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Particulate Penetration of Porous Foam Used as a Low Flow Rate Respirable Dust Size Classifier

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Porous foam has been used as a material for classification of particulate matter into various size fractions. The penetration characteristics of a nominal 90 pores per inch porous foam were studied at various flow rates, face velocities, and foam plug diameters and compared to the aerosol penetration of a 10 mm Dorr Oliver cyclone operated at 1.7 L/min. Poly-dispersed triethanolamine spheres were classified through porous foam plugs and the resulting penetration was determined using an aerodynamic particle sizer. Results showed that for a given plug diameter, as face velocity increased from 26 to 39 cm/sec, the 50 percent cut point decreased from 4.5 to 3.8 μm. Furthermore, as the diameter of the plug increased from 4 to 12 mm, the 50 percent cut points were similar to other plug diameters at equivalent face velocities. The best match to the 1.7 L/min cyclone penetration characteristics occurred at a flow rate of 250 ml/min through a 25 mm by 4 mm diameter section of 90 pore per inch foam. Because of the need to provide short-term or real-time estimates of worker respirable dust exposure, porous foam may be a viable classification media for a low flow rate, disposable respirable dust sampler for use in the coal mining industry.

Keywords Porous Foam, Dust, Sampling

Prolonged exposure to airborne respirable coal dust is responsible for coal workers' pneumoconiosis (CWP). Respirable dust, although historically defined in various ways, is qualitatively defined as that fraction of particle size which is capable of penetrating to the alveolar lung region. The current accepted definition of respirable dust recommended for industrial hygiene practice is the ACGIH/CEN/ISO convention.[1,2,3] However, the U.S. coal mining industry is regulated by the Mine Safety and Health Administration (MSHA) for respirable dust using the 10 mm nylon cyclone operated at 2.0 L/min as a particulate size classifier. When the 10 mm nylon cyclone is operated at the recommended flow rate of 1.7 L/min,[4] the agreement with the ACGIH/CEN/ISO convention is improved but still possesses a steeper slope in the penetration characteristic. Therefore, this device does not correspond to the ACGIH/CEN/ISO convention at either flow rate.

Health research studies have identified that the severity of CWP is directly related to the amount of dust exposure and the coal rank.[5–7] Because the passage of the 2.0 mg/m^3 TWA (time-weighted average) exposure limit dust standard in the Federal Coal Mine Health and Safety Act of 1969,[8] average dust levels were reduced from over 6 mg/m^3 to current levels just under the 2.0 mg/m^3 standard.[9]

The National Institute for Occupational Safety and Health (NIOSH) has recently determined through their Coal Worker's X-ray Surveillance Program that coal miners continue to have an elevated risk for CWP under the current 2.0 mg/m^3 dust standard and recommended a 1.0 mg/m^3 dust standard to reduce the prevalence of CWP.[10] In view of this finding, it becomes increasingly important to adequately monitor the miner exposure in a timely manner.

In the Report of the Secretary of Labor's Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers,[11] several recommendations deal with the development of continuous respirable dust monitors to help protect the workers' health. In addition, the NIOSH Criteria Document[10] lists improved sampling devices as a research need pertinent to coal miner respiratory health and prevention of disease. Several approaches are being taken to address these needs. These studies include, but are not limited to (1) a machine-mounted respirable dust monitor,[12] (2) light scattering dust monitors,[13,14] and (3) pressure drop evaluation of filter media[15] as well as other novel techniques. One of the principle goals of each of these efforts has been to identify or develop an instrument that will give short-term or real-time measurements of worker dust exposure.

A dust dosimeter concept study using the pressure drop method was evaluated for feasibility.[16] Because the new dust dosimeter was to operate at a flow rate of about 250 ml/min, a respirable classification device such as the 10 mm cyclone that operates at 1.7 or 2.0 L/min could not be used. An integral part of the dosimeter is a section of porous foam that provides an approximate respirable classification of airborne dust. Chen et al.[17] evaluated various porous foam combinations of pore density and thickness in the same face velocity range as the present study, 25–50 cm/s. However, because the diameters were large, being on the order of 25 mm, the flow rates were approximately 10 L/min. Chen's recommendation was that the sampler could be miniaturized for smaller sampling flow rates to fit the capacity of personal sampling pumps. The present study involves miniaturization to a significantly smaller flow rate. Also, because porous foams have been demonstrated by Aitken[18] to be respirable classifiers at approximately 2.0 L/min and have numerous advantages, they appeared to be a viable choice for a 250 ml/min flow rate sampler. However, it is important to have well-defined foam porosities (in the present context, uniform compression of foam) from sampler to sampler and this variability should be determined.

Specifically, to match the 10 mm nylon cyclone classification as used by MSHA, the classifier required must (1) provide nearly 100 percent filtration of particles greater than 7 μm equivalent aerodynamic diameter (EAD), (2) allow a percentage penetration of respirable particle sizes, and (3) not provide a significant pressure restriction, either initially or during sample collection. These characteristics are also those usually associated with low-efficiency filters. The porous foam classification technique takes advantage of the typical disadvantage of virtually all dust filtration concepts—a decreasing collection efficiency for particle sizes below 10 μm. The objective of this work is to evaluate the particulate penetration of porous foam for application as a size selective device within an inexpensive, disposable, short-term respirable dust measurement device which approximates the 10 mm nylon cyclone penetration operated at a flow rate of 1.7 L/min.

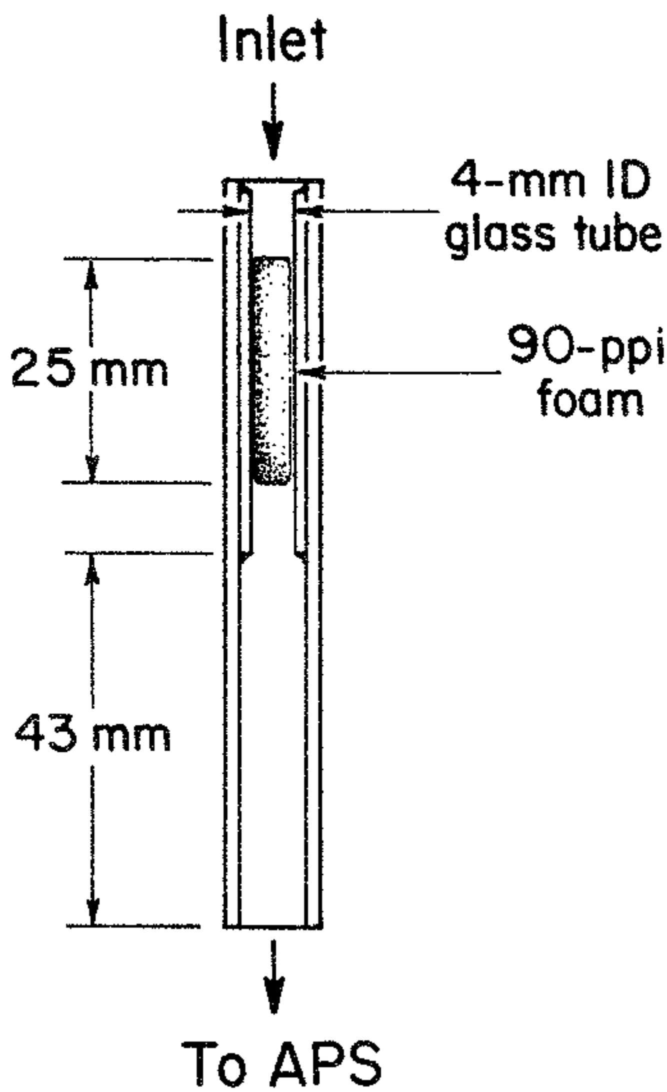

FIGURE 1
Construction of the 90 pores per inch (ppi) foam particle classifier used to obtain a respirable size fraction.

EXPERIMENTAL METHODS

Materials

The tests used nominal 90 ppi (pore per inch) foam (PCF Foam Corporation of America, Hamilton, Ohio) plugs approximately 25 mm in length. Pore sizes were measured by Foam-X Corporation (Eddystone, Pennsylvania) using both microscopy and pressure measurements. Plugs of diameter 4, 6.3, and 12 mm were mounted in glass tubes. Figure 1 shows the specific tube configuration for testing the 4.0 mm foam plugs. Larger tube diameters 6.3 and 12 mm were used without the 4 mm insert to hold the large diameter foam sections. Three similar tubes were constructed with the 4.0 mm foam to estimate the inter-sampler variability.

Procedures

The porous foam and 10-mm nylon cyclone sampler penetration curves were measured using the sampler exposure system shown in Figure 2. The aerosol was generated from an ultrasonic nebulizer (Sonotek, Poughkeepsie, New York) that was fed a solution of triethanolamine (TEA) in isopropanol from a syringe pump. The nominal droplet size from the nebulizer was 30 μm with a geometric standard deviation (GSD) $\cong$ 1.3. The final droplet median aerodynamic diameter of approximately 4 μm was selected by using a dilution of 4 g/L of TEA in isopropanol. This centered the mode at the sample cutpoint to optimize statistical precision in this range. The droplets were transported to the collection chamber for further mixing and dilution.

The sampler penetration was measured with an Aerosol Particle Sizer (APS3300, TSI, St. Paul, Minnesota), the use of which

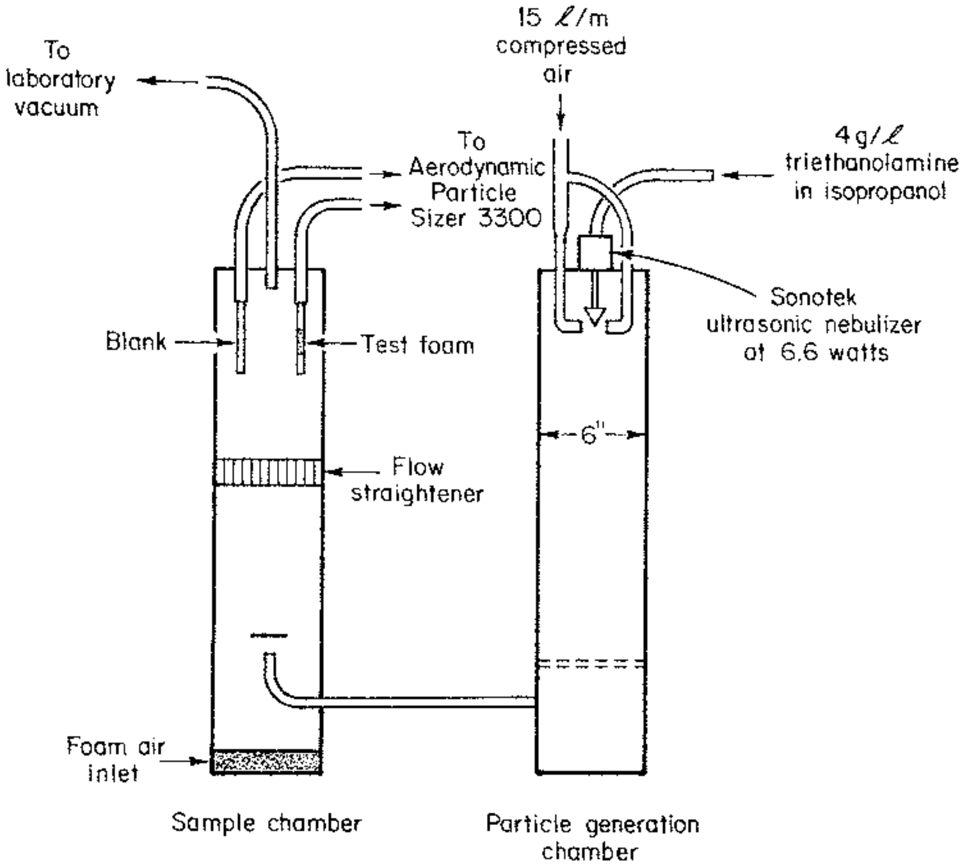

FIGURE 2
Laboratory apparatus used to generate the test aerosol.

has been adequately described previously.[17,19–22] The APS calibration was checked using monodisperse latex particles (Bangs Laboratories, Inc., Fishers, Indiana). Size measurements of some oil droplets were found to be incorrect for the APS because of droplet distortion in the high acceleration sensor region of the APS.[21,22] TEA was chosen for the penetration measurements because its high viscosity would reduce distortion. Measurement of TEA droplets generated with a vibrating orifice monodisperse aerosol generator (Model VOMAG, TSI, Inc., St. Paul, Minnesota) suggested that TEA droplet distortion did not occur and accurate particle size measurements could be made with this material. Measurements of the TEA polydisperse test aerosol using impactors of known cutpoints (Table I) showed agreement with the APS, suggesting that errors due to either droplet distortion or otherwise did not occur. The ultrasonic nebulizer thus produced spherical particles within a stable size distribution with controllable median size.

The size distributions used to determine the porous foam penetration were measured alternately using tubes with and without (blank reference measurement) the foam material. The size distributions used to determine the cyclone penetration were measured in the same manner. The reference distributions before and after each sampler test were averaged channel-by-channel of APS counts, where possible, to reduce bias due to small changes

TABLE I
Classifier data obtained to verify aerosol particle sizer (APS) calibration

Test material	Classifier	Flow rate ml/min	50% cut point, μm, measured	50% cut point, μm, calculated
Triethanolamine	Impactor #1	760	2.7	2.7
Triethanolamine	Impactor #2	200	2.9	2.9
Triethanolamine	Cyclone	1700	4.0	4.0

in size distribution during the sampler test. In some instances, one of the two reference size distributions showed instability. When this occurred, only the one stable reference size distribution was used. Visual examination of the sampler test, in comparison to other sampler tests, was sufficient to establish whether or not the aerosol was stable during the test. If instability was detected, the entire set was discarded.

For the cyclone penetration only two valid replications were made. However, the low replicate variance in the foam cut point determinations as well as previous reports[4,23] which show the inter-cyclone variability to be between two and five percent relative standard deviation allows for confidence in the measured cyclone cut point. Also, subsequent gravimetric comparison of the cyclone with the optimum foam dosimeter testing showed good agreement.[16]

Data Analysis

The APS accumulated particle count data in discrete channels covering a range from 0.5 μm to 14.9 μm particle size. Due to the small number of counts in channels below 1.0 μm and above 6.3 μm, only the 26 channels between these size values were used. Additionally, this size range was considered to be an appropriate range for comparison to 10 mm cyclone penetration data. Error per channel due to phantom particle counts caused by coincidence was estimated to be less than 0.1 percent for channels below 4.4 μm particle size. In the size range between 4.4 and 5.8 μm this error increased up to 4.2 percent. At and above 6.3 μm, count error often exceeded 20 percent. These estimates were made by averaging the APS count data in channel sizes above 10 μm, where the aerosol generator was very unlikely to generate particles, and dividing this average value by the particle count for each channel between 1.0 μm and above 6.3 μm. Because this error was typically less than 0.1 percent in the approximate region of interest (4 μm), the error was not subtracted from each channel. Adjusting the data would only improve the polynomial fit in the size range above 5.5 μm.

The sampler penetration as a function of aerodynamic size was calculated by dividing the sampler aerosol distribution by the reference distribution, channel by channel. The median cut point of each sampler was determined by fitting a polynomial function to the penetration curve. The fits were efficient ($R^2 \geq 0.98$) and allowed prediction of the aerodynamic particle size at 50 percent penetration. Although a sigmoidal-type curve would provide a better fit to the penetration data over the entire size range tested, the functional form used is not important to obtain an estimate of the 50 percent cutpoint so long as the fit is reasonable over the region of interest.

Particulate penetration through foam was determined semi-empirically by Vincent et al.,[24] using data from Gibson and Vincent[25] and Wake and Brown[26] and others. The Vincent model describes the particle penetration P to be:

$$\ln P = -\frac{t}{d_f}\left[54.86 S_t^{2.382} + 38.91 N_g^{0.880}\right] \qquad [1]$$

where

t = the foam thickness,
d_f = the equivalent fiber diameter of the porous foam.

The equivalent fiber diameter d_f, has been empirically related to foam porosity p_o at the Health and Safety Executive of the United Kingdom to be:

$$d_f = (0.009633\, p_o)^{-1.216}. \qquad [2]$$

S_t, the inertial parameter, and N_g, the gravitational parameter, are defined as:

$$S_t = \frac{d_{ae}^2 \gamma g U}{18 \eta d_f} \qquad N_g = \frac{d_{ae}^2 \gamma g}{18 \eta U} \qquad [3]$$

where

d_{ae} = the aerodynamic diameter,
γ = the density of water,
η = the viscosity of air,
U = the velocity of air through the foam, and
g = the acceleration due to gravity.

RESULTS AND DISCUSSION

Table II summarizes the test results of the 90 ppi foam samplers over a range of flow rates from 200 to 2730 ml/min. Figure 3 shows the results of the three similar 4.0 mm tubes tested at flow rates of 200, 250, and 300 ml/min. As would be expected, the 50 percent cut point is seen to decrease with increasing flow rate, presumably due to impaction effects. Overall, the relationship between cut point and flow rate appears somewhat non-linear as would be expected for an asymptotic approach to a limiting value of the cut point due to particle impaction since subsequent increases in flow rate must produce smaller changes in the cut point. Inertial impaction theory states that the cut point varies directly as the square root of the Stokes number and, therefore, inversely as the square root of the volumetric flow rate.[27] The variability of the cut points between the three tubes, as well as the replicate variability for each tube, was small in comparison to the effect due to the flow rate.

Considering that the foam plugs were cut and inserted into the glass tubes, there is the possibility that nonuniformity of the plugs and slight compression on insertion into the tube could affect the penetration characteristics of the classifier tubes. If such variations were important, they would manifest themselves in changes of the perimeter- to-surface area ratio. Figure 4 shows the 50 percent cut point variation with foam face velocity for tube diameters of 4.0, 6.3, and 12 mm. Differences in 50 percent cut point at equivalent face velocities were insignificant. This suggests that the primary collection is inertial impaction within the foam and not wall losses or sedimentation.

TABLE II
Summary of 90 ppi porous foam tests

Sampler ID	Sampler diameter, mm	Flow rate, ml/min	Filter face velocity, cm/sec	Mean 50% cut point, μm	Standard deviation, σ	N replicates
1	4.0	200	26.4	4.5	0.17	3
2	4.0	200	26.4	4.5	0.06	3
3	4.0	200	26.4	4.5	0.08	3
1	4.0	250	33.0	4.2	0.06	2
2	4.0	250	33.0	4.2	0.05	3
3	4.0	250	33.0	4.0	0.14	5
1	4.0	300	39.6	3.8	0.04	3
2	4.0	300	39.6	3.9	0.05	3
3	4.0	300	39.6	3.7	0.10	3
4	6.3	630	33.7	4.3	0.04	3
4	6.3	760	40.7	4.0	0.22	3
4	6.3	970	51.9	3.5	0.27	4
5	12.0	2260	30.0	4.6	0.21	3
5	12.0	2730	36.3	4.0	0.17	4

To compare the penetration curves of the cyclone and the experimental foam, the cyclone penetration was measured with the same apparatus at 1.7 L/min. The cyclone penetration data was fit using the functional form of the ISO penetration curve as recommended by Soderholm[3] and adjusting the function parameters to give close agreement at approximately 4.0 μm. Figure 5 shows the fit of the cyclone data with the ISO function with adjusted parameters $\Sigma' = 1.25$ replacing $\Sigma = 1.5$ and the coefficient (.11)d replacing (.06)d in the ISO respirable definition. An equivalent alternative method, employed by Chen et al.,[17] is an integrated lognormal distribution model.[28] Chen also stated that there is no suitable universal model for all cyclones currently available. Foam penetration data was then compared to the derived equation to determine the closest match to the cyclone penetration. Comparison of all the foam classifier penetration curves showed that the 4.0 mm tube operated at

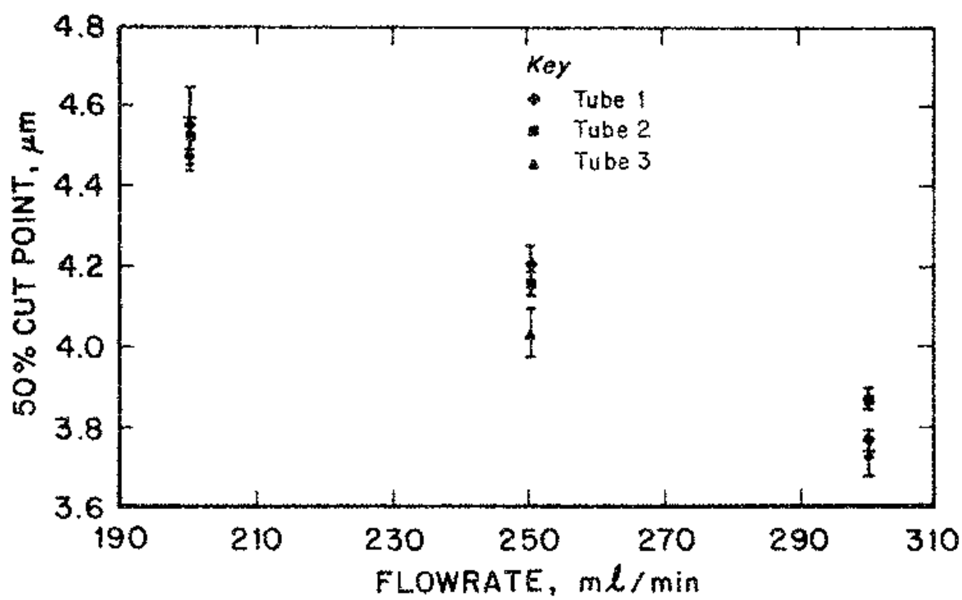

FIGURE 3
50 percent cut point results for three similar 4.0 mm samplers constructed and tested at flow rates of 200, 250, and 300 ml/min. The standard error bars are shown.

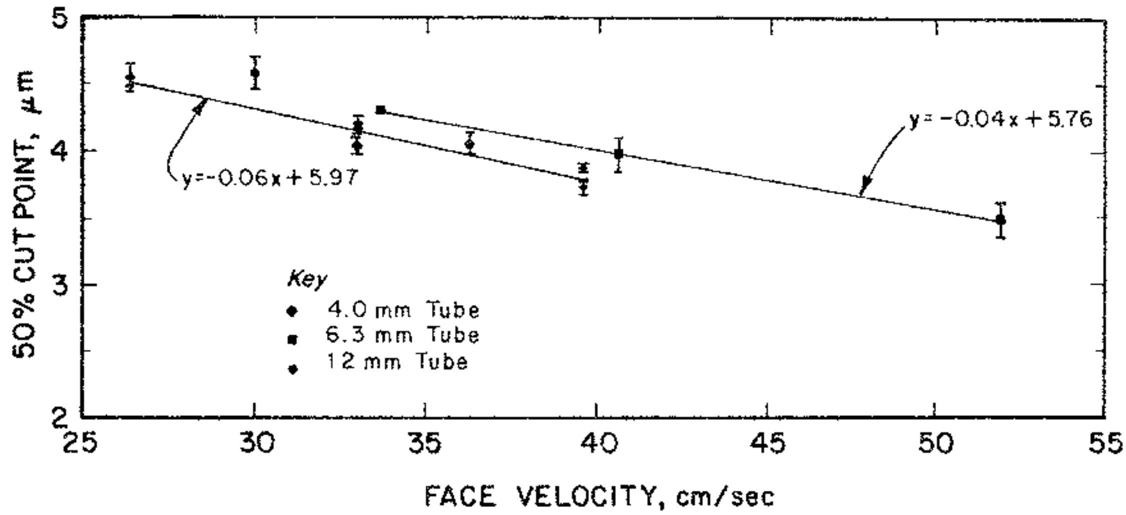

FIGURE 4

50 percent cut point results for 4.0, 6.3, and 12 mm tubes constructed and tested at flow rates of 200, 250, and 300 ml/min. The standard error bars are shown.

250 ml/min provided the closest match to the cyclone penetration. Figure 6 shows a typical representation (one out of ten tests using three different 4.0 mm tubes at 250 ml/min) of this comparison. Although the foam classifier shows a somewhat lower penetration below 3 μm, the comparison appears reasonable.

The theoretical particulate penetration of the foam used in this study was determined using Equations 1–3, the experimental flow rate of 250 ml/min, and a measured pore size of 86 ppi determined by Foam-X Corporation. The resulting aerodynamic d_{50} was calculated to be 3.8 μm. This compares favorably to the experimentally measured aerodynamic d_{50} of 4.0 μm.

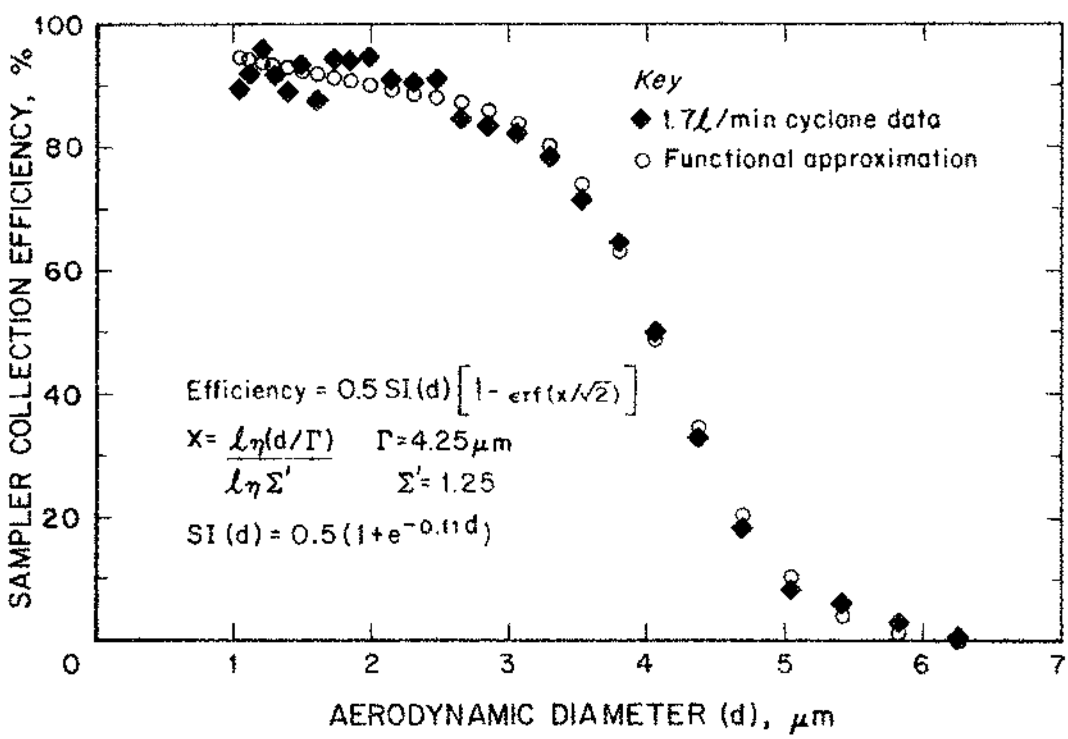

FIGURE 5

Approximation of the 10 mm nylon cyclone tested by the functional form of the ISO respirable definition, using modified parameters $\Sigma' = 1.25$ replacing $\Sigma = 1.5$ and the coefficient (.11)d replacing (.06)d in the ISO respirable definition.

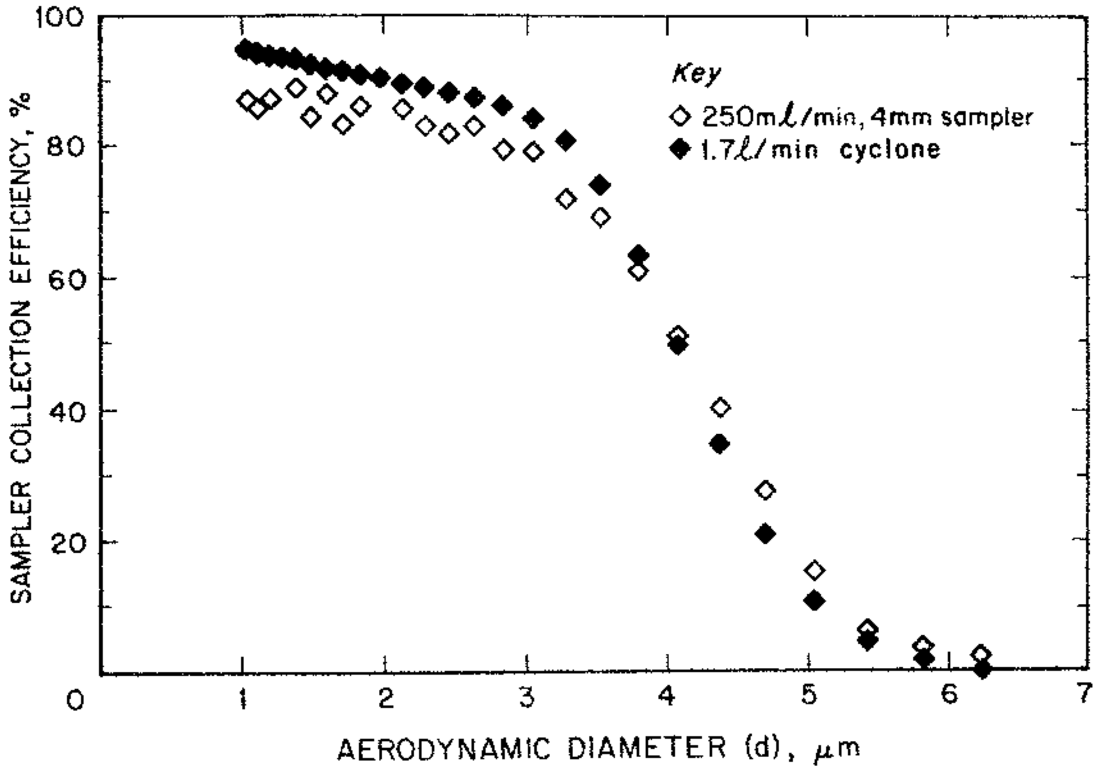

FIGURE 6

Comparison of the 4 mm tube with 90 ppi foam classifier operated at a flow rate of 250 ml/min with the 1.7 L/min nylon cyclone penetration function determined in Figure 5.

Assessment of personal respirable dust exposure is an important step in eliminating many dust-related occupational illnesses and diseases. One method of eliminating occupational dust diseases by reducing worker dust exposure is effective monitoring with immediate feedback of exposure results to workers. However, analysis of the filter obtained from the conventional gravimetric sampler method used in coal mining takes several weeks to process before results are reported to the mine. As stated earlier, one of the recommendations of the Report of the Secretary of Labor's advisory committee was to develop an instrument that will give short-term or real-time measurements of worker dust exposure. The concept of the dust dosimeter was developed to provide an inexpensive, short-term measurement of the cumulative personal dust exposure of a worker during a shift, but not intended to be a replacement or substitute of the current approved dust sampler used to determine compliance with federal regulations. The results of the presently described work demonstrates that a low flow rate configuration of porous foam can reasonably pattern the penetration of the 10 mm nylon cyclone which is currently used for measuring respirable coal mine dust exposure. Because of this, the porous foam can be used as a respirable particulate classifier in a low cost, disposable dust dosimeter configuration currently under development.

CONCLUSIONS

A small-diameter tube with 90 ppi foam and 250 ml/min flow rate at a face velocity of 33 cm/sec yields a 50 percent cut point of 4 μm and may possibly be used as a classifier of respirable dust. This configuration has been found to approximate the 10 mm nylon cyclone particulate penetration at 1.7 L/min. Cut point variation with foam face velocity in different tube sizes was not significant. Laboratory tests for tube diameters of 4.0, 6.3, and 12 mm suggest that the primary collection mechanism of the detector tube is inertial impaction within the foam and not wall losses or sedimentation.

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