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Respirator-Cartridge Filter Efficiency under Cyclic and Steady-Flow Conditions

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Respirator-Cartridge Filter Efficiency under Cyclic and Steady-Flow Conditions

by

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ABSTRACT

Respirator filter cartridges are routinely tested under steady-flow conditions to provide a basis for predicting their future performance under cyclic-flow conditions produced by various human breathing efforts. Because filter efficiency is a function of velocity, as well as particle size, it was considered necessary to perform tests to define aerosol penetration through respirator filter cartridges under both cyclic- and steady-flow conditions. These tests effectively evaluate the adequacy of existing steady-flow test procedures. A breathing pump was used to simulate different human breathing patterns during work ranging from sedentary to extra heavy. Steady-flow conditions were identical to those recommended by the Bureau of Mines for permissibility tests of respiratory protective devices. Solid, monodisperse, polystyrene latex aerosols ranging from 0.176 to 2.02 μm in size, as well as liquid monodisperse 0.3- μm dioctyl phthalate were used as the test aerosols. A method was devised to sample during cyclic flow without altering the flow pattern by sampling continuously downstream from the respirator cartridge. Experimental data obtained during steady and cyclic flow are compared as a function of aerosol size, breathing pattern, and type of aerosol. Theoretical steady-flow aerosol penetration through fibrous filters is compared to penetrations associated with variable velocities produced during cyclic flow.

I. INTRODUCTION

Practical and theoretical performance of filtration media used in respirator cartridges for personal protection has usually been evaluated under steady or constant flow conditions.¹ The U.S. Department of the Interior, Bureau of Mines, specification under Schedule 21 B for permissibility testing of dust, fume, and mist respirator filter cartridges is based on a steady flow rate of 32 liters/min, except for those respirators designed for dual filters tested at 16 liters/min.² Tests run under steady-flow conditions are used

to predict future performance of filter cartridges under varied cyclic flow conditions. Velocity of an aerosol stream passing through a respirator filter as normally used varies from zero to some maximum value, and back to zero, because of the normal human breathing pattern. The variation in air velocity through the filter approaches a rectified sinusoidal wave form. Because filter efficiency is a function of velocity, as well as particle size, a test system was designed and tests were performed to define aerosol penetration through respirator filter cartridges during cyclic

TABLE I
SILVERMAN'S MEASUREMENTS AT
VARIOUS WORK RATES

Measurement	Seden- tary	Work Rate (kg-m/min)				
		208	415	622	830	1107
Subjects tested	29	12	14	12	59	46
Pulse rate/min	73	105	116	128	158	166
Respiration rate/min	14.6	21.2	22.7	23.0	30.4	34.8
Minute volume, liters	10.3	20.8	29.9	37.3	54.7	75.3
Maximum inspiratory flow, liters/min	40	63	84	100	149	194
Maximum expiratory flow, liters/min	32	58	85	107	154	211

flow simulating different human breathing patterns, and during steady flow.

Silverman defined six different working levels using a number of subjects performing tests on a bicycle ergometer.³ He measured cyclic flow rate, respiration rate, pulse rate, and a number of other physiological parameters. Work rate varied from sedentary work through work levels of 1,500, 3,000, 4,500, 6,000, and 8,000 ft-lb/min (208, 415, 622, 830, and 1,107 kg-m/min). An extra heavy work level is considered to be 830 kg-m/min but few people can attain 1,107 kg-m/min. Table I shows some of the parameters measured at the various work rates.³

In 1961, Jordan and Silverman reported the effect of cyclic air flow on fiberglass filter efficiency.⁴ Their study utilized an aerosol with a count median diameter of 0.78 μ m and a geometric standard deviation of 1.13. Their results indicate that aerosol penetration through filters during cyclic flow with a given time-averaged mean velocity could not be predicted from penetration obtained during steady flow. Aerosol penetration during cyclic flow was lower

at low time-averaged mean velocities, and higher at high time-averaged mean velocities, than penetration measured at corresponding steady-flow velocities.

A preliminary comparative study of cyclic and steady-flow tests was performed at Los Alamos.⁵ Cyclic flow was produced by a calibrated Scott breathing pump which is a cam-driven piston and cylinder-type mechanical breather.⁶ At the Los Alamos Scientific Laboratory (LASL), the preliminary study was limited to cyclic flow tests simulating a work load of 830 kg-m/min.⁵ If the filter cartridge being tested was designed for use on respirators requiring one or two filters, steady-flow tests were performed at 32 or 16 liters/min, respectively. These preliminary tests used a spherical uranine methylene-blue aerosol generated by a spinning-disk aerosol generator⁷ that fractionates droplets into two size ranges, primary and satellite particles. The monodisperse primary aerosols ranged from 1 to 3 μ m, whereas the satellite aerosols consisted of sub-micron particles with a bimodal size distribution. The 1-to-3- μ m monodisperse aerosol particles generally produce higher penetration during cyclic flow at a work rate of 830 kg-m/min. Because of the complex bimodal distribution of the satellite aerosol, no conclusive information could be drawn for the submicron aerosol tests.

Austria, the Federal Republic of Germany, Italy, and Yugoslavia have established respirator filter quality-control test procedures incorporating cyclic flow to simulate human breathing patterns.⁸ The U.S. Bureau of Mines has approached cyclic flow with a test procedure for evaluating entire respirator performance in their "man-tests" that requires sampling a dioctyl phthalate (DOP) aerosol from within and outside of a mask worn by an individual.² This test is designed to evaluate both respirator filters and the facial fit of mask. An oversimplification in this test results since 8 liters/min is continually sampled from within the mask. Therefore, during inhalation, the

filtration velocity is the sum of that imposed by the individuals breathing pattern and an additional velocity resulting from the constant 8-liter/min sampling rate. This test condition does not represent respirator performance during actual use.

Because 0.1- to 2.0- μm particles are significantly deposited within the respiratory system, and because 0.3- μm monodisperse liquid DOP has been accepted as a standard test aerosol in the United States,² a study was initiated to define filter efficiency under cyclic and steady flow using monodisperse solid and liquid submicron aerosols. It is desirable to define specific test procedures in terms of aerosol particle size, air velocity, and type of aerosol that produce maximum penetration for each type of filter and proposed use.

II. EQUIPMENT

We used Dow Chemical Company polystyrene latex particles (PSL) in essentially monodisperse⁹ size ranges from 0.176 to 2.02 μm as the solid test aerosol. We used monodisperse 0.3- μm DOP as the liquid test aerosol because of its size, the vast amount of previous filtration information obtained using it, and its possible selection as a standard test aerosol for evaluating respirator performance. Because instrumentation techniques have improved vastly over the last few years, we were able to benefit from the apparent limitations in previous studies, and could develop a unique test system to duplicate man's breathing pattern through respirator filters more accurately. An aerosol-generation test system (Fig. 1) used in previous experiments was adequate for the

Fig. 1. Aerosol generation system.

cyclic-flow tests. The PSL aerosol was generated from three Hudson Oxygen Therapy Sales Company Pen-i-sol nebulizers and then impacted on disks to collect or break up agglomerates produced by the nebulizer. The aerosol then traversed the first drying chamber to a tritium deionizer to reduce any charge incurred during nebulization.¹⁰ The tritium source consisted of two sheets of tritiated foil 1/4 in. apart and having 4 Ci of tritium adsorbed in a titanium layer (U.S. Radium Corporation, Morristown, New Jersey). The tritium creates charge equilibrium on the PSL aerosol particles by secondary ionization in air and helps prevent agglomeration by creating a Boltzman equilibrium charge distribution on the aerosol population.¹¹ Aerosol-particle net charge for 0.312- μm and smaller particles was measured with a parallel plate capacitor. The deionizer was found to reduce the latex aerosol charge on the 0.312- μm particles by 90% and that on the 0.176- μm particles by more than 98%.¹² Aerosol charge for 0.312- μm particles was found to be 0.7 electron charges per particle after neutralization. The experimental method we used to measure aerosol charge made it impractical to try to measure charge on particles larger than 0.312 μm because of their lower electric mobility¹¹ and because of difficulties in constructing longer parallel plates. The concentration of single particles as determined by electron microscopy ranged from 85 to 100% for all sizes.

After the tritium deionizer, dilution air entered the system and the aerosol traversed a second drying tube. The aerosol-generation system and the test system were joined by an air-balance box to ensure balanced air flow between the two. If DOP was used in place of polystyrene latex, it was introduced into the coupling box. DOP was generated from a Q-127 respirator-filter canister tester.¹³ This unit heats DOP to 172°C and condenses the vapor with cooler dilution air to produce a relatively monodisperse aerosol ($\sigma_g \leq 1.2$). Particle size

Fig. 2. Air sampling system.

was kept at $0.3 \mu\text{m}$ by controlling the temperature of the dilution air. DOP size was routinely monitored with an electronic "OWL" that measures the polarization ratio of light scattered at 90° by the aerosol.¹⁴ Confirmation of aerosol size indicated by the OWL was obtained using the spiral centrifuge aerosol spectrometer.

Figure 2 shows the air-sampling test system. The aerosol entered a copper tube containing a Stairmand disk to ensure proper mixing ahead of the filter holder. The Scott breathing pump was used to simulate human breathing patterns during various work efforts. A number of "guillotine" low-impaction solenoid valves, represented by X's and O's in Fig. 2, minimized aerosol loss.¹⁵ Conventional solenoid valves were undesirable because of the high loss due to impaction with this type of valve. The guillotine valve is shown in Fig. 3. Surgical tubing passes between a solenoid-actuated pincher bar and a flat pressure base plate. The hose is kept loosely in position by retainers on each side of the pincher. Direct-current energizing of the solenoid effectively pinches the hose shut. When the assembly is properly adjusted, no leakage can be detected with 11 in. of positive pressure on the tubing. This is well above the usual air pressure of the scattering-chamber system. When de-energized, the loosely guided pincher bar is held up

by the resilience of the tubing with no perceptible dimpling in the line. The valve system was designed so that sampling would occur only during the inhalation cycle. This was accomplished by switches at the extremes of the pistons on the breathing pump.

The aerosol concentration on each side of the filter was analyzed using two LASL-designed light-scattering photometers.¹⁵ The photometers were calibrated against each other with identical aerosols on all scales to verify that their responses and linearities were identical. These photometers gave us an order of magnitude more sensitivity than commercially available instruments.

In Fig. 2 each guillotine valve is marked with an X or an O. The X valves are open during inhalation and closed during exhalation. The O valves are closed during inhalation and open during exhalation. To understand the air-flow patterns, one must know what occurs during both inhalation and exhalation.

During inhalation, air is drawn through the filter by piston No. 1 of the breathing pump (Fig. 2). Piston No. 2 is filled with clean air through filter E and air in back

Fig. 3. Solenoid valve.

of the piston is pushed out through an in-line clean-air filter (A). Both upstream and downstream photometers sample the air-stream at a flow rate of 8 liters/min. An additional (supplemental air) 8 liters/min is introduced radially downstream from the test filter and in the direction of the downstream photometer. This supplies the sampling flow for the downstream photometer and closely approximates a flow pattern applied by an individual's breathing through a respirator filter cartridge. This supplementary flow produces a variable downstream dilution factor by changing the air flow throughout the inhalation cycle, and does not allow direct computation of aerosol penetration through a filter. Penetration can be determined if air-flow rate is known at all points throughout the inhalation cycle. This method of computation is explained in Sec. IV. Air flow and test filter pressure drop is continuously monitored by a pneumotachograph (PNT) connected to a differential-pressure transducer that relays an electrical signal through an amplifier circuit to both a 12-channel strip-chart recorder and an automatic data-acquisition system that will be explained later.

During exhalation, piston No. 2 of the breathing pump introduces clean air previously received through filter E during inhalation back towards the test filter, pushing aerosol-contaminated air out of the system through filter A. Air that was drawn into piston No. 1 during inhalation is discharged through an in-line filter (B) to the room atmosphere. Clean air is drawn through in-line filters (C, D) to purge both light-scattering photometers. Aerosol-laden air in front of the test filter is removed (G) to prevent buildup of aerosol concentration during exhalation.

A three-channel digital-data acquisition system was developed to record, continually, data from the two light-scattering photometers and the pneumotachograph flow meter. Pressure drop can also be recorded in place of one of the photometer signals.

The data-acquisition system records the signal on a Tally Corporation Model P-120 tape punch. Data recorded on the tape are conducive to computer analysis.

III. TEST PROCEDURE

Two types of respirator filter cartridges and one flat air-sampling medium were tested under cyclic-flow work rates of 830, 622, and 415 kg-m/min. Each was also tested under a steady-flow rate of 16 liters/min. Preliminary cyclic-flow tests using respirator filter cartridges indicated that poor quality control made it impossible to duplicate any results reliably. Therefore we selected two types of cartridges, MSA Type-S and Welsh 7500-7, and bought a number of cartridges so that we could perform our own quality-control tests. We chose these two types of filters because they gave enough aerosol penetration to allow us to measure concentrations downstream from the filter effectively. We chose Whatman 41 as the flat air-sampling medium for testing. All respirator cartridges were initially tested with a 0.3- μ m DOP aerosol at a steady-flow rate of 16 liters/min. All MSA Type-S cartridges with a penetration of $1.5\% \pm 0.5\%$ and Welsh 7500-7 cartridges with a penetration of $12.5\% \pm 2.5\%$ were selected for the cyclic- and steady-flow tests. Polystyrene latex particle sizes of 0.176, 0.234, 0.312, 0.5, 0.79, 1.011, and 2.02 μ m, as well as 0.3- μ m DOP, were used as the test aerosols. Three different filters of each type were tested using each particle size at every cyclic-flow work rate and under steady-flow conditions. Before testing, each filter's pressure drop and the test flow rate were recorded on the strip-chart recorder and data-acquisition system. The aerosol was then introduced, and aerosol penetration and air-flow measurements were recorded for 5 to 10 breaths. At the end of each test run, filter pressure drop was again recorded to determine if the filter had loaded during the test.

TABLE II
MAXIMUM AND TIME-AVERAGED MEAN FLOWS
THROUGH VARIOUS FILTERS

Filter Type	Work Rate (kg-m/min)	Max Flow Through Filter (liters/min)	Time Av Mean Flow Through Filter (liters/min)	Max Vel Through Filter (cm/sec)	Time Av Mean Vel Through Filter (cm/sec)
MSA Type "S"	415	42	29.69	2.69	1.90
MSA Type "S"	622	50	35.35	3.21	2.27
MSA Type "S"	830	75	53.03	4.81	3.40
Welsh 7500-7	415	42	29.69	15.32	10.83
Welsh 7500-7	622	50	35.35	18.23	12.89
Welsh 7500-7	830	75	53.03	27.35	19.34
Whatman 41	415	42	29.69	18.29	12.93
Whatman 41	622	50	35.35	21.78	15.40
Whatman 41	830	75	53.03	32.67	23.10

MSA "type "S" filter area = 260 cm²

Welsh 7500-7 filter area = 45.7 cm²

Whatman 41 filter area = 38.26 cm²

Because there was a variable dilution factor throughout the entire inhalation period, penetration was calculated at 10 equally spaced times throughout the breath. The number of particles passing the filter per unit time is equal to the true concentration (C_T) times the instantaneous flow rate (Q) at that time. Because the flow rate changes continually throughout the cyclic-flow cycle, the concentration of particles also changes. If 8 liters/min were added downstream, the actual concentration would be changed to some apparent concentration (C_A); therefore, the following relationship should hold true to calculate the actual concentration.

$$C_T Q = C_A (Q + 8),$$

and solving for C_T ,

$$C_T = C_A \left(1 + \frac{8}{Q}\right).$$

This formula was also used to check for complete mixing of the 8-liter/min dilution air with the aerosol concentration before the balancing air was added. If the calculated concentration matched the measured concentration, we were confident of proper

mixing between the aerosol passing the filter and the supplementary clean air introduced downstream from the filter. In all cases, complete mixing was verified by these tests.

Every data point for cyclic flow on all of the following graphs represents the average penetrations of each of three filters during several individual breaths. Analysis of each breath consisted of at least 10 penetration measurements averaged to give the average aerosol penetration throughout that breath. Table II presents the maximum and time-averaged mean flow through the filter as well as the associated velocities for each type of filter tested. Velocities through Welsh-7500-7 and Whatman 41 filters at corresponding flow rates are approximately six times those through MSA Type-S filters. This is because MSA Type-S filters are pleated to provide maximum filtration area and minimum pressure drop.

IV. RESULTS

Figure 4 shows aerosol penetration as a function of particle size for MSA Type-S

Fig. 4. Aerosol penetration of MSA Type-S filter cartridges at cyclic-flow work rates of 415, 622, and 830 kg-m/min.

filter cartridges at cyclic-flow work rates of 415, 622, and 830 kg-m/min and a steady-flow rate of 16 liters/min. There is no significant difference in aerosol penetration as a function cyclic-flow work rate except at the smaller particle sizes ($<0.3 \mu\text{m}$). This curve rises so rapidly at the smaller size ranges that it may be questionable to suggest a significant change in penetration for different work rates, even here. Penetration by polystyrene latex under cyclic-flow work conditions varies from 0.5 to 21% throughout the entire aerosol size range tested. Penetration values for $0.3\text{-}\mu\text{m}$ DOP were less than 0.2% for all cyclic-flow conditions; therefore, use of this DOP aerosol would considerably overestimate this filter's effectiveness in removing solid particulates. Although theoretical single-fiber filtration-efficiency steady-flow equations predict that $0.3 \mu\text{m}$ is the particle size producing maximum penetration,¹⁶ this is not the particle size that produces maximum penetration of this filter during cyclic flow. Figure 4 also

shows filter-cartridge efficiency as a function of particle size for a steady-flow rate of 16 liters/min. Maximum penetration occurs at a particle size of approximately $0.3 \mu\text{m}$ which is consistent with theoretical single-fiber predictions.¹⁶ However, all steady-flow penetration values are well below those for cyclic flow, indicating that this steady-flow test, used by the Bureau of Mines under Schedule 21 B,² overestimates the effectiveness of the respirator filter as it would normally be used. It especially overestimates the filter effectiveness at particle sizes below $0.3 \mu\text{m}$ and above $1.2 \mu\text{m}$. Particles larger than $1.2 \mu\text{m}$ are of considerable significance because of their mass which is still respirable.¹⁷ Liquid $0.3\text{-}\mu\text{m}$ DOP penetration during steady flow approximates that of solid polystyrene latex under the same conditions.

Apparently, as will be shown later, a different particle size produces maximum penetration of each type of filter during cyclic flow. Figure 4 indicates that $0.176\text{-}\mu\text{m}$, or smaller, particles give maximum penetration through MSA Type-S filters during cyclic flow. Because of limited aerosol-generation techniques, we were unable to produce a PSL aerosol smaller than $0.176 \mu\text{m}$ owing to excessive aerosol agglomeration. We expected that filter penetration would decrease owing to Brownian diffusion somewhere below this size range. However, during cyclic flow particles probably never reach zero velocity because of the short time they experience zero flow, and because some kinetic energy is maintained by the particles throughout the cycle. The kinetic energy of particles larger than $1.0 \mu\text{m}$ may cause the increase in penetration shown in Fig. 5. If this kinetic energy is greater than the sum of forces that could cause collection, we would expect the particle to penetrate through the filter. There would, of course, be some particle size large enough that penetration would again drop to zero.

Fig. 5. Aerosol penetration of MSA Type-S filter cartridges at cyclic-flow work rates of 622 kg-m/min and 622 kg-m/min plus 8 liters/min.

Figure 5 shows aerosol penetration of MSA Type-S filter cartridges, with and without the air balancing system, as a function of particle size at a cyclic work rate of 622 kg-m/min. The proposed Bureau of Mines man test specifies, under Schedule 21 B, that a sample at 8 liters/min should be withdrawn continuously from inside the mask during these tests. This imposes a higher velocity through the filter during inhalation and could keep the exhalation valve of the respirator mask closed until the man's exhalation rate became greater than 8 liters/min. The air-balancing system of our experimental apparatus more closely approximates a "true" breathing pattern. Figure 5 shows that this air balancing has little effect on MSA Type-S filter cartridges except for polystyrene latex particles much smaller than 0.312 μm , at which point the man test may indicate a considerably lower penetration than that to be expected during actual use. DOP gives an approximately 6% difference in penetration during simulated man tests and during true cyclic flow, thereby providing a conservative test. Again, as we will see with other filters, we would expect penetration to decrease at some smaller particle size, and 0.176- μm

TABLE III
PLEATED-CARTRIDGE PRESSURE DROP VS
FILTER-DISK PRESSURE DROP

Cartridge No.	Cartridge ^a ΔP -Cartridge Holder ΔP (in H_2O)	Disk ^b ΔP (in H_2O)	Cart. ΔP Disk ΔP
92	0.603	0.405	1.489
93	0.670	0.363	1.846
94	0.595	0.354	1.681

$$\bar{X} = 1.672$$

^aCartridge air-flow rate = 85 liters/min
Cartridge air velocity = 5.45 cm/sec

^bDisk air-flow rate = 12.6 liters/min
Disk air velocity = 5.45 cm/sec

aerosol probably approaches the size for maximum penetration.

Because MSA Type-S cartridges contain pleated filters, we needed to know whether the entire filter area was being used effectively. If it is, we would expect the same pressure drop using the cartridge at the calculated filtration velocity and using a circular disk of the medium at this same incident velocity. We selected three MSA Type-S filter cartridges and performed these tests. The pressure-drop data in Table III were derived from tests of the entire cartridge, the cartridge holder without the filter medium, and the filter disk from the medium in each cartridge. These data indicate that pressure drop caused by the cartridge filter medium is a factor of 1.67 greater than that produced by the disk, indicating that the entire pleated area does not experience the same filtration velocity. This suggests that a more effective filter-pleating design would be desirable to minimize pressure drop.

Figure 6 shows aerosol penetration of Welsh 7500-7 filter cartridges as a function of particle size at cyclic-flow rates of 415, 622, and 830 kg-m/min, and a steady-flow rate of 16 liters/min. Steady flow at 16 liters/min shows the classical separation of diffusion and impaction filtration mechanisms, and the maximum penetration is by

Fig. 6. Aerosol penetration of Welsh 7500-7 filter cartridges at cyclic-flow work rates of 415, 622, and 830 kg-m/min.

0.3- μ m particles, as theoretical single-fiber equations predict.¹⁶ During cyclic flow at all work rates, predominant maximum penetration is by 0.5- μ m particles. Penetrations vary from 2.5 to 38% throughout the entire particle-size range tested. There are no significant differences in penetration among the three different cyclic-flow work rates for particle sizes below 0.8 μ m; however, above 0.8 μ m penetration increases at the two higher work rates. At 830 kg-m/min, an increased penetration by 1.01- μ m particles is apparent but at 622 kg-m/min there is no increase until we use 2.02- μ m particles. This follows the kinetic energy hypothesis suggested previously. The kinetic energy of 1.011- μ m particles is great enough to overcome the filtration forces at 830 kg-m/min but not at the two lower cyclic-flow work rates. At 622 kg-m/min, the kinetic energy of 2.02- μ m particles is, again, large enough to overcome the filtration mechanisms, but at 415 kg-m/min it is not. At 415 kg-m/min, the velocity does not seem great enough to supply enough kinetic energy to the larger size particles. Again, particles larger than 1.0 μ m are of significant concern because of their much greater mass compared to submicron particles.

Fig. 7. Aerosol penetration of Welsh 7500-7 filter cartridges at cyclic-flow work rates of 622 kg-m/min and 622 kg-m/min plus 8 liters/min.

Because of the penetration spike at 0.5 μ m during cyclic-flow tests, it appears that 0.3- μ m DOP provides an underestimate of aerosol penetration of Welsh 7500-7 filters under steady-flow conditions. Steady flow at any of the particle sizes tested is not a reliable test method for this filter as it will be used on a respirator.

Figure 7 shows the relationship of true cyclic flow to cyclic flow plus an 8-liter/min sampling rate (man-test situation) at a work rate of 622 kg-m/min. When the balancing-air system is used to produce true cyclic flow, penetrations are significantly higher using particles larger than 0.3 μ m. This indicates that proposed man-test techniques will overestimate the effectiveness of filter performance. Peak penetration occurs using 0.3- μ m particles without the air-balancing system. DOP penetration values determined without the air-balancing system are slightly higher. Tests with Welsh 7500-7 filter cartridges indicate that either steady-flow tests with 0.3- μ m DOP or conventional DOP man tests as proposed by the U.S. Bureau of Mines under Schedule 21 B² overestimate filter performance. For quality-control and man-test

applications of Welsh 7500-7 filters, a 0.5- μm monodisperse aerosol would provide a more critical test. Comparative data for MSA Type-S and Welsh 7500-7 filters imply that individual test procedures may have to be developed for each type of respirator filter cartridge.

Figure 8 presents aerosol penetration of Whatman 41 medium as a function of particle size at cyclic-flow rates of 415, 622, and 830 kg-m/min and a steady-flow rate of 16 liters/min. This type of filter was used to compare respirator filter media and a medium that is often used for air sampling. Significant differences in penetration are seen below 1.5- μm particle size. Penetration varies from approximately 1 to 40% throughout the entire size and work-effort range tested. Although 0.5- μm particles cause peak penetration to occur during cyclic flow, this maximum penetration increases as the cyclic-flow work rate decreases. This would be expected because the time-averaged mean velocity at the higher

Fig. 8. Aerosol penetration of Whatman 41 filter medium at cyclic-flow work rates of 415, 622, and 830 kg-m/min.

Fig. 9. Aerosol penetration of Whatman 41 filter medium at cyclic-flow work rates of 622 kg-m/min and 622 kg-m/min plus 8 liters/min.

work rates is greater, and impaction mechanisms can become more effective. Penetration decreases below 0.5 μm , as was true for Welsh 7500-7 filter cartridges. This is probably because diffusion mechanisms become more effective. DOP penetration is, again, slightly higher than polystyrene latex penetration. At 16 liters/min steady flow, 0.234- μm polystyrene latex produces peak penetration, in agreement with previous experimental tests.¹² Below 0.4 μm , steady flow appears to give an underestimate of filter performance and the converse is true above 0.4 μm . These tests indicate that performance tests with 0.5- μm monodisperse aerosols or a polydisperse aerosol with a unit density 0.5- μm count median diameter would be desirable. The tests also indicate, again, that each type of filter is different, and individual performance tests should be prescribed for each type of filter and its use.

Figure 9 shows the relationship of true cyclic flow to cyclic flow plus an 8-liter/min sampling rate (man-test condition) at a work rate of 622 kg-m/min. The true cyclic-flow rate produced with the air-balancing

system gives significantly higher penetration values than those found when the balancing system is not employed. Although this type of filter is not used in respiratory protection, these data indicate that the DOP man-test methods suggested by the Bureau of Mines Schedule 21 B should be re-evaluated. Peak penetration occurs at less than 0.2- μ m particle size without the air-balancing system. This, again, could be because impaction mechanisms become more effective at smaller particle sizes owing to the added velocity. DOP values, with and without the air-balancing system do not differ significantly.

V. SUMMARY

Practical and theoretical performance of filtration media used for respirator filter cartridges have usually been investigated under steady- or constant-flow conditions. Steady-flow tests are currently used to predict future cartridge performance under various cyclic-flow conditions.

We tested aerosol penetration as a function of particle size using two respirator filter cartridges and one air-sampling medium during both steady flow and cyclic flow that simulated differing human breathing efforts. Maximum penetration of all filters does not occur at the same particle size during either cyclic or steady flow. Maximum penetration also occurs at a different particle size during cyclic flow as compared to steady flow. Generally the maximum penetration during cyclic flow is considerably higher than corresponding steady-flow values. Penetration of respirator cartridges and air-sampling filters by aerosols larger than 1.0 μ m was found to increase at some work rates. This is significant because the total mass of these particles is considerably greater than that of 0.3- μ m particles.

Steady-flow rates may provide a considerable overestimate of filter performance. True cyclic flow that is close to

the exact human breathing pattern, as opposed to true flow plus an 8-liter/min sampling rate, is a more accurate method of estimating overall respirator performance.

The general implication of this study is that test procedures for assessing acceptance criteria as well as personnel protection should be re-evaluated. Because all filters are different, a specific set of test procedures should be prescribed for each type of filter. These tests should be performed so as to simulate an individual's "true" breathing pattern.

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