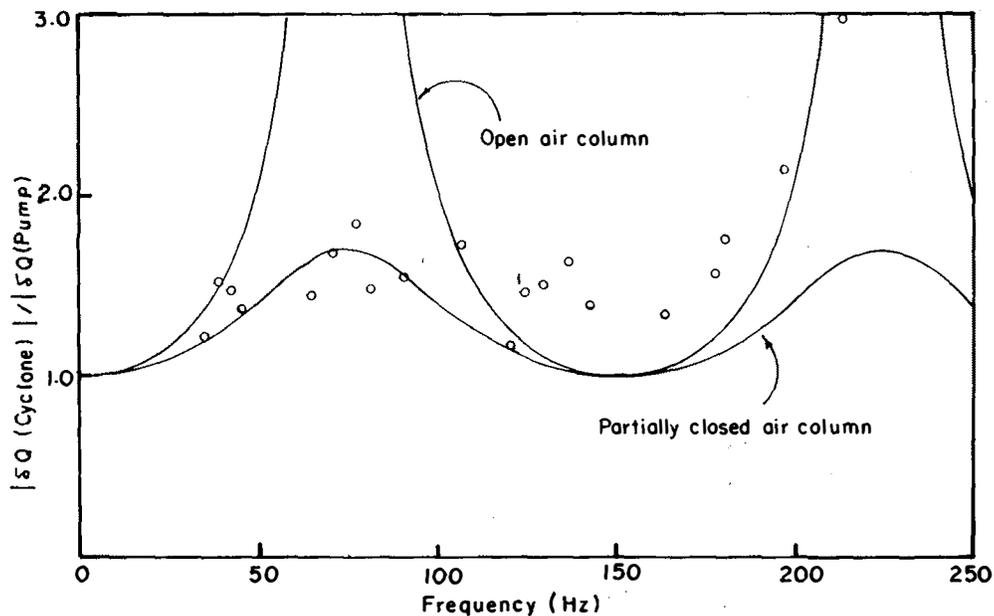


Figure 2 — Transfer of fluctuations from pump to cyclone aperture in terms of frequency, as determined at various pump harmonics. Solid curves give predictions of semi-quantitative model for both open and partially closed (by filter) tubing (see the appendix).

dependence of the instantaneous pressure drop across the filter upon oscillation frequency. Slight reduction in the frequency from that calculated simply from the speed of sound is attributable to the reduction of wave speeds by the elasticity of the plastic tubing walls. A semi-quantitative theoretical treatment of these ideas appears in the appendix.

Several conclusions may be drawn from these results. In characterizing the effect of pump pulsations within a given sampling unit, the relevant fluctuations are those at the cyclone. As indicated above, a particular cyclone, filter, filter cassette, tubing combination could clearly affect the transfer of fluctuation from pump to cyclone. Therefore, the most straightforward characterization entails measurement of time dependent air flow close to the cyclone inlet with the entire CMDPSU assembled.

Sampling Pump Characterization

Several commercially available personal sampling pumps were evaluated in order to obtain a realistic estimate of the pulsation effects to be expected in respirable dust sampling. Measurements of the instantaneous air flow were made both

near the pump without load and also at the aperture of the cyclone with the entire CMDPSU assembled. The MSA sampling head (including filter cassette and cyclone with holder) was used in all subsequent tests.

Four of each of the types MSA Model G, Bendix Micronair II and Du Pont P-2500 pumps, all with pulsation dampeners, were tested. The first two pump models are those presently in use within the Federal coal mine dust sampling program and are controlled manually with the help of their rotameter readings. The third pump has automatic flow control and, though it is not yet certifiable (it lacks a rotameter) for coal mine dust sampling, is finding increasing use in the sampling of other respirable dusts.

Two values of mean flow rate were selected for pump evaluation: 2.0 L/min and 1.2 L/min. The flows were set approximately equal to 1.2 L/min and 2.0 L/min and then were measured accurately with a bubble meter (with standard error of about 1%). The value, 2.0 L/min, is the flow rate presently used for coal mine dust sampling. The lower flow rate was chosen on the basis of an optimized fit⁽¹¹⁾ of cyclone collection characteristics to the British Medical Research

TABLE I
Frequencies f_j (Hz) and Amplitudes A_j (L/min) of Dominant Pump Harmonics at Cyclone Aperture at Mean Flow Q (L/min)

No.	Q	$[f_1, A_1]$	$[f_2, A_2]$	$[f_3, A_3]$	$[f_4, A_4]$	$[f_5, A_5]$
MSA Model G Pump:						
1	1.88	41, 0.258				
2	1.94	46, 0.206				
3	2.00	43, 0.271				
4	1.98	43, 0.199				
1	0.93	35, 0.092				
2	1.05	42, 0.098				
3	1.06	39, 0.093				
4	1.07	40, 0.091				
Bendix Micronair II Pump:						
1	2.02	99, 0.229	49, 0.120	74, 0.064	148, 0.064	25, 0.050
2	2.06	95, 0.238	48, 0.106	143, 0.098	24, 0.094	119, 0.082
3	2.12	86, 0.192	43, 0.108	129, 0.101	107, 0.079	21, 0.063
4	2.11	34, 0.211	69, 0.128	103, 0.105	17, 0.082	86, 0.074
1	1.20	104, 0.141	52, 0.066	78, 0.061	156, 0.054	26, 0.038
2	1.21	102, 0.120	25, 0.071	153, 0.062	127, 0.049	76, 0.045
3	1.29	92, 0.109	137, 0.062	23, 0.048	46, 0.045	114, 0.044
4	1.29	78, 0.100	39, 0.098	117, 0.076	20, 0.072	98, 0.042
Du Pont P-2500 Pump:						
1	2.22	73, 0.295	145, 0.077			
2	2.08	73, 0.648	145, 0.194			
3	2.15	75, 0.703	149, 0.209			
4	2.16	68, 0.727	137, 0.165			
1	1.30	44, 0.295	89, 0.079			
2	1.34	49, 0.568	98, 0.159			
3	1.24	46, 0.596	92, 0.158			
4	1.29	44, 0.652	88, 0.163			

Council definition of respirable dust.⁽¹²⁾ Both flows were tested because of concern that the ratio of fluctuation amplitude to mean flow might become large as the flow was reduced.

The results of the measurements are presented in Table I in terms of amplitudes (L/min) and frequencies (Hz) of the dominant pump harmonics. Characteristic instantaneous air flow rates vs. time are shown in Figures 3-5. Figure 3 displays a comparison of the MSA Model G pump fluctuations at mean flows equal to 2.0 L/min and 1.2 L/min. It can be seen that the fluctuation magnitude is reduced in proportion to the mean flow. Similar behaviour is observed for the Bendix Micronair II pumps as indicated in Table I. In contrast, the Du Pont P-2500 pump fluctuation decreases in frequency but not amplitude as shown in Figure 4. In this case, the mean flow is reduced by lowering the pump frequency rather than by restricting the flow. The result is a larger ratio of pulsation amplitude to mean flow at the lower flow rate. Figure 5 shows a comparison of fluctuation at the loadless pump with that at the cyclone aperture for sampling using a Bendix Micronair II pump. Resonant effects on the fluctuation, as described in the previous section, are evident. Although the fundamental is the largest oscillation mode observed at the pump, resonant amplification leaves the fifth or sixth harmonic dominant in the fluctuation at the cyclone.

It is noted that the pulsation induced by the Du Pont P-2500 pump as given above appears much larger in comparison with the MSA Model G pump than that reported elsewhere.⁽¹⁰⁾ The discrepancy is apparently due to differences in method, however, since the fluctuation measurements⁽¹⁰⁾ were carried out in an entirely different manner from those

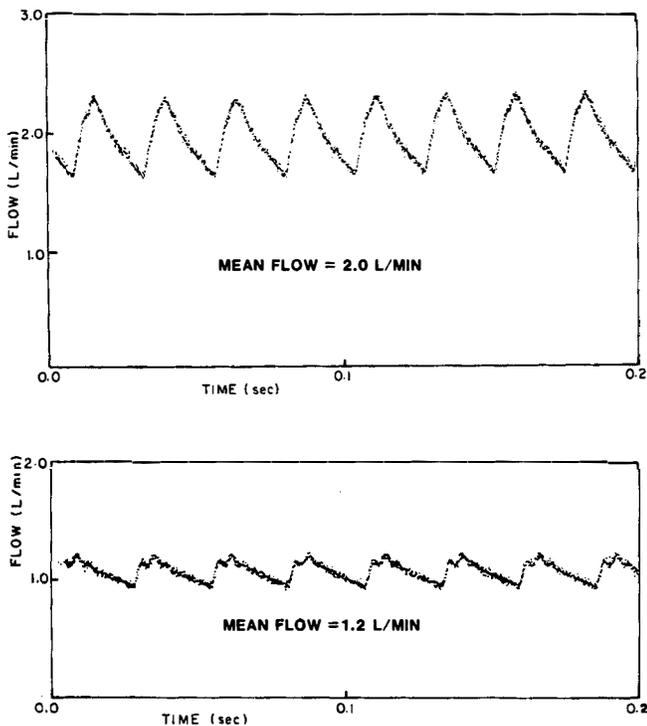


Figure 3 — Decrease in MSA Model G pump fluctuations at cyclone aperture as mean flow is reduced from 2.0 L/min to 1.2 L/min.

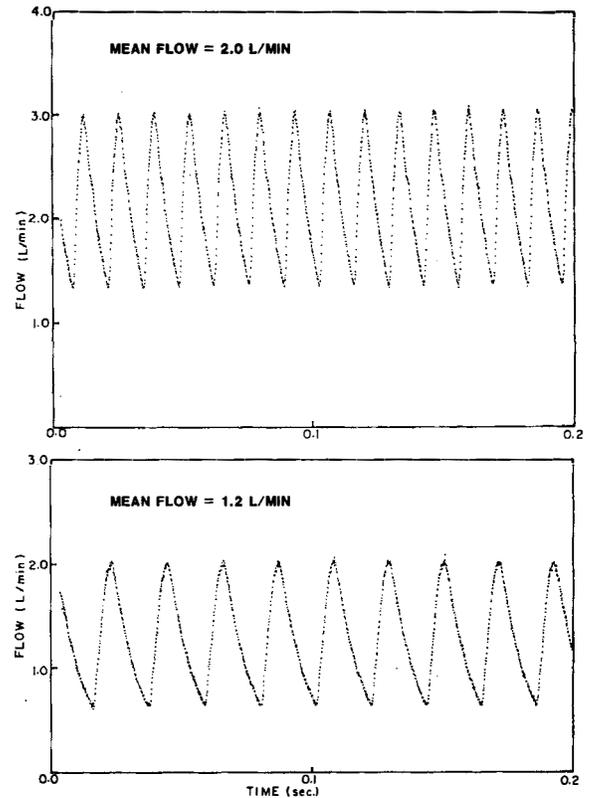


Figure 4 — Comparison of Du Pont P-2500 pump fluctuations at cyclone at mean flows equal to 2.0 L/min and 1.2 L/min.

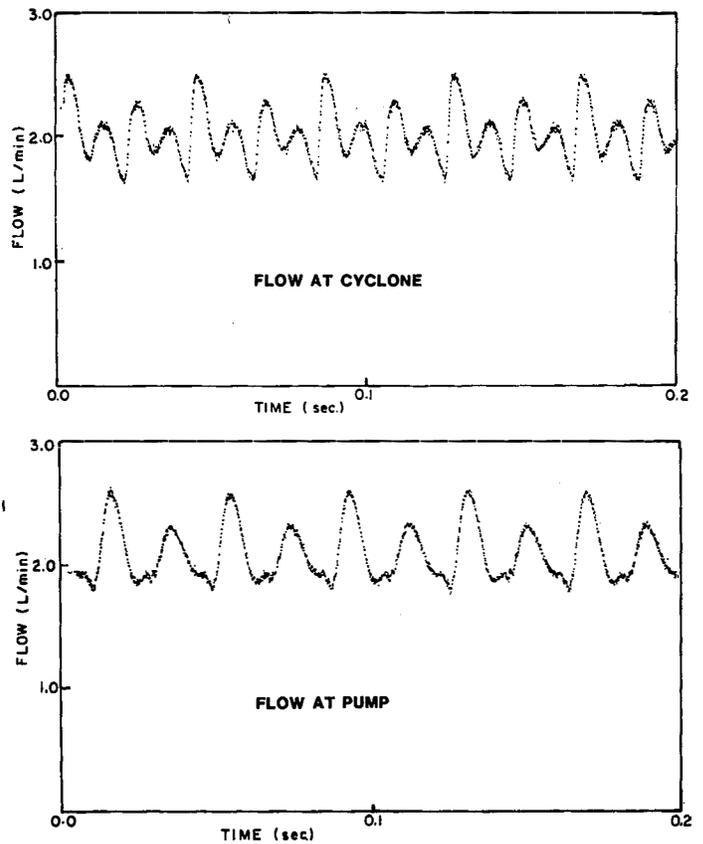


Figure 5 — Comparison of Bendix Micronair II pump pulsations at cyclone aperture with those measured at the pump itself. Note resonant alteration of fluctuation shape.

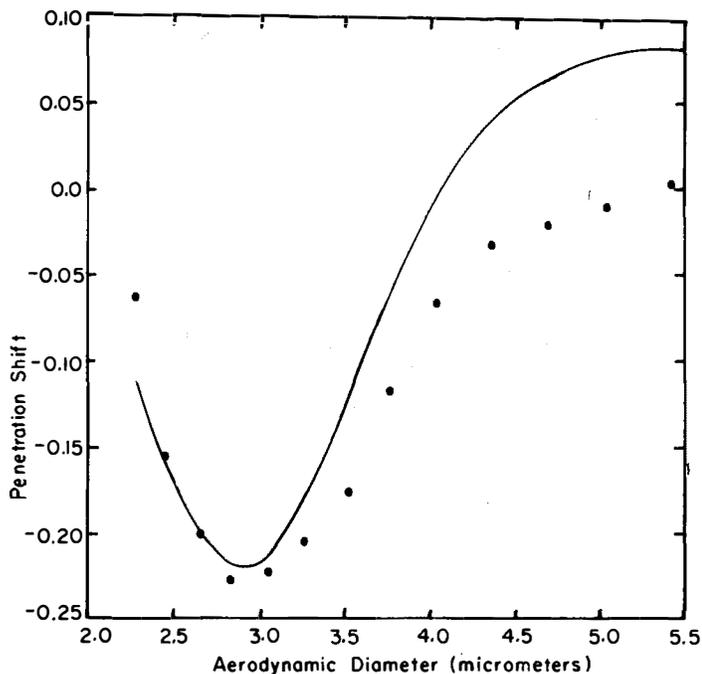


Figure 6 — Inadequacy of static theory (solid curve) to describe measured penetration shift (solid dots), particularly at the larger particle sizes. The pulsation amplitude is equal to 91% of mean flow, and the penetration shift measurements were made at a frequency equal to 66 Hz.

described here. Rather than using an anemometer probe near the cyclone aperture, a pressure transducer was employed to monitor the pressure shift across a constriction in a line between pump and cyclone sampling head. Differences in the sensors, as well as in the resonant character of the two separate flow arrangements, can easily account for the contrasting results. Variation in the pumps themselves can be ruled out, as we were afforded the chance to measure the

very pumps used in the other investigation⁽¹⁰⁾ and found results in agreement with those presented in Table I. In any case, side-by-side evaluations⁽¹⁰⁾ of coal dust sampling with flow controlled by critical orifice in comparison with the Du Pont P-2500 pump appear not inconsistent with the results of the next section.

Effect of Pulsation on Cyclone Penetration

Measurement of cyclone penetration shift in terms of pulsation is necessary to estimate the effect of a given pump's fluctuations on cyclone operation from data such as that in the previous section. Since the time t_c required for sampled air to make a single loop within the cyclone is an order of magnitude shorter than typical pump pulsation periods, it might be expected that frequency dependent effects would be insignificant. In other words, the shift in the cyclone penetration might simply be computed as a numerical average of constant flow penetrations over a single pump cycle. However, experiment shows this static or cycle average theory to be inadequate for predicting actual penetration shifts corresponding to frequencies of interest. The inadequacy of static theory, particularly at large particle diameters, may be seen in Figure 6. The calculated penetration shift is compared with that measured as described below corresponding to pulsation amplitude equal to 91% of a 2.0 L/min mean flow.

The TSI Aerodynamic Particle Sizer (APS) was employed to measure the cyclone penetration shift effected by controlled pulsation. Penetration curves for an MSA cyclone at zero fluctuation were measured at flow Q equal to 1.5 L/min, 2.0 L/min and 2.5 L/min using experimental techniques described elsewhere.⁽¹³⁾ Figure 7 shows experimental cyclone penetration as a function of aerodynamic diameter D and the computed values from a mathematical model function $Pen(D, Q)$ as described elsewhere.⁽¹¹⁾

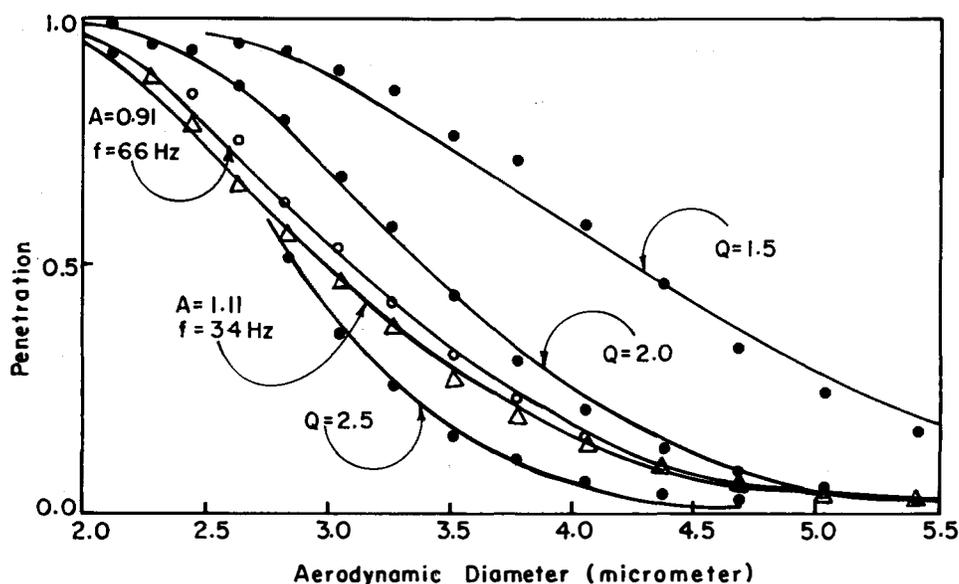


Figure 7 — Comparison of model (solid curves) and experimental values of penetration. Solid points correspond to zero pulsation and open points to fluctuation about mean flow equal to 2.0 L/min.

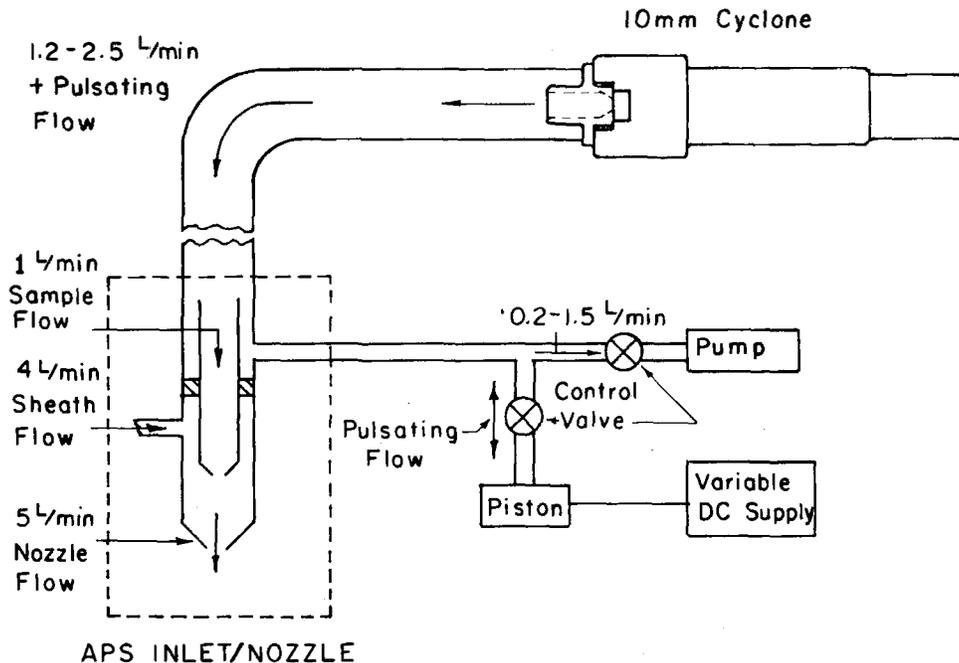


Figure 8 — Experimental arrangement for producing controlled sinusoidal pulsation.

The functions $Pen(D, Q)$, represent the penetration $Pen_{static}(D, \{Q(t)\})$ for pulsations of arbitrary amplitude within the cycle. Note that the quantity Pen_{static} is explicitly denoted as a function of the entire time dependent function $Q(t)$. Pen_{static} is the average of constant flow $Pen(D, Q)$ over a pump pulsation cycle:

$$Pen_{static}(D, \{Q(t)\}) = \frac{\int dt Q(t) Pen(D, Q(t))}{\int dt Q(t)} \quad (1)$$

The integration limits in Equation 1 are equal to the sampling period, but can be replaced by the pump period if the latter is small compared to the sampling period.

The APS was used to measure cyclone penetration with a sinusoidal fluctuation superimposed upon the constant flow. Constant flow was provided by the APS needle-valve controlled pumps while the pulsating flow was provided by simple piston arrangement as indicated in Figure 8. The oscillation frequency was fixed by the voltage of a DC motor driving the piston. Pulsation was monitored by an anemometer probe cemented to the cyclone as described above. Measurements indicated that no calibration shift or resolution degradation of the APS occurred under fluctuating flow conditions. Furthermore, penetration measurements with and without the probe in place at the cyclone aperture showed that the probe itself did not alter the cyclone inlet characteristics.

Data for the cyclone penetration at two pulsation frequencies and amplitudes for mean flow equal to 2.0 L/min are given in Figure 7. As mentioned above, Pen_{static} obtained by numerical computation using Equation 1 is insufficient for predicting penetration shifts for the larger particles. Therefore, in order to represent the data, a frequency dependence in the penetration function is essential. An arbitrary, real, coherent flow fluctuation $\delta Q(t)$ about mean

flow \bar{Q} with amplitudes $A_j (= A_j^*)$ and frequencies $f_j (= -f_{-j})$ may be represented by

$$\delta Q(t) = \sum_j (A_j/2) \exp(-i2\pi f_j t) \quad (2)$$

As a tentative empirical model, the following functional form for the penetration in terms of $\delta Q(t)$ has been adopted:

$$Pen(D, \{Q(t)\}) = Pen_{static} + Pen_{dynamic} \quad (3)$$

where Pen_{static} is given by Equation 1. $Pen_{dynamic}$ is taken to be

$$Pen_{dynamic} = \sum_j a_1 (A_j/\bar{Q})^2 \sqrt{f_j t_c} (D/D_{cut} - a_2)^3 D_{cut} \partial Pen(D, \bar{Q}) / \partial D \quad (4)$$

where the dimensionless constants $a_1 = 1.63$ and $a_2 = 0.735$ were selected to fit the data of Figure 7, D_{cut} is the diameter at which $Pen(D, \bar{Q}) = 0.50$ and t_c is set equal to $0.04 \text{ cm}^3/\bar{Q}$.

The functional form of the frequency and diameter dependence adopted for Equation 4 is purely empirical. However, the indicated dependence on the separate fluctuation harmonics is suggested by the following. Just as a very general class of functions of a single variable can be expanded about a point as a Taylor's series expansion, suppose that the functional $Pen_{dynamic}$ is expressible as an expansion in the function $\delta Q(t)$ about zero:

$$Pen_{dynamic} = \int dt_1 p_1(D; t_1) \delta Q(t) + \int dt_1 \int dt_2 p_2(D; t_1, t_2) \delta Q(t_1) \delta Q(t_2) + \dots \quad (5)$$

Carrying out the integrations indicated in Equation 5 using Equation 2 shows that terms linear in the amplitudes A_j , including interference terms from separate modes of oscilla-

tion, average to zero. Thus to lowest order in A_j , $Pen_{dynamic}$ is given by

$$Pen_{dynamic} = \sum_j |A_j/2|^2 p(D, f_j), \quad (6)$$

(where $p(D, f_j) = p_2(D; f_j, -f_j)$, the double Fourier transform of the Taylor coefficient function $p_2(D; t_1, t_2)$). Equation 6 shows the rationale for the quadratic dependence on amplitude and the additivity of contributions by different harmonics as appear in the model function, Equation 4.

The above model may be applied to the computation of the bias expected in dust concentration estimates obtained by sampling with a fluctuating pump in comparison with a constant flow pump. This model involves an extrapolation and therefore may be expected to predict only order of magnitude effects. Nevertheless, the results are presented here for several of the pumps described in the previous section.

For a given dust size distribution, it is possible to compute the bias defined by

$$BIAS = [Pen(D, \{Q\}) - Pen(D, \{Q(t)\})] / Pen(D, \{Q\}) \quad (7)$$

For realistic calculation, several log-normal size distributions presumed⁽¹⁴⁾ to be characteristic of coal mine dusts were used. The expected bias computed for several representative pumps and mean flow rates is presented in Table II at specific values of mass median diameter (MMD) and geometric standard deviation (GSD). The calculational accuracy is reflected in the BIAS digits significant to 0.001, although the accuracy as a predictive estimate is as yet unknown.

Note that at flow near 2.0 L/min, the predicted bias is of the order of -1% for the Bendix and MSA pumps. On the other hand, the bias induced by the Du Pont P-2500 pumps at 2.0 L/min (Figure 4) is predicted to be approximately -5%. This may be compared with the laboratory evaluation of dust sampling using the Du Pont P-2500 pumps reported elsewhere⁽¹⁰⁾ where the bias was found to average about -2.5% for dusts of unknown size distribution.

Similarly, at lower flow rates, such as near 1.2 L/min, both the MSA Model G and Bendix Micronair II pumps are expected to induce negligible fluctuation related bias in the respirable coal mine dust concentration estimates because the fluctuation is proportional to flow rate in these pumps. On the other hand, as seen in Table II, the bias from the Du Pont P-2500 pump at lower flow rates may be on the order of -20% for some dust size distributions. Such a large bias — together with inescapable random errors — would preclude validation according to the NIOSH standard⁽¹⁵⁾ requiring better than 25% accuracy in any given sample at the 95% confidence level. Furthermore, because of the variability of the bias over the test size distributions, the bias cannot be eliminated by calibration. It may be possible, however, to select an optimal value of mean flow for this pump (with its large fluctuations) for estimating respirable dust, if inter-pump variation of the fluctuations is negligible. Alternatively, the pulsation dampener of the Du Pont P-2500 pump could be improved.

Conclusions

This paper has described research into the effects on respirable dust sampling due to fluctuations in the flow of sampled

TABLE II
Estimated Bias (Relative to Zero-Pulsation Sampling) Computed for Given Mass Median Diameter and Geometric Standard Deviation

MMD (micrometers)	GSD	BIAS
Du Pont P-2500 Pump No. 3, Mean Flow = 2.15 L/min:		
10.6	2.20	-0.069
3.01	1.87	-0.055
7.70	3.01	-0.049
3.07	2.81	-0.035
10.1	2.92	-0.055
2.88	2.19	-0.043
3.79	2.42	-0.046
11.3	2.40	-0.066
11.1	2.80	-0.058
11.4	2.60	-0.062
MSA Model G Pump No. 1, Mean Flow = 1.88 L/min:		
10.6	2.20	-0.010
3.01	1.87	-0.008
7.70	3.01	-0.007
3.07	2.81	-0.005
10.1	2.92	-0.008
2.88	2.19	-0.006
3.79	2.42	-0.007
11.3	2.40	-0.010
11.1	2.80	-0.008
11.4	2.60	-0.009
Bendix Micronair II Pump No. 1, Mean Flow = 2.02 L/min:		
10.6	2.20	-0.014
3.01	1.87	-0.009
7.70	3.01	-0.009
3.07	2.81	-0.006
10.1	2.92	-0.010
2.88	2.19	-0.008
3.79	2.42	-0.008
11.3	2.40	-0.013
11.1	2.80	-0.011
11.4	2.60	-0.012
Du Pont P-2500 Pump No. 3, Mean Flow = 1.24 L/min:		
10.6	2.20	-0.220
3.01	1.87	-0.076
7.70	3.01	-0.119
3.07	2.81	-0.065
10.1	2.92	-0.144
2.88	2.19	-0.067
3.79	2.42	-0.086
11.3	2.40	-0.199
11.1	2.80	-0.159
11.4	2.60	-0.178

air. The complexity of the transfer of fluctuations from sampling pump to sampling head appears to mandate characterization by measurement of the fluctuation near the sampling head during operation of the entire CMDPSU. Several units were characterized in this manner and Fourier components of the flow pulsations were computed. In order to understand the significance of these results to dust sampling, the penetration of the cyclone was measured with sinusoidally fluctuating flow. Simply computing the average of constant flow penetration curves over the fluctuation cycle was found inadequate in predicting the experimental penetration curves. Thus, the fluctuation induced penetration shift includes a significant frequency dependent contribution which was found, moreover, to increase rapidly with aerosol diameter.

A pulsation effect model was adopted to estimate the bias in concentration measurements for any given dust size distribution and pump fluctuation profile. These results may be applied to CMDPSU and other respirable dust sampler design. Furthermore, if present policy of restriction of coal dust sampling to the use of the 10 mm cyclone is continued, the measurement and analysis techniques described in the paper provide the basis for a test method for alternate pumps.

Aside from these immediate applications, the research suggests several areas for further study. The confidence in the mathematical model adopted above and its domain of applicability requires improvement by experimental comparisons. Furthermore, extension of sampling head characterization to other sampling heads, such as the Bendix unit, and to the measurement of variability between samplers of the same type seems reasonable in view of the possible effect of the filter capsule flexibility on the resonant flow structure. Clearer understanding of the frequency dependence of the cyclone's penetration would be useful — perhaps dust can penetrate initial parts of the cyclone during low flow portions of the pump cycle only to be impacted on normally clean areas of the cyclone surface during high flow. Finally, research on pump fluctuation effects on the performance of other types of sampling instruments seems warranted.

Acknowledgements

The authors would like to thank Ova Johnston and W. James Woodfin for constructing a piston used in the experimentation of this paper, Donald J. Murdock for the excellent draw-

ings, and Kenneth Williams and George Schnakenberg, Bureau of Mines, for providing Du Pont P-2500 pumps for comparison with NIOSH equipment.

References

1. Anderson, D.P., J.A. Seta and J.F. Vining, III: *The Effect of Pulsation Dampening on the Collection Efficiency of Personal Sampling Pumps*. DHEW, Cincinnati, OH (1971).
2. Lamonica, J.A. and H.N. Treaftis: *The Effect of Pulsation Damping on Respirable Dust Collected by Coal Mine Dust Personal Samplers*. BOM Report of Investigations 7636 Pittsburgh, PA (1972).
3. Blachman, M.W. and M. Lippmann: Performance Characteristics of the Multicyclone Aerosol Sampler. *Am. Ind. Hyg. Assoc. J.* 35:311-316 (1974).
4. Caplan, K.J., L.J. Doemeny and S. Sorenson: *Evaluation of Coal Mine Dust Personal Sampler Performance*. Final Report, NIOSH Contract No. PH CPE-R-70-0036 (1973).
5. Lamonica, J.A. and H.N. Treaftis: *Investigation of Pulsation Dampers for Personal Respirable Dust Samplers*. BOM Report of Investigations 7545, Pittsburgh, PA (1971).
6. LaViolette, P.A. and P.C. Reist: Improved Pulsation Dampener for Respirable Dust Mass Sampling Devices. *Am. Ind. Hyg. Assoc. J.* 33:279-282 (1972).
7. McCawley, M.A. and M.M. Roder: Test Procedure for Coal Mine Dust Personal Sampling Units. NIOSH Report, NTIS No. PB 251 353, Morgantown, WV (1976).
8. McCawley, M.A. and M.M. Roder: Test Procedure for Coal Mine Dust Personal Sampler Unit Pulsation Dampener. NIOSH Report, NTIS No. PB-247 425, Morgantown, WV (1975).
9. *Code of Federal Regulations*, Title 30, Part 74 (1974).
10. Timko, R.J., K.L. Williams and G.H. Schnakenberg, Jr.: *Laboratory Evaluation of the Du Pont P-2500 Automatic Flow-controlled Personal Dust Sampling Pump*. BOM Report of Investigations 8637, Pittsburgh, PA (1982).
11. Bartley, D.L. and G.M. Breuer: Analysis and Optimization of the Performance of the 10 mm Cyclone. *Am. Ind. Hyg. Assoc. J.* 43:520-528 (1982).
12. **British Medical Research Council**: Recommendations of the MRC Panels Relating to Selective Sampling. In *Inhaled Particles and Vapours*. Pergamon Press, Oxford, U.K. (1961).
13. Baron, P.A.: *Sampler Evaluation with an Aerodynamic Particle Sizer*. Int. Symp. on Aerosols in the Mining and Industrial Environment, NIOSH, Minneapolis, MN (1981).
14. Bowman, J.D., D.L. Bartley, G.M. Breuer, L.J. Doemeny and D.J. Murdock: *Accuracy Criteria Recommended for the Certification of Gravimetric Coal Mine Dust Samplers*. NIOSH Report, Cincinnati, OH (1984) (in press).
15. Gunderson, E.C. and C.C. Anderson: *Development and Validation of Methods for Sampling and Analysis of Workplace Toxic Substances*. DHHS (NIOSH) Publication No. 80-133, Cincinnati, OH (1980).

APPENDIX

A semi-quantitative treatment of the resonance of the air column in the tubing between pump and sampling head is given here. A simple derivation of the functional form of the response of a partially closed air column is presented. The expression obtained involves a single parameter r ($|r| < 1$), a reflection coefficient, which is selected to fit the data of Figure 1 over a limited range of frequencies. It is then shown that the value so obtained for r can be almost entirely explained by the pressure drop imposed by the sampling filter.

Probably the simplest understanding of flow fluctuations moving as waves at the speed c of sound in an air column of length L is gained by considering the reflection of sharp pulses from the partially closed end. Assume that a pulse, upon such reflection, is simply reversed in direction and is multiplied by a constant r . Neglected here are effects of the tubing flexibility (reducing the wave speed slightly) and also corrections of the order of magnitude of the ratio v/c due to the non-zero mean velocity v of air flowing through the tube.

What is desired is the velocity fluctuation $\delta v(x,t)$ at time t and at position $x = L$ (the open end) in terms of that defined by the pumping system at $x = 0$. To calculate $\delta v(x,t)$, it is simplest first to calculate the response $g(x,t)$ due to a single (normalized) pulse $\delta(t - x/c)$ from a fictitious pump at $x = 0$. Then because of the linearity of the system, $\delta v(x,t)$ can be constructed by superimposing such responses due to pulses set up, like a histogram, to mimic the actual pump action:

$$\delta v(x,t) = \int_{-\infty}^t dt' g(x,t-t') \delta v(0,t') \quad (\text{a1})$$

The response function $g(x,t)$ itself may be built up out of individual pulses. The only constraints are the reflection rule given above for $x = L$ and the fact that $g(x,t)$ is maintained equal to zero at the pump (at $x = 0$) for all time $t > 0$ after the initial pulse is released. Therefore, the pulse $\delta(t - x/c)$ gives rise to a reflected pulse $r\delta(t + x/c - 2L/c)$. This reflected pulse is met at $x = 0$ by a pulse $r\delta(t - x/c - 2L/c)$, selected to keep $g(x,t) = 0$ at $x = 0$ for all $t > 0$. This third pulse moves towards $x = L$ and is reflected, repeating the process. The result is an infinity of reflections which define $g(x,t)$ as

$$g(x,t) = \delta(t - x/c) + \sum_{j=1}^{\infty} (-r)^j [\delta(t - x/c - 2Lj/c) - \delta(t + x/c - 2Lj/c)] \quad (\text{a2})$$

(The first three terms are precisely the waves described above.)

Now suppose that the air flow fluctuation at the pump is purely harmonic with frequency $f = \omega/(2\pi)$; *i.e.*, let

$$\delta v(0,t) = \delta v_0 e^{i\omega t} \quad (\text{a3})$$

Substituting the expressions of Equations a2 and a3 into Equation a1 and carrying out the integration gives the fluctuation $\delta v(L,t)$ near the open end of the air column as

$$\delta v(L,t) / [\delta v_0 e^{i\omega(t-L/c)}] = (1+r) \sum_{j=0}^{\infty} (-r)^j e^{-i2Lj\omega/c} \quad (\text{a4})$$

$$= [1+r] / [1 + re^{-i2L\omega/c}] \quad (\text{a5})$$

Calculating the magnitude of both sides of Equation a5 yields.

$$|\delta v(L,t) / \delta v(0,t)| = [\cos^2(L\omega/c) + B^2 \sin^2(L\omega/c)]^{-1/2} \quad (\text{a6})$$

where B is defined by

$$B = (1-r)/(1+r) \quad (\text{a7})$$

The right side of Equation a6 has extrema equal to B^{-1} at frequencies where $\cos(L\omega/c) = 0$; *i.e.*, at $f = c(2n+1)/(4L)$ (integer n).

The expression (a6) can now be compared with the data of Figure 1. First note that $B = 0$ ($r = 1$) corresponds to an open tube, for which Equation a6 is plotted in Figure 1; whereas $B = \infty$ for a closed tube. Judging from the data of Figure 1, the system clearly appears to lie between these two extremes. Furthermore, as the peak at $f = 3c/(4L)$ is larger than that at $f = c/(4L)$, B appears to be a decreasing function of frequency. As the data maximum at $f = c/(4L)$ is roughly equal to 1.7, the quantity B is evidently of the order of 0.6 in this frequency range. The corresponding values of Equation a6 for a partially closed air column are given in Figure 1.

As a candidate for the underlying cause of the air column closure, it is natural to consider the sampling filter. Suppose the pressure drop across the filter is proportional to the velocity. Therefore, if p is the pressure just inside the air column and p_0 is atmospheric pressure, then

$$\delta(p - p_0) = b\rho_0 c \delta v \quad (\text{a8})$$

where p_0 is the mass density of air. The dimensionless constant b is easily measured under static conditions ($f = 0$) and found to equal approximately 1.2 for the MSA filters of interest here. Now, by slight manipulation of the equations of fluid dynamics (the Navier-Stokes and continuity equations), Equation a8 can be expressed as a ("mixed") boundary condition which $\delta v(x,t)$ must satisfy near the filter:

$$(b\partial/\partial ct + \partial/\partial x)\delta v(x,t) = 0 \quad (\text{at } x = L) \quad (\text{a9})$$

Finally, it is a simple matter to show that Equation a9 is satisfied, term-by-term in Equation a2, if $B = b$.

Therefore the filter pressure drop is more than enough to reduce the infinite peaks down to the experimental values. The explanation of the apparent f -dependent drop in B is as yet unknown, but may be due, for example, to the flexibility of the filter.

4 February 1983; Revised 22 August 1983