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AUGUST 1986

To be submitted for publication in Applied Industrial Hygiene Journal

MINERAL AND ENERGY TECHNOLOGY
MINING RESEARCH LABORATORIES
DIVISION REPORT MRL 87-17(J)

A REFERENCE SIZE SELECTIVE SAMPLER FOR RESPIRABLE DUST

by

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Theoretically calculated stepped horizontal elutriator samplers are proposed as reference size-selective dust samplers for use in calibration of practical respirable dust samplers. The practical calibration would be carried out in polydisperse dust clouds by direct comparison. It is shown that when using multiple horizontal elutriator channels with the same width and airflow, but differing lengths a good match to the proposed ACGIH respirable dust specification can be obtained. They would also match the thoracic deposition specification at a higher air flow rate.

Keywords: Respirable dust; Dust sampling; Reference sampler.

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INTRODUCTION

The reproducibility of respirable dust sampling is necessary for enforcement of regulations. However, sampler design and use should not be stultified by rigid choice of the dust sampling method.

The American Conference of Governmental Industrial Hygienists (ACGIH) has chosen fairly broad criteria for size selection by a dust sampler (1). The International Standards Organization (ISO) has chosen even wider criteria (2). As shown by Bartley and Doemeny, these criteria, even though they are within the range of human variability, can show unacceptable differences in reproducibility (3). A further problem arises in that changes in the sampling train after the size-selector can affect the indication of respirable dust size selection. We have found two to one differences in nylon cyclone sampling trains and attributed the errors to airflow pulsation and deposition on filter holder surfaces.

The problem with the North American approach using monodisperse aerosols for calibration is that the errors in the determination for each size can mount up to an unacceptable reproducibility between different types of samplers. Also, the calibration takes time and few instruments, and especially variant sampling trains, have been calibrated.

The proposal put forward here is that a stepped horizontal elutriator be designed theoretically to match the ACGIH respirable size-selection curve, and that it be used as a reference size-selective sampler for calibrating practical respirable dust samplers by comparisons in polydisperse dusts. Such comparisons are much more rapid than calibrations in monodisperse dusts.

DESIGN OF STEPPED HORIZONTAL ELUTRIATOR

The principle of particle size classification by elutriation is well known; the particles are entrained in a stream of air which is aspirated slowly through a duct in which the larger particles fall out of the stream by gravitational settlement whereas the smaller ones are carried through and may be collected. The theory of the method when applied to sampling from air has been given (4,5). It was shown that the fraction of particles removed by the elutriator increases linearly with falling speed, rising from zero for very small particles to 100% for all falling speeds greater than a critical value. The cloud penetrating the elutriator can, therefore, be represented by the equation $C/C_o = 1 - f/f_C$, where C and C_o are the concentrations of particles of falling speed f in penetrating and initial dust clouds, respectively, and f_C is the critical value of the falling speed above which there is no penetration. The falling speed of a particle is proportional to the square of the aerodynamic size, thus $C/C_o = 1 - d^2/{d_C}^2$ where d is the aerodynamic diameter of the particle considered and d_C the critical diameter.

The criteria considered specifically in the design of the stepped horizontal elutriator are:

1. the ducts should be of uniform rectangular cross-section;
2. the airflow should be evenly divided between the multiple ducts;
3. there should be no interference between the ducts in size selection.

Criterion 1 was considered desirable for ease of construction. Criterion 2 is considered satisfied by the use of the one third height sawn entry slits as used in the NCB MRE gravimetric sampler (6). Criterion 3 requires that the coarse particles just penetrating the shorter channels do not settle onto the floors of the longer channels. This could be a limitation in the design of stepped horizontal elutriators with only a few channels.

The stepped elutriator is considered as a sum of the individual channels with the same airflow, but differing in length. The actual elutriators considered are intended to be constructed by modifying the fine-size-cut eight-channel modified version of the NCB MRE gravimetric sampler built at one time by Casella Ltd. (6,7). They could also be modified from the four-channel version.

Three designs are considered:

1) The size-cut of each successive channel starting at the coarse end is chosen such that at its maximum it just reaches the ACGIH mid-point line (Median cut size is 3.5 μm; $\sigma g = 1.5$).

2) The same as 1), but chosen to reach the upper limit of the ACGIH tolerance band (Median cut size 3.8 μm; $\sigma g = 1.6$).

3) Designs 1) and 2) lead to either the requirement of a low flow about 1.4 L/min or longer channels than in the NCB MRE. In this design the three finest plates are shortened to a 4.48 μm top cut corresponding to a flow of 2 L/min in the modified elutriator.

The stepped elutriator designs are given in Table 1 and the size cuts achieved are shown plotted in Figure 1.

Design 1 is within the ACGIH tolerance band between 2.0 and 8.5 μm, and is very close to the mid-value between 3 and 8 μm. The shape of the size selection given by the one coarsest channel is extended by the symbol ▲. It can be seen that a single channel gives a concave plot on these scales. Design 2 is within the ACGIH tolerance band from 1.8 to 10.5 μm. Design 3 is above the middle criterion line from 3 to 4.5 μm and remains below the ACGIH maximum criteria.

CONSTRUCTION DETAILS

It is recommended that the NCB MRE gravimetric sampler size-selector and filter holder be used as a model in the construction of a stepped elutriator sampler because it incorporates many required features (6). However, the turned up ends of the channel floors are not required in a

Table 1 - Design of stepped horizontal elutriator samplers.

Channel	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
	Aerodynamic Size µm / Penetration through each channel									
Design 1										
1	0.123	0.118	0.110	0.098	0.083	0.062	0.042	0.016	0	
2	0.122	0.114	0.101	0.082	0.056	0.025	0	0		
3	0.122	0.110	0.094	0.068	0.035	0				
4	0.121	0.107	0.086	0.055	0.015					
5	0.120	0.103	0.078	0.040	0					
6	0.119	0.099	0.070	0.025						
7	0.117	0.094	0.058	0.006						
8	0.116	0.088	0.045	0						
Total	0.959	0.833	0.542	0.374	0.189	0.087	0.042	0.016	0	0
Design 2										
1	0.124	0.120	0.115	0.107	0.096	0.083	0.069	0.051	0.032	0.011
2	0.123	0.117	0.107	0.093	0.074	0.051	0.051	0	0	0
3	0.122	0.115	0.101	0.082	0.056	0.025	0			
4	0.121	0.109	0.095	0.068	0.035	0				
5	0.121	0.108	0.085	0.054	0.013					
6	0.119	0.103	0.075	0.037	0					
7	0.118	0.097	0.062	0.015						
8	0.116	0.088	0.043	0						
Total	0.965	0.857	0.683	0.456	0.274	0.159	0.120	0.051	0.032	0.011
Design 3 (channel 1-5 as Design 1)										
6,7 & 8	0.119	0.100	0.070	0.025	0					
Total	0.963	0.852	0.579	0.418	0.189	0.087	0.042	0.016	0	0

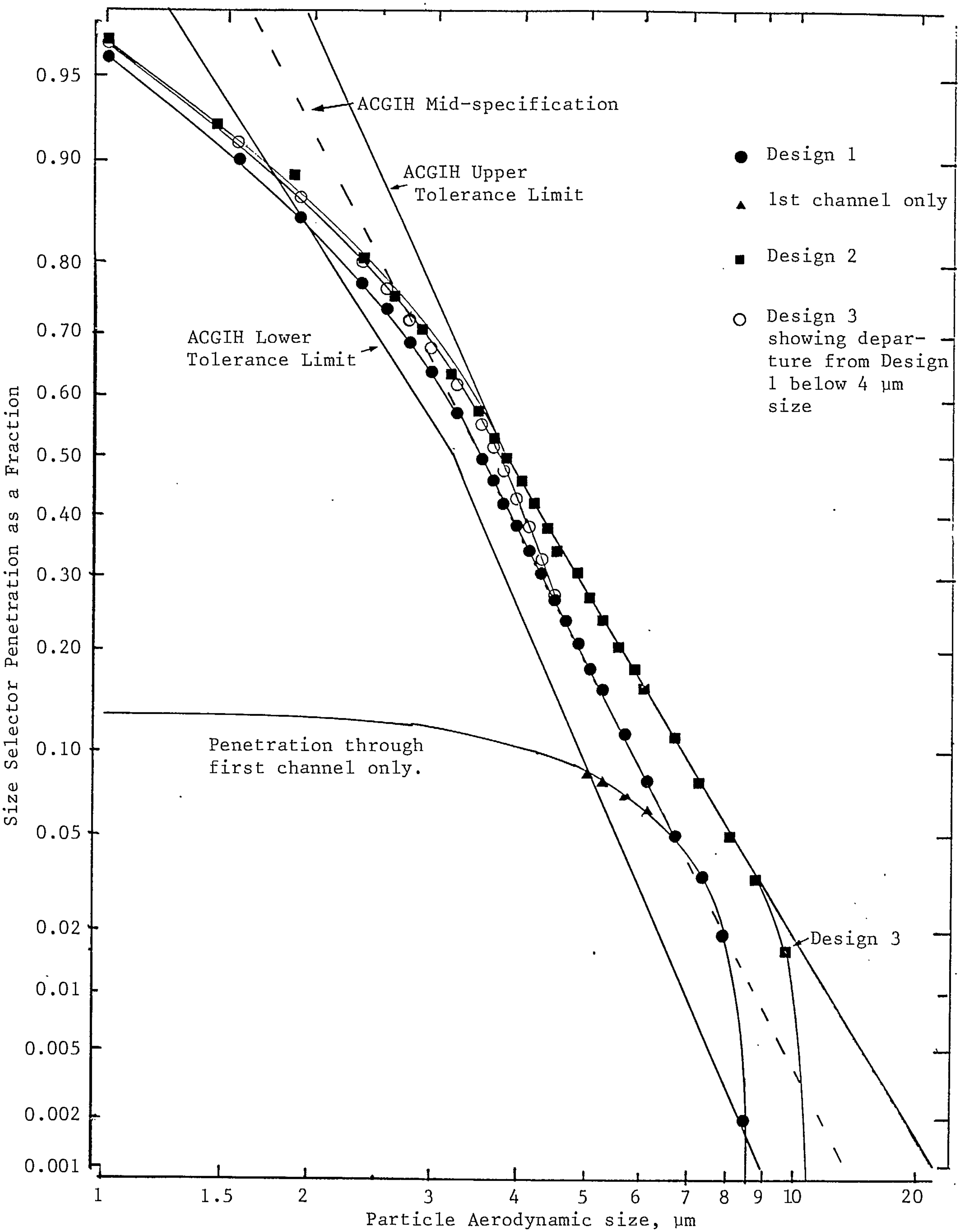

Fig. 1 - Size selection characteristics of stepped horizontal elutriator with ACGIH respirable dust size selection criteria.

carefully handled laboratory sampler and are undesirable as they probably give rise to a slight loss of the coarser dust expected to penetrate the elutriator by an inertial effect as the air sweeps up and over the turned up ends.

Table 2 shows the lengths required for the individual channels and flow rate assuming that the same width is used as in the NCB MRE sampler (6). Figure 2 shows a side view of the eight-channel stepped elutriator design 3.

COMPARISON USING COMPUTER SIMULATION

A comparison between the stepped elutriators and the ACGIH mean respirable dust specification (MMD = 3.5 μm, GSD = 1.5) was carried out by computer simulation in dust clouds with a logarithmic normal size distribution (1). The techniques used are similar to previous publications such as (3,9).

The integrations were carried out over the size range 0 to 20 μm in steps of 0.01 μm.

The fraction of dust in a given size step is given by:

$$f = \frac{1}{\ln \sigma_g . \sqrt{2\pi}} \left[\exp\left(\frac{-\ln d - \ln d_m)^2}{\ln_2 \sigma_g}\right] . \left[\ln(N + 0.5)/(N - 0.5) \right]$$

where, σ_g is geometric standard deviation

d is particle diameter

d_m is mass median diameter

ln is natural logarithm

N is the step number.

The sum total of f approximates to 1 except for the coarser dust clouds with a significant fraction above the integration limit of 20 μm.

The ACGIH respirable dust mean specification penetration was calculated as 1 - P(x) using the expansion given in paragraph 26.2.18 in reference (10).

The penetration of dust through the elutriators was given using the formulae given previously.

Table 2 - Construction details of stepped elutriators based on the NCB MRE gravimetric sampler.

Channel No.	Design 1 Top Cut µm	Design 1 Channel Length mm	Design 2 Top Cut µm	Design 2 Channel Length mm	Design 3 Top Cut µm	Design 3 Channel Length mm
1	8.6	32	10.49	21.5	8.6	46
2	6.74	52	7.88	38	6.74	75
3	5.91	67	6.80	51	5.91	94
4	5.34	83	5.92	67	5.34	120
5	4.85	100	5.32	84	4.85	145
6	4.46	118	4.78	103	4.48	171
7	4.05	144	4.28	129	4.48	171
8	3.71	171	3.72	171	4.48	171
Airflow L/min	1.37		1.38		2.0	
Channel Width mm	40		40		40	

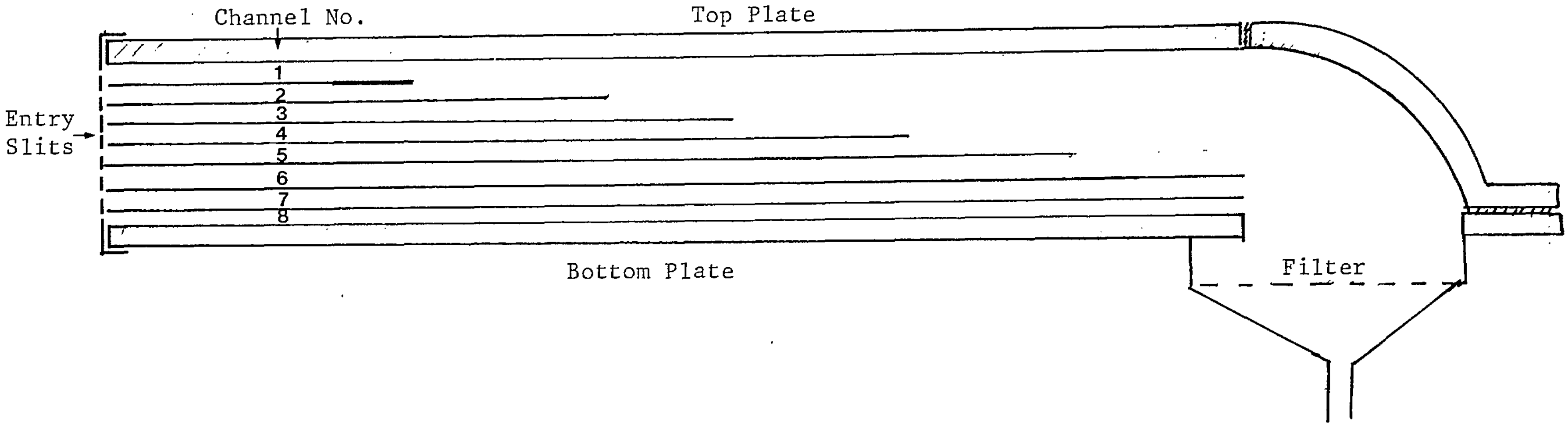

Fig. 2 - Stepped horizontal elutriator, side view - design 3.

The penetration of the commonly used nylon cyclone was calculated with the hyperbolic tangent formula with a 50% cut at 3.5 μm (11). This is given for appreciating the accuracy obtained in current usage.

Table 3 shows the ratios between the amount of dust expected to be collected by each type of respirable dust sampler and that expected by the ACGIH mean specification. It can be seen that the first design of stepped elutriator gives good agreement as long as the respirable dust is more than one tenth of the total dust. The modified design 3 gives better agreement at 0.985 as a mean over the normal range of industrial dust clouds, 0.5 to 15 mmd and 2-3 gsd. The agreement could be improved to a mean of 1.00 by operating this design at 2.015 L/min. Design 2 shows substantial change as the dust cloud becomes coarser. So, curiously enough, does the nylon cyclone using the hyperbolic tangent formula.

DISCUSSION

It is shown that a stepped elutriator can be designed to be a good match to the ACGIH specification in the size range between 2 μm aerodynamic size and 8 to 9 μm for an eight-channel elutriator. The upper size limit can be increased by using more stepped channels. The three designs of eight-channel elutriators undersample coarse dust by no more than 2%, and is not more than 0.2% below the ACGIH lower limit.

It does not appear possible to correct the undersampling, a maximum of 4% that occurs below the 2 μm size.

Thus, the stepped elutriator is a good match in the range between 2 and 8 μm. Outside this range the alveolar deposition is probably not well represented by the ACGIH respirable dust specification and the application of respirable dust sampling to dust clouds with the bulk of the dust outside this size range requires special consideration. As pointed out, different

Table 3 - Instrument to ACGIH respirable dust ratio.

GEOMETRIC STANDARD DEVIATION: 1.5

MMD um	EL1/RD	EL2/RD	EL3/RD	NYLON CYC/RD	RD /TOTAL
.2	.9977	.9980	.9980	.9994	1.0000
.5	.9862	.9882	.9877	.9985	.9996
1.0	.9574	.9652	.9634	1.0017	.9855
1.5	.9395	.9578	.9533	1.0155	.9302
2.0	.9368	.9714	.9607	1.0276	.8354
3.0	.9513	1.0359	.9947	1.0121	.6060
5.0	.9756	1.2151	1.0320	.8809	.2670
7.0	.9711	1.4067	1.0173	.9644	.1139
10.0	.9181	1.6632	.9444	4.2080	.0352
15.0	.7491	1.8888	.7578	47.5240	.0074
20.0	.5542	1.8376	.5571	211.7170	.0025
30.0	.2621	1.3261	.2625	1100.1400	.0007

GEOMETRIC STANDARD DEVIATION: 2.0

MMD um	EL1/RD	EL2/RD	EL3/RD	NYLON CYC/RD	RD /TOTAL
.2	.9959	.9965	.9964	.9993	.9998
.5	.9814	.9849	.9841	1.0000	.9923
1.0	.9613	.9744	.9702	1.0056	.9406
1.5	.9518	.9782	.9675	1.0097	.8544
2.0	.9485	.9902	.9703	1.0104	.7574
3.0	.9493	1.0239	.9804	1.0092	.5779
5.0	.9556	1.0982	.9971	1.0612	.3361
7.0	.9592	1.1670	1.0046	1.2862	.2075
10.0	.9584	1.2560	1.0047	2.1430	.1136
15.0	.9466	1.3735	.9896	5.4446	.0530
20.0	.9279	1.4623	.9664	11.5458	.0300
30.0	.8824	1.5826	.9128	32.8771	.0134

GEOMETRIC STANDARD DEVIATION: 2.2

MMD um	EL1/RD	EL2/RD	EL3/RD	NYLON CYC/RD	RD /TOTAL
.2	.9950	.9958	.9956	.9993	.9994
.5	.9804	.9849	.9836	1.0007	.9859
1.0	.9629	.9781	.9724	1.0053	.9212
1.5	.9548	.9830	.9703	1.0083	.8308
2.0	.9514	.9936	.9721	1.0100	.7373
3.0	.9503	1.0209	.9788	1.0179	.5736
5.0	.9535	1.0779	.9909	1.0921	.3578
7.0	.9560	1.1294	.9978	1.2896	.2391
10.0	.9569	1.1954	1.0013	1.8748	.1459
15.0	.9526	1.2830	.9971	3.7036	.0784
20.0	.9444	1.3512	.9872	6.6236	.0494
30.0	.9228	1.4512	.9611	15.5740	.0254

Table 3 - Cont.

GEOMETRIC STANDARD DEVIATION: 2.4

MMD um	EL1/RD	EL2/RD	EL3/RD	NYLON CYC/RD	RD /TOTAL
.2	.9941	.9951	.9948	.9994	.9985
.5	.9798	.9853	.9836	1.0012	.9781
1.0	.9644	.9811	.9743	1.0052	.9032
1.5	.9571	.9865	.9724	1.0083	.8113
2.0	.9537	.9959	.9734	1.0119	.7221
3.0	.9516	1.0185	.9780	1.0270	.5721
5.0	.9527	1.0639	.9870	1.1103	.3772
7.0	.9543	1.1042	.9929	1.2806	.2670
10.0	.9553	1.1554	.9971	1.7080	.1760
15.0	.9539	1.2234	.9975	2.8607	.1046
20.0	.9502	1.2770	.9937	4.5146	.0709
30.0	.9393	1.3576	.9810	9.1070	.0404

GEOMETRIC STANDARD DEVIATION: 2.6

MMD um	EL1/RD	EL2/RD	EL3/RD	NYLON CYC/RD	RD /TOTAL
.2	.9932	.9945	.9942	.9996	.9971
.5	.9794	.9859	.9837	1.0015	.9696
1.0	.9657	.9837	.9758	1.0053	.8870
1.5	.9590	.9891	.9740	1.0093	.7955
2.0	.9556	.9974	.9745	1.0150	.7108
3.0	.9530	1.0166	.9777	1.0353	.5725
5.0	.9526	1.0538	.9845	1.1206	.3945
7.0	.9534	1.0864	.9893	1.2680	.2918
10.0	.9542	1.1276	.9935	1.5964	.2036
15.0	.9539	1.1822	.9958	2.3910	.1301
20.0	.9521	1.2254	.9949	3.4425	.0932
30.0	.9464	1.2912	.9890	6.1489	.0574

GEOMETRIC STANDARD DEVIATION: 3.0

MMD um	EL1/RD	EL2/RD	EL3/RD	NYLON CYC/RD	RD /TOTAL
.2	.9918	.9938	.9932	.9999	.9928
.5	.9792	.9874	.9842	1.0021	.9521
1.0	.9678	.9875	.9780	1.0067	.8604
1.5	.9620	.9927	.9763	1.0132	.7724
2.0	.9588	.9994	.9762	1.0221	.6962
3.0	.9556	1.0138	.9778	1.0480	.5766
5.0	.9537	1.0406	.9817	1.1291	.4242
7.0	.9533	1.0636	.9850	1.2424	.3335
10.0	.9534	1.0924	.9884	1.4586	.2514
15.0	.9533	1.1303	.9914	1.9096	.1774
20.0	.9528	1.1604	.9926	2.4422	.1367
30.0	.9510	1.2067	.9922	3.6730	.0935

respirable dust samplers in coarse dust clouds can indicate very different respirable dust concentrations (3).

Dust samplers with a size selection curve shown either experimentally or theoretically to be in the range of the ACGIH specification should be calibrated against the stepped elutriator in a polydisperse dust cloud with an acceptable size distribution. This calibration should be used either to obtain a correction factor or to modify its performance, flow rate adjustment for instance.

Substantially more freedom in respirable dust sampler application could be obtained if the respirable dust size selection specification error bars were increased and calibration factors used. For instance, in quartz assessment in hard rock mines when fine diesel exhaust particulate controls filter dust loading, more quartz could be collected with a coarser size selection criterion. We have found in our work in mines no exceptions to a constant ratio between one specific nylon cyclone sampling train and another impaction size selector train matching the coarser British Medical Research Council respirable dust specification within the limits of experimental error in hard rock mines.

This reference sampler has the great advantage that it could be reproduced accurately with respect to size selection by most machine shops.

THORACIC DEPOSITION SAMPLING

The ACGIH specification for thoracic dust is similar to that for respirable, but with an increased median size (1). The same stepped elutriator would be a good match if the airflow is increased by 8.17 (i.e., $(10/3.5)^2$) times. However, the significance of possible entry losses would have to be investigated prior to recommending it as a thoracic reference sampler.

RECOMMENDATIONS

1) The stepped horizontal elutriator, design 3, should be adopted as a reference dust sampler to the proposed ACGIH respirable dust sampling specification (1). It should be used at a flow rate of 2.015 L/min. (Note a 1% error in flow rate setting corresponds to a 3% error in respirable dust mass.)
2) Other respirable dust sampling trains should be calibrated by comparison with the reference dust sampler in a polydisperse dust cloud.
3) The test dust cloud should have a respirable to total dust ratio between 0.3 and 0.7. This corresponds approximately to a mass median diameter between 2 and 7 μm. Finer or coarser dust clouds are likely to decrease the accuracy of calibration.
4) Estimated dust concentrations to the ACGIH specification could be obtained by multiplying the measured dust concentration by a scaling factor determined in the calibration above.
5) Some sampling trains could be adjusted to give a 1:1 ratio by adjusting the flow rate.

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