

A cyclone separator for aerosol sampling in the field

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INTRODUCTION

The concentration of bacteria in the open air is usually very small—of the order of 1 viable organism in some tens of litres. Spores and fragments of moulds are more frequent by a factor of about 100. Both figures fluctuate wildly with season and weather, and even from hour to hour. Higher concentrations are found downwind of local sources of contamination; for example, ploughing and harrowing in dry soil and discharge of raw sewage. But even in such instances nearly all the organisms which become airborne are of no consequence to public health or agriculture except perhaps as indicators. Effective biological analysis of the airborne particles, and especially the detection of significant changes in concentration, therefore calls for the use of samplers working at a high flow rate and capable of concentrating the particulate contents of a large volume of air into a small volume of liquid.

Large cyclones have long been in industrial use as coarse filters for removing dust. But to be effective in removing fine particles a cyclone must be small in physical size and must be worked at a high gas velocity. No satisfactory theory of the cyclone has been evolved, but existing analyses suggested that a cyclone of the dimensions shown in Fig. 1 would (*a*) collect 50% of particles 0.85 μ in diameter (Lapple, 1950), or (*b*) collect all particles greater than 2.2 μ in diameter (Davies, 1952), the particles being of unit density and the flow rate 75 l./min. Fuchs's (1964) general discussion further supported this estimate, on which our design is based.

A cyclone which is to be used as a sampling device and not merely as a scavenger must be provided with a ready means for removing the deposited particles either continuously or at frequent intervals. In large cyclones cleaning is often carried out by injecting a spray of water (Stairmand, 1956). The water drops are themselves thrown to the walls and wash down the deposit through the tail pipe into an airtight container. Whether the same principle would be effective on a small scale seemed at first doubtful, if only because of surface tension effects. Experiment showed that injected water collected as an uneven film completely covering the inner wall and moving helically towards the lower apex, where the rotation was very rapid and turbulent. Continuous scrubbing was achieved by inducing a slight suction at the tail pipe, so that the liquid was drawn into the receiver.

CONSTRUCTION AND USE

The cyclone has been made in two sizes in either Perspex or stainless steel (Plate 1). Stainless steel is much the heavier and more difficult to machine, but its robustness is a great advantage in field work, where the operator's care may be reduced

by exposure to uncomfortable conditions for long periods. The smaller cyclone is intended to work at a flow rate of about 75 l./min. with a pressure drop of 75 mm. Hg; the larger at about 350 l./min. at a pressure drop of 200 mm. Hg. It will be sufficient to describe the smaller.

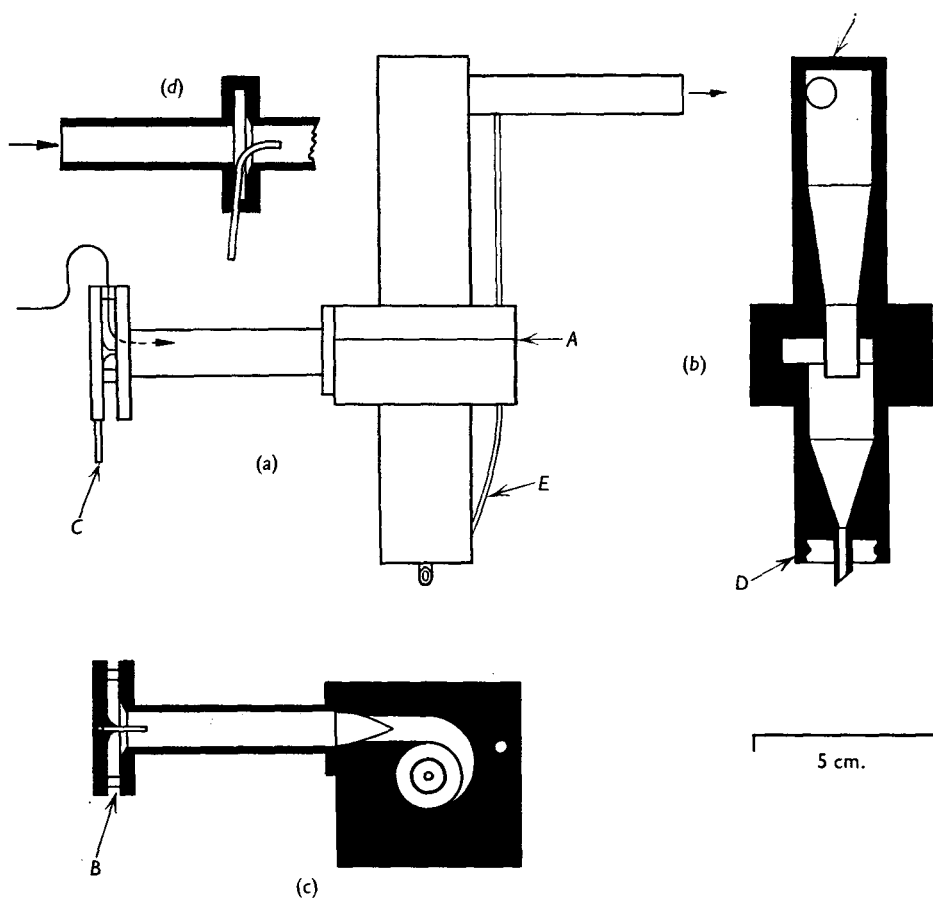


Fig. 1. (a) Side elevation of cyclone. *A*, Junction of upper and lower components; *C*, side-tube for introducing scrubbing liquid; *E*, tube connecting receiver to outlet. (b) Axial section normal to axes of inlet and outlet pipes. *D*, Hood for connecting sample receiver, *F*, outlet pipe set tangentially. (c) Transverse section through axis of inlet pipe. *B*, Annular gap for entry of aerosol. (d) Adapter for coupling to closed chambers; section.

The internal diameter over the cylindrical part (Fig. 1*b*) is $\frac{1}{2}$ in., and the other dimensions are in the proportions suggested by Lapple (1950), except that there is a volute entry (Fig. 1*c*). The throat is $\frac{1}{4}$ in. square in section, giving an average normal acceleration of about 10^7 cm./sec.² ($10^4 \times$ gravity) at the top of the cyclone. The main body is constructed in two parts, joined at *A* (Fig. 1*a*). Before assembly the volute is formed by end-milling in the upper face of the lower part, and the overflow pipe by machining the lower face of the upper part. Thereafter the inlet tube is

screwed on and the junction faired from a circular to a square section by means of a taper reamer. The actual inlet is an annular gap between two plates (*B*; Fig. 1*c*), one of which is a flange on the inlet tube. The other carries a fine tube at its centre through which the scrubbing liquid is fed *via* the side-tube *C* (Fig. 1*a*). In field use, the face of the outer plate is presented to windward and serves to exclude coarse particles. This plate may be replaced by an adapter (Fig. 1*d*) for sampling from experimental chambers.

Samples are collected in bijou bottles screwed into the hood *D* (Fig. 1*b*) enclosing the tail pipe; the joint must be airtight. In order to ensure the transfer of the scrubbing liquid to the bottle, the hood is connected by a fine tube, 0.6 mm. inside diam. (*E*; Fig. 1*a*) to the outlet, where the pressure is lower. Even in the absence of liquid the air flow ('underflow') through the side-tube is very small compared with the total flow, and cannot appreciably upset the working. The scrubbing liquid is best supplied by a peristaltic pump giving a continuous flow. The pumping rate should be variable within the range 0.5–2 ml./min., because only a variable fraction of the injected liquid reaches the receiver. There are two causes of loss: (i) Some of the liquid impinges in the volute, and the reverse eddy in this region (van Tongeren, 1935) causes part of this liquid to creep over the roof of the cyclone and the outside of the overflow tube into the outlet. The loss of deposited particulates (most of which impinge at a lower level) from this cause appears to be negligible; (ii) The scrubbing liquid is brought into intimate and violent contact with the air; the amount which evaporates varies with the ambient humidity. The pump, then, should be adjusted so that liquid is delivered to the receiver at an approximately constant rate, e.g. about 0.75 ml./min.; the particulate contents of 100 l. of air are then concentrated into about 1 ml. of liquid. The sample volumes should be measured, or else made up to a convenient fixed volume.

In order to minimize pressure drop and at the same time to encourage entrained liquid to creep along the walls rather than to be broken up and become airborne, the overflow tube widens gradually into a cylindrical enlargement in which the outlet tube is set tangentially (*F*; Fig. 1*b*). Most of the entrained liquid evaporates in this upper chamber.

The air flow through the cyclone is best regulated by interposing a critical orifice (Druett, 1955) between cyclone and pump. The orifice should be rated to pass 84 l./min.; this corresponds to a flow of 75 l./min. of free air entering the cyclone. The pump displacement then needs to be 120–150 l./min.; a suitable pump is the 'Wade Minor 300F' (Messrs. J. T. Wade and Sons, Ltd., High Wycombe, Bucks).

The linear dimensions of the larger cyclone are twice those of the smaller (Plate 1), and the proportions are the same except that the throat is relatively smaller; it is rectangular, $\frac{1}{2}$ in. deep in the direction of the main axis and $\frac{3}{8}$ in. wide in the radial direction. The larger cyclone permits of concentrating the particulate contents of 500 l. of air into 1 ml. of liquid. The loss by evaporation of the liquid is correspondingly greater.

The pressure at the lower apex of a cyclone is below that at the inlet, and no liquid is lost if a sample container is detached. At the same time little liquid can accumulate during the few seconds required to change a container, and it is un-

necessary to interrupt the flow of either liquid or air. It is thus easy to obtain an indefinitely long and uninterrupted series of samples.

PERFORMANCE

Small cyclone

Some typical experiments only are described here, but it is to be understood that the conclusions asserted are supported by a multiplicity of experiments of each kind.

Expt. (a)

A suspension of *Bacillus globigii* spores, 9×10^9 /ml., was sprayed into a chamber from a standard 3-jet Collison atomizer. Samples of the aerosol were taken by means of Porton impingers (May & Harper, 1957) alternately directly from the test chamber and after passing through the cyclone into a subsidiary chamber. After each sampling period the cyclone, drawing atmospheric air at 75 l./min., was scrubbed by the injection of saline; three successive samples each of 2 ml. were collected. The liquid samples were plated out in the conventional way on tryptone agar. Control samples of atmospheric air were taken into impingers; they were found to contain a negligible number of recognizable *B. globigii*.

The direct impinger counts gave for the chamber concentration 244 spores/l. (391 colonies actually counted). In the air passing the cyclone, the count was 48.5/l. (80 colonies counted). This gives an apparent gross efficiency of 80%.

Each cyclone sampling period represented 505 l. of chamber aerosol, equivalent to 123,100 spores. The washings contained on average:

1st washings	101,700 (305 counted)
2nd washings	6,900 (104 counted)
3rd washings	3,100 (460 counted)
Ratio 1st/2nd 15:1	

—total 111,700, implying an apparent gross efficiency of 91%. The difference from the preceding figure is not significant.

This result illustrates a phenomenon found to be general: the washing of organisms from the cyclone wall is far from instantaneous, and the concentration in successive washings does not decrease in geometrical progression. The latter fact means that deposited organisms are not homogeneous in respect of their susceptibility to removal; this is not surprising, since particles of different sizes (and containing different numbers of organisms) are deposited at different levels in the cyclone. The lag in delivery to the sample receiver is due in part to the accumulation of a rotating hollow plug of liquid in the lowest part of the cyclone.

Expt. (b)

The numbers of organisms entering the cyclone in experiment (a) were much larger than is usual in field work, and the failure of the scrubbing process to follow an exponential law suggested that single organisms in small numbers might be

retained tenaciously. Under the conditions used in the preliminary experiments there was some evidence for retention.

A suspension of *B. globigii* spores, 3×10^9 /ml., was sprayed from a Collison atomizer into the test chamber. At this concentration it is known that most of the aerosol particles contain one organism or none. The chamber concentration as estimated from impinger samples was 22.7 spores/l. In the air passing through the cyclone the concentration was 5.4 spores/l.—an apparent efficiency of 76%. After a sampling period of 1 min., the cyclone was scrubbed with two portions of 2 ml. of saline while drawing clean air. The numbers recovered were

1st washings 900
2nd washings 220
Ratio 4.1:1

Seventy litres of aerosol passed into the cyclone during sampling, corresponding to 1590 spores; the 1120 recovered were thus 70% of the total.

Replicate experiments of this kind gave figures of 65–70% as the apparent collection efficiency for single spores.

Expt. (c)

In the previous experiments, scrubbing was carried out as a separate operation for analytical purposes. In practice, sampling and scrubbing go on simultaneously. It might be expected that particles impacted on a dry wall would be removed with more difficulty than if impacted on a surface already wetted with a film of liquid; and this was found to be true. (Experience with large cyclones is that the droplets of scrubbing liquid collect few particles while they are airborne; the spray is effective in removing particles only at and after their impact on the walls (Stairmand, 1956). Further, the inclusion of a detergent in the scrubbing fluid greatly increased the rate of transfer of impacted organisms to the sample container; the collection efficiency as estimated from limited periods of scrubbing was increased correspondingly.

An aerosol of *B. globigii* was set up by spraying a suspension containing 8.6×10^8 spores/ml. The cyclone sampled the aerosol for 1 min., and was then allowed to draw clean air for a further 9 min. The scrubbing liquid, a standard glycine buffer (pH 8.3), was injected throughout, and the liquid in the underflow was collected as two successive 5 min. samples. The experiment was then repeated, using as scrubbing liquid the same buffer with addition of 0.1% (w/v) Tergitol. The numbers of spores collected were as follows (numbers actually counted in parentheses):

Scrubbing liquid	1st washings	2nd washings	Ratio
Control	18900 (189)	945 (183)	20:1
Tergitol	19800 (198)	300 (30)	66:1

Five other detergents, including cationic and anionic types, were tested similarly; Tergitol appeared to give most improvement, but Triton X100 and BRIJ 35 were hardly less effective. A non-ionic detergent is in any case to be preferred for its relative chemical inertness. We therefore adopted as standard a solution con-

taining sodium chloride, 0.11 M, sodium phosphate (pH 7.8), 0.02 M, together with 0.1 % w/v of BRIJ 35 (lauryl ether of polyoxyethylene). Using this solution as scrubbing liquid, the collection efficiency for single spores was greatly improved.

The following example illustrates the improvement, and at the same time indicates the desirability of keeping approximately constant the rate at which the liquid sample is collected.

An aerosol of *B. globigii* spores was set up as before and sampled for 1 min. into the cyclone, which thereafter drew clean air for a further 14 min. Scrubbing with the detergent saline was carried on throughout, and the liquid collected as three successive 5 min. samples. The rate of collection in the third sample was approximately twice that in the second. The result was (numbers actually counted in parentheses):

	Sample volume, ml.	Spores/ml.	Total spores
1st washings	3.3	12,910	42,620 (1033)
2nd washings	2.5	518	1296 (337)
3rd washings	4.25	378	1608 (246)

Here, although the concentration in the third washings was less than in the second, the total collected was greater. The rate at which organisms are washed out depends largely on the 'dilution rate' of the liquid accumulated above the tail pipe, i.e. the ratio of the liquid flow rate to the volume of accumulated liquid.

In this same experiment an impinger sample of the chamber aerosol taken immediately before the cyclone sample showed that 55,300 spores entered the cyclone (estimated from 589 colonies actually counted); the total of 45,000 recovered thus implies a collection efficiency of 82 %. The mean efficiency in five such experiments was 85 ± 12 %.

Our colleague G. J. Harper (unpublished) has made an extended comparison of the smaller cyclone with a number of accepted instruments of known performance. He finds its efficiency to be closely similar to that of the Litton Large Volume Sampler (Messrs. Litton Industries, Minneapolis, Minnesota, U.S.A.) and to be about 92 % that of the cascade impactor (May, 1945), an instrument which in its modern form is sensibly perfect over most of the important range of particle diameters (say 0.5–15 μ).

Expt. (d)

Vegetative, and especially Gram-negative, bacteria are damaged by the cyclone as by some other sampling devices (May & Harper, 1957). The loss of viability actually incurred depends on the stresses the organisms have already suffered: the materials associated with them in the particles, the time for which they have been airborne, the ambient temperature and humidity, and the presence in the air of toxic substances. Because of the great potential variability, no one experiment can be considered typical. However, we found losses of 20–40 % in the viability of *Escherichia coli* aerosols sampled from a test chamber after holding times of 5–70 min., using detergent-saline scrubbing fluid.

The loss of viability can often be mitigated by suitable additions (e.g. of carbohydrates) to the sampling fluid—simple saline solutions appear to be the least

advantageous. But the best choice of a medium appropriate to the species and experimental conditions usually calls for special investigations (Cox, 1966*a*, *b*; 1967).

Another colleague, E. J. Morris (unpublished), has used the cyclone to sample aerosols containing poliomyelitis, encephalomyocarditis and Semliki Forest viruses. He finds losses of infectivity ranging from 0 to 60 %, depending on species and holding time.

Large cyclone

Because of its large sampling rate (up to 400 l./min.) we had no ready means of carrying out formal tests of collection efficiency in the larger cyclone. Since however it is designed on the same principles as the smaller, its performance would be expected to be closely similar. It was in fact found to be so by repeated comparison in the field with instruments of known performance. An example of some independent interest is described in the next section.

Estimates of the lag were obtained by an artificial procedure; for example, the cyclone was set up in the open air and run at 338 l./min. For 10 min. a saline suspension of *B. globigii* spores (about 10^3 /ml.) was pumped in. Then the scrubbing fluid was changed to the standard sterile detergent-saline, and after 10 sec. the issuing liquid was collected in five successive 1 min. samples. The pump was adjusted so that the sample volumes were near 1 ml. The numbers found in the samples were

1st washing	420 (143)
2nd washing	73 (25)
3rd washing	18 (6)
4th washing	12 (4)
5th washing	0

Ratio 1st/2nd: 5.7

Afterwards the upper and lower parts of the cyclone were separately washed with 10 ml. of saline; no *B. globigii* was found in 0.85 ml. of either washing. This last result was repeatedly obtained; it indicates that spuriously high counts due to the detachment of accumulated clumps or flakes will be rare.

A FIELD SAMPLING EXPERIMENT

A sampling station was set up on chalk downland to leeward of a ploughed area (Fig. 2). Apart from the scrub vegetation, there were no concentrated sources of biological contamination for several kilometres upwind. Three kinds of sampler were worked during the period of the experiment: the two cyclones, drawing 75 and 338 l./min., and a slit sampler drawing 28 l./min. (The slit sampler was a modification, due to K. R. May and W. C. Wright, of the original design (Bourdillon, Lidwell & Thomas, 1941); the sampler plate, charged with a tryptone agar medium, was rotated stepwise about a horizontal axis, the entrance slit being presented directly to windward.) The cyclones were fed with the buffered detergent saline solution at about 1 ml./min. and samples were taken every 5 min. for 65 min. Afterwards the samples were each made up to 5 ml. and measured volumes were plated out on tryptone agar. The plates were incubated for 36 hr. at 35°C. For the

present limited purpose all visible colonies were counted without distinction of kind; a large proportion were obviously moulds.

The meteorological conditions (2 February 1968, 10.35–11.40 a.m. G.M.T.) were:

Mean wind: 220°, 5 kt. at 2m. above ground level; 8 kt. at 10 m.

Temperature: 4.5°C.

Relative humidity: 96 %.

Sky fully overcast; very thin spasmodic rain.

During the period of sampling, a dung-spreader distributed a load of farmyard manure over the ploughed area at a distance of 600 m. upwind (Fig. 3), returned to a store 800 m. distant to be reloaded, and distributed its second load similarly.

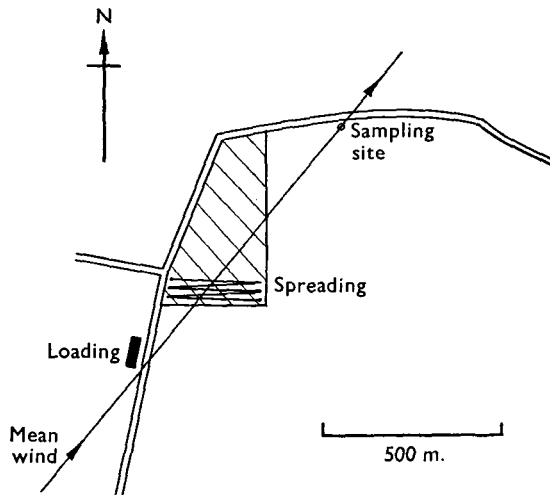


Fig. 2. Layout of field sampling experiment. Shaded area ploughed; heavy bars indicate passage of dung-spreader.

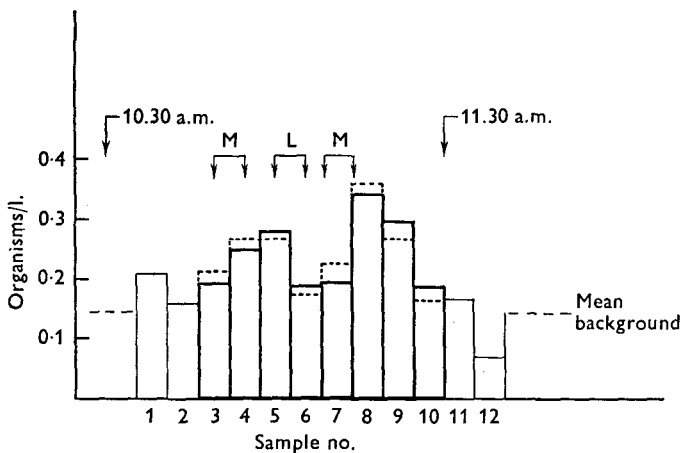


Fig. 3. Field sampling experiment. Histogram of concentrations (large cyclone); dotted ordinates corrected (Equation 3). Samples 3–10 (heavier lines) may have contained organisms derived from manuring. Activity of dung spreader indicated by yoked arrows: M, manuring; L, loading.

The timing of these operations is indicated in Fig. 3. The crude estimates of the concentration of viable particles and organisms are given in Table 1. The estimates of concentration of organisms should be regarded as nominal; apart from random sampling error, they are likely to be less than the true values because not all composite particles will be dispersed into their constituent organisms by the

Table 1. *Concentration of viable organisms in the open air, 600 m. downwind of a manuring operation*

Time	Concentrations			Concentration attributable to manuring (organisms/l.)
	Slit sampler (particles/l.)	Small cyclone (organisms/l.)	Large cyclone (organisms/l.)	
10.50-	0.000(0)	0.204 (11)	0.184(40)	0.059
10.55-	0.021(3)	0.148 (8)	0.235 (51)	0.092
11.00-	0.043(6)	0.074 (4)	0.262 (57)	0.097
11.05-	0.014(2)	0.185 (10)	0.179 (39)	0.028
11.10-	0.029(4)	0.204 (11)	0.184 (40)	0.069
11.15-	0.071(10)	0.259 (14)	0.322 (70)	0.185
11.20-	0.029(4)	0.241 (13)	0.280 (61)	0.015
11.25-	0.064(9)	0.167 (9)	0.179 (39)	0.013
Dosage	1.36 particle-min./l.	7.41 ± 2.11 organism-min./l.	9.12 ± 1.07 organism-min./l.	

samplers. From a total of eight samples taken outside the period of interest (10.50–11.30 a.m.) the background concentration (i.e. the concentration already in the air of organisms from distant sources) was estimated as 0.143 organisms/l. It will be seen that all three samplers indicate a maximum in concentration in the 8th (11.15–11.20 a.m.) sample; this suggests—though one uncontrolled example can hardly be taken to prove—that appreciable aerial contamination results from the process of manuring. The right-hand column of Table 1 gives the presumptive values of contaminant concentration attributable to manuring; these values were obtained by separately correcting the estimates obtained from the two cyclones (Appendix, equation (3)), forming weighted means, and deducting the background.

The dosages at the foot of Table 1 are simply the sums of the concentrations in the same column multiplied by the sampling interval (Appendix, Equation (4) with $g = 0$). The nominal dosages indicated by the cyclones (organism-min./l.) are about 6.5 times that from the slit sampler (particle-min./l.); the ratio is approximately the mean number of organisms per particle, say \bar{z} —again, the ratio is likely to be underestimated. Accordingly, the standard errors attached to the cyclone estimates are minimum values based on \bar{z} and Σx , the total numbers of colonies counted. It will be seen that in this case the larger cyclone gives the higher estimate, but the difference is not significant. Over the whole period of the experiment (background samples included) the dosages were

$$\begin{aligned} \text{Small cyclone:} & \quad 10.37 \pm 2.43 \\ \text{Large cyclone:} & \quad 11.96 \pm 1.32 \end{aligned}$$

—here again there was no indication of an appreciable difference in the gross efficiencies.

SUMMARY

Two cyclones for sampling dilute aerosols in the field are described. Their advantages are their robustness and reliability, the high degree of concentration achieved, and the ease with which they will provide a long uninterrupted sequence of samples.

Methods of correcting estimates of cloud concentration for transfer lag in the cyclone are derived.

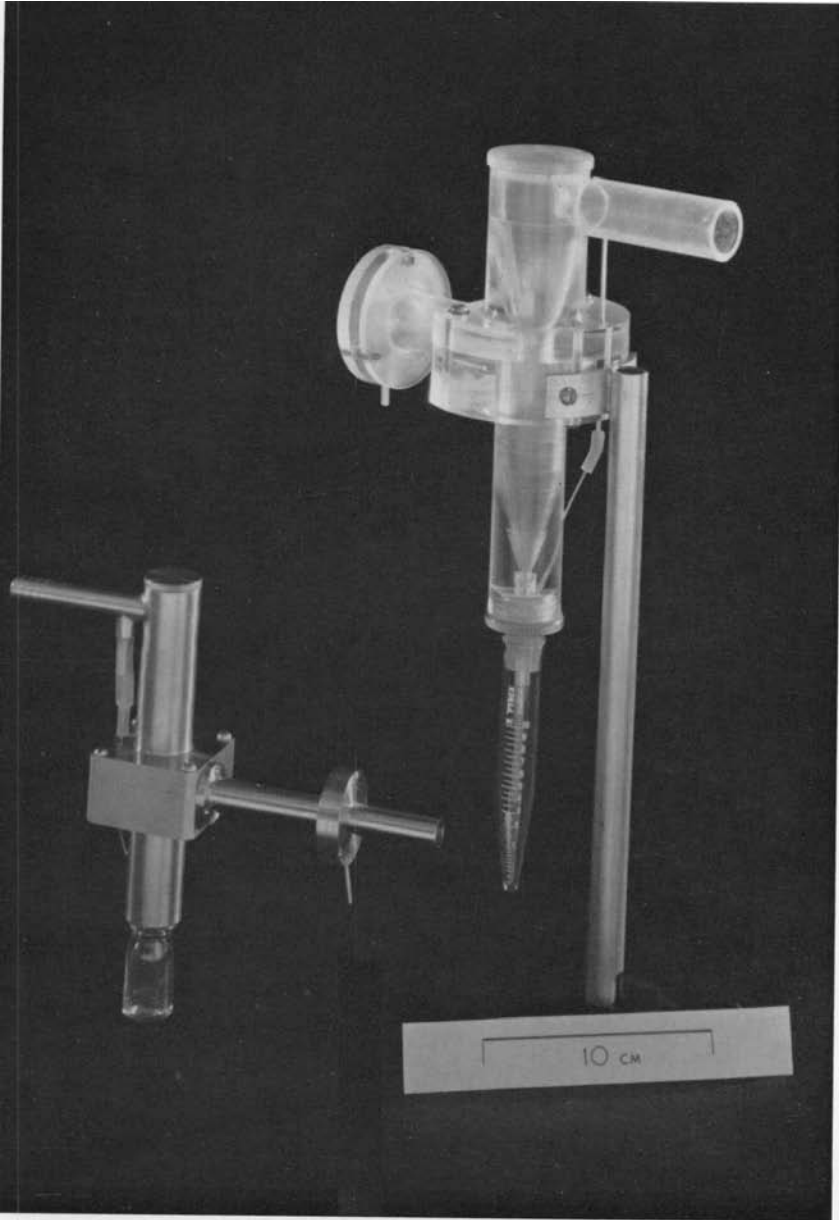
The cyclones were constructed by J. Nott. We are indebted to G. J. Harper and E. J. Morris for allowing us to make use of their observations, and to Dr J. S. Paterson (Superintendent, Allington Farm) for providing the realistic aerosol at our convenience.

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EXPLANATION OF PLATE 1

Left: Small cyclone in stainless steel with adapter for sampling from test chamber. Right: Large cyclone in Perspex with graduated sample receiver.



APPENDIX

Adjustment of data from cyclone samples

The delay in the transfer of organisms from the cyclone into the sample receiver can be characterized by a time constant (τ , say): if at any instant there are n_0 organisms within the cyclone, the number (n) of these remaining (i.e. not washed out) after time t will be given by

$$n = n_0 e^{-t/\tau}. \quad (1)$$

The lag τ can be estimated from experiments like those quoted above; if x_1 and x_2 are the numbers of organisms found in the liquid from two successive washings of equal duration Δt , and if meanwhile no new organisms enter the cyclone,

$$\tau = \frac{\Delta t}{\log(x_1/x_2)}.$$

The quantity so found will depend on the rate of scrubbing, and will appear to vary with Δt , since the removal of organisms does not follow an exponential law in fact. Only the early stages of transfer are quantitatively important, however, and a very rough value is acceptable. Thus for the first experiment quoted under (c) above (p. 391) the τ are 1.7 min. (control washing fluid) and 1.2 min. (detergent added). Unless τ is short compared with the sampling periods Δt , the lag is sufficient to introduce appreciable error into the estimates of a varying concentration (cf. Fig. 3). For during a sampling period some of the organisms entering the cyclone will not be washed down into the receiver; some which are washed down will have entered the cyclone during earlier periods. A correction for lag is easily made.

Suppose that a cyclone is sampling an aerosol of variable concentration $C(t)$ (organisms per unit volume) at a constant flow rate V . The rate at which organisms enter the cyclone is $VC(t)$ and the rate at which they are washed out by scrubbing is n/τ , where n is the number present (by differentiation of Eqn. (1)). Thus

$$\frac{dn}{dt} = VC(t) - \frac{n}{\tau};$$

if x is the number of organisms in the receiver,

$$\frac{dx}{dt} = \frac{n}{\tau},$$

and so

$$VC(t) = \frac{dx}{dt} + \tau \frac{d^2x}{dt^2}.$$

The number collected over a short interval, say from t to $t + \Delta t$, is now given by

$$V \int_t^{t+\Delta t} C(t) dt = \left[x \right]_t^{t+\Delta t} + \tau \left[\frac{dx}{dt} \right]_t^{t+\Delta t}. \quad (2)$$

Suppose now we consider three successive samples each collected over an interval Δt and containing respectively x_{r-1} , x_r , x_{r+1} organisms. Applying (2) to the middle sample, we note that

$$\int_t^{t+\Delta t} C(t) dt / \Delta t$$

is the mean concentration C_r in the aerosol for the period t to $t + \Delta t$, and that the first term on the right of (2) is simply x_r :

$$\Delta t V C_r = x_r + \tau \left[\frac{dx}{dt} \right]_t^{t+\Delta t}.$$

In the first of the three sampling periods, $t - \Delta t$ to t , the mean value of dx/dt is $x_{r-1}/\Delta t$; in the second, $x_r/\Delta t$. Taking their mean as an approximation for the derivative at t ,

$$\left. \frac{dx}{dt} \right|_t = \frac{x_r + x_{r+1}}{2\Delta t},$$

and similarly for the derivative at $t + \Delta t$.

Hence

$$\left[\frac{dx}{dt} \right]_t^{t+\Delta t} = \frac{x_{r+1} - x_{r-1}}{2\Delta t}$$

and

$$C_r = \frac{1}{V\Delta t} \left\{ x_r + \frac{\tau}{2\Delta t} (x_{r+1} - x_{r-1}) \right\}.$$

Or, if we write S_r for the uncorrected estimates ($x_r/V\Delta t$) of mean aerosol concentration in the r th sampling period,

$$C_r = S_r + \frac{\tau}{2\Delta t} (S_{r+1} - S_{r-1}). \tag{3}$$

It frequently happens that we are interested in the aerosol generated by a particular event of limited duration. In such a case the plot of concentration against time at a sampling point usually gives a bell-shaped curve, the cloud profile, but the curve may be quite erratic because of changes in wind velocity and source strength. In order to compare one profile with another, it is therefore desirable to be able to record a summary description of important features in terms of a few parameters. The first three moments of the profile form a convenient basis for such a summary. It is essential to the method that the series of samples be long enough to bracket the profile, so that its more extreme members are free from organisms derived from the source of interest, and the corresponding profile ordinates are zero.

The crude moments of the observations about a given or implied time origin are

$$m_g = \sum t_r^g S_r \Delta t \quad (g = 0, 1, 2), \tag{4}$$

where the t_r are the times from the origin to the centres of the sampling intervals. Corrected moments M_g are then given by (3):

$$M_g = \sum t_r^g C_r \Delta t = \sum t_r^g S_r \Delta t + \frac{1}{2} \tau (\sum t_r^g S_{r+1} - \sum t_r^g S_{r-1}).$$

The summations on the right can be effected by noting that

$$t_r = t_{r-1} + \Delta t = t_{r+1} - \Delta t.$$

and that, since the profile is bracketed and the extreme S_r are zero,

$$\sum t_{r+1}^g S_{r+1} = \sum t_{r-1}^g S_{r-1} = \sum t_r^g S_r.$$

Hence

$$M_0 = m_0; \quad M_1 = m_1 - \tau m_0; \quad M_2 = m_2 - 2\tau m_1.$$

Finally we may adopt as our summary values: (i) the crude moment of zero order, m_0 ; this is conventionally called the 'dosage'. (ii) The reduced first moment about the origin

$$\mu'_1 = M_1/M_0 = m_1/m_0 - \tau.$$

This is the time at the centroid of the profile. (iii) The reduced second moment about the centroid, namely

$$\mu_2 = M_2/M_0 - (M_1/M_0)^2,$$

is analogous to the variance of a frequency distribution and its square root is a measure of the duration of the cloud at the sampling point. Dr K. P. Norris (personal communication) has suggested that the 'passage time' should be taken as

$$2\sqrt{(3\mu_2)};$$

this is the (temporal) width of a rectangular profile having the same first three moments as the actual profile. In terms of the crude moments, and including the usual Sheppard correction for grouped data,

$$\mu_2 = \frac{m_2}{m_0} - \left(\frac{m_1}{m_0}\right)^2 - \tau^2 - \frac{(\Delta t)^2}{12}.$$

The above analysis is somewhat superficial in that it implicitly assumes the numbers and concentrations of organisms to be continuously variable quantities. A more rigorous stochastic treatment would, however, have little added practical value. It should be noted moreover that the corrected values of equation (3) are no more than improved estimates of the number of organisms actually entering the cyclone per unit volume of air passed. Regarded as estimates of the aerosol concentration itself, they are still subject to a sampling error.