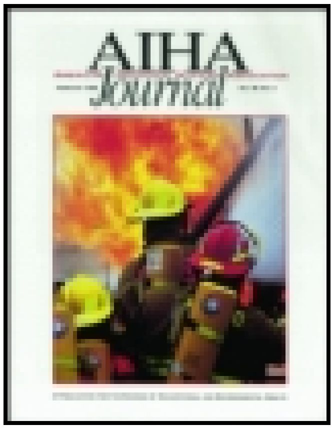

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Aerosol Penetration through Respirator Exhalation Valves*

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Exhalation valves are a critical component of industrial respirators. They are designed to permit minimal inward leakage of air contaminants during inhalation and provide low resistance during exhalation. Under normal conditions, penetration of aerosol through exhalation valves is minimal. The exhalation valve is, however, a vulnerable component of a respirator and under actual working conditions may become dirty or damaged to the point of causing significant leakage. Aerosol penetration was measured for normal exhalation valves and valves compromised by paint or fine copper wires on the valve seat. Penetration increased with increasing wire diameter. A wire 250 μm in diameter allowed greater than 1% penetration into the mask cavity. Dirt or paint accumulated on the exhalation valve allowed a similar level of penetration. Work rate had little effect on observed penetration. Penetration decreased significantly with increasing aerosol particle size. The amount of material on the valve or valve seat necessary for significant (greater than 0.5%) inward leakage in a half-mask respirator could be readily observed by careful inspection of the exhalation valve and its seat in good lighting conditions.

Engineering controls are accepted by occupational health professionals as the best means of protecting workers from exposure to toxic substances. Respiratory protection can be used instead of engineering controls in certain limited circumstances. These are (1) when engineering controls are not feasible, or cannot reduce the hazards to safe levels; (2) while engineering controls are being designed or installed; (3) in specific situations defined in some Occupational Safety and Health Administration (OSHA) regulations such as the asbestos, benzene, and lead standards.

Despite these restrictions on the use of respirators, an estimated 2.6 million workers wear respirators on a routine or occasional basis.[1] In some settings, such as maintenance or abrasive blasting of ships or buildings, respiratory protection may be the only feasible method of providing adequate protection to workers. Respirators may also be used under conditions in which exposure to toxic substances is usually at safe levels, but overexposure is possible.

Respirators can provide adequate protection against toxic substances only when used properly. Proper respirator selection, adequate supervision and training of respirator wearers, adequate maintenance of respirators, and proper functioning of the respirator are all required to achieve adequate protection. Aerosol penetration into a mask can occur by three routes: filter penetration, facial seal leaks, and exhalation valve leakage. The first two mechanisms usually are the most important, although the latter can be significant in certain circumstances, such as when the valve is dirty or malfunctioning. This paper addresses the nature and extent of exhalation valve leakage, that is, back leakage of outside air through the exhalation valve as it closes and seals during inhalation.

PREVIOUS WORK

There have been few studies evaluating aerosol leakage through respirator exhalation valves.[2,4–6] In general these studies have found valve leakage to be low for properly functioning valves. However, the valve is a vulnerable respirator component and if malfunctioning creates the potential for significant leakage.

Burgess evaluated respirator exhalation valve performance under a variety of conditions.[2] Leakage of test aerosol through the standard mushroom-shaped exhalation valves ranged from 0.002 to 0.05% at a work rate of 830 kg-m/min. Having the valve cover in position improved performance 2.5-fold. Burgess observed a 19-fold increase in penetration for a 830 kg-m/min work rate over that for a sedentary work rate.

A 1973 study of respirator practices in spray painting operations documented serious deficiencies in respiratory protection programs.[3] In this study, a survey of 159 spray painting operations, 28% of the respirators observed were not in acceptable working condition. Defects included deteriorated mask rubber, inhalation valves stuck closed, exhalation valves stuck open, cracked or warped exhalation valves, leakage around the filter elements, and missing head straps.

The Los Alamos Scientific Laboratories (now Los Alamos National Laboratory) published two reports describing their research on leakage through respirator exhalation valves.[4,5]

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Held et al. reported on the development of a respirator exhalation valve test system. Using a mechanical breathing machine, instantaneous airflow through an isolated exhalation valve was measured during inhalation. Airflow was found to be greatest at the start of the cycle. A clean mushroom-shaped exhalation valve showed an average leak of 6 mL/min during inhalation. With two hairs placed between the valve and the valve seat, this average leak flow increased to 17 mL/min. The airflow employed in their test was not mentioned. These leakage rates would correspond to an average leak of 0.008 and 0.02%, assuming they used a breathing pattern associated with a 622 kg-m/min work rate.[4]

Douglas used a dioctyl phthalate (DOP) test aerosol of unspecified size to measure aerosol penetration through respirator valves photometrically.[5] A breathing machine was used with a 622 kg-m/min cam operated at 27 cycles/min. Average leakage through clean exhalation valves was 0.04% without the exhalation valve cover in place and <0.01% with the cover in place. The authors concluded that properly functioning exhalation valves contribute little to respirator leakage.

Imel, in research reported at the 1985 American Industrial Hygiene Conference, measured aerosol penetration through valves covered with 25 to 75 mg of several types of dust. She observed penetration ranging from 1.33 to 17.1%.[6]

Several investigators have reported that respiratory protection programs are often substandard. A National Institute for Occupational Safety and Health (NIOSH) survey of personal protective equipment used in foundries found significant problems in the selection, care, and use of personal protective equipment.[7] Hosein and Farkas reported very poor respirator use practices among urethane foam applicators.[8] Evaluating respiratory protection in eight coal preparation plants, Enviro Control Inc. reported that none of the plants had respiratory protection programs in place, and that only 72% of the workers were able to achieve the rated protection factor for the respirator they were using.[9] Rosenthal presented data showing that 27% of the respiratory protection programs reviewed by federal OSHA health inspectors were deficient.[10]

From the research above one can conclude that properly functioning exhalation valves permit minimal inward leakage but valve performance can deteriorate significantly if the valve is compromised. The extent of mechanical interference needed to compromise valve performance significantly has not been evaluated. The effect of work rate on aerosol penetration through compromised exhalation valves, as well as the effect of aerosol particle size, have not been well evaluated. This paper presents a systematic evaluation of the effect of compromised exhalation valve function on particle size specific aerosol penetration through exhalation valves.

EXPERIMENTAL MATERIALS AND METHODS

Aerosol penetration through an exhalation valve in simulated use was evaluated for an MSA Comfo II half-face mask respirator sealed to a manikin in an aerosol test chamber. A dual piston mechanical breathing machine was used to simulate average human respiration at 0, 208, 415, and 622 kg-m/min work rates. The stroke rate (frequency) for these work rates was 19.6, 20.6, 22.7, and 29 cycles/min, respectively. Measurements were made for four test aerosol particle sizes, 0.5, 2, 4, and 8 µm. Aerosol concentrations inside and outside the mask during inhalation were sampled simultaneously. The entire inhalation flow was sampled to avoid streaming sampling errors described by Myers.[11,12]

Experimental measurements were made using a bench scale aerosol test chamber, described previously.[13] The 109-L chamber has a top mixing section, a honeycomb flow laminator section, a 52-L transparent plastic cylindrical aerosol test section (40-cm diameter), and a bottom exhaust plenum. The vertical airflow velocity, about 4 cm/sec, is uniform within 20% of the mean throughout the test section, and test aerosol concentrations are uniform within 5% and stable within 5% for more than 1 hr.

The respirator was sealed to the face section of a fiberglass manikin with hot melt adhesive. The Model SM 701 manikin (Silvestri California, Los Angeles, Calif.) has a face length of 11.2 cm and face width of 13.4 cm, a facial size that is in the overlapping range of males and females.[14] The adequacy of the facepiece-to-face seal of the respirator was evaluated by blocking the filter inlets and measuring the pressure drop generated by withdrawing a flow of 4.5 cc/min from the mask. A pressure drop of more than 50 mm of water was considered an indication of an adequate seal of the mask to the manikin. This corresponds to a 0.004% leak for the breathing profile associated with a work rate of 415 kg-m/min.

To make measurements of valve penetration of less than 0.03%, it was necessary to reduce filter penetration by supplying excess clean air to the filter element inlet. The aerosol chamber dilution air was HEPA-filtered, so a portion of this air was diverted to the respirator filters through 13-mm I.D. rubber tubing. A flow rate of 75 L/min was directed to a tee attached to each filter's inlet, as diagramed in Figure 1. This flow rate was greater than the greatest peak inhalation flow rate used. The clean air entered the filter cartridges through the base of the tee and the surplus clean air continued to the chamber exhaust, bypassing the chamber itself. The back pressure at the filter inlet created by this arrangement was less than 0.03 mm water. The peak

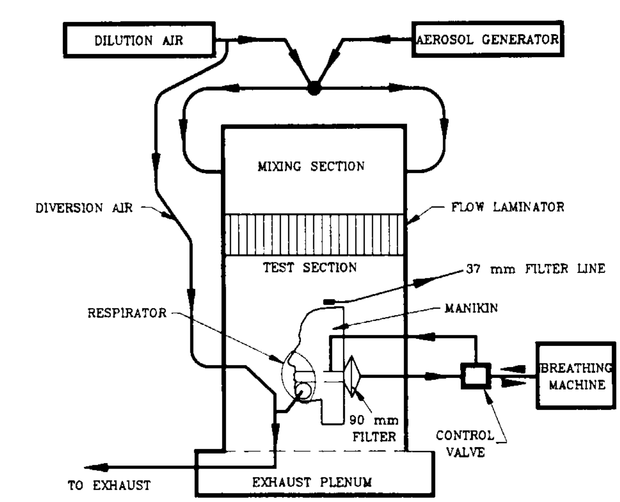

Figure 1. Schematic diagram of test system.

respirator pressure drop observed during inhalation remained unchanged from that observed with normal filter use.

The entire inhalation airflow for each breath cycle passed through a 90-mm high-efficiency glass fiber filter positioned immediately behind the manikin's mouth. Stroke volume and minute volume produced by the breathing machine were calibrated using a Model P-1300 13.5-L respirometer (Warren C. Collins, Braintree, Mass). Exhalation flow bypassed the filter, and exited through the respirator exhalation valve. A 47-mm filter was evaluated initially but was found to have excessive resistance.

The chamber aerosol concentration was measured during each run by sampling with a 37-mm in-line filter cassette at a flow rate of 4.6 L/min. Chamber concentration was 12 mg/m^3 for the polydisperse aerosol. The filter holder was positioned at the top of the manikin head, with the inlet axis horizontal. This sampling condition exceeds Davies' criteria for unbiased sampling of up to 20-μm particles.[15] Sample flow rate was controlled using a calibrated critical flow orifice.

Sample time ranged from 5 min to 1 hr. Long sample times were required to evaluate aerosol penetration through clean exhalation valves. Compromised valves did not require such long sample times. Sample times of less than 5 min did not give reliable results for the external filter sample. The aerosol concentration inside the chamber was allowed to stabilize for 2 min before any sampling was initiated.

An oleic acid aerosol tagged with uranine (sodium fluorescein) was used for all leakage measurements. After each filter sample was taken, the filter was extracted for 30 min in 0.2 molar boric acid buffer (pH = 9). The fluorescence of the eluant was measured with a Perkin Elmer Model 650 fluorometer at an excitation wavelength of 490 nm and an emission wavelength of 515 nm. The polydisperse test aerosol of 0.51-μm mass median aerodynamic diameter (MMAD) (geometric standard deviation = 2.1) was generated using a TSI Constant Output Aerosol Generator. Monodisperse aerosols (2, 4, and 8 μm aerodynamic diameter) were generated using a TSI Vibrating Orifice Aerosol Generator. Aerosol number concentration was estimated to be 1 to 20 particles/cm^3.

Although moisture in the exhaled breath may affect exhalation valve performance in actual use, the exhaled air was not humidified in this test situation. This was because the fluorescent dye used is freely soluble in water. While this solubility provided an advantage in extracting the sample filters, it might have biased the authors' measurements if water had collected around the exhalation valve or other respirator components. In addition, previous research has indicated that wetting the exhalation valve will improve its performance against aerosol leakage into the respirator, so the evaluation of dry valves represents a worst-case condition.[2]

In order to simulate valve defects in a controlled way, copper wires of known thickness were placed in direct contact with the exhalation valve seat. Wire thicknesses were 0.03, 0.08, 0.13, and 0.25 mm, the same order of magnitude as human hair.[16] A short length of wire was positioned radially on the exhalation valve seat and bent to follow the contours of the seat. The wire was held in position by small pieces of tape. The tape was carefully positioned so it would not interfere with valve function or potential leak flow.

Four tests were conducted using valves compromised by paint on their exterior surface—one coated with spray paint in the lab, and three valves coated with paint during normal use in an industrial spray painting operation. The latter had been discarded and were selected from a group of 85 used respirators in poor condition. The tested respirators were MSA Comfo II or Binks respirators. The latter appeared identical to the MSA respirators. Conditions under which the used valves were contaminated with paint were not evaluated.

Mask performance was evaluated by simultaneous measurement of aerosol concentration inside and outside the mask. Aerosol mass was estimated by the fluorescence of uranine dye in extracted samples. Each test condition was repeated three to five times. The mean and standard deviation of percent penetration through the mask at each test condition were calculated using the ratio of averages method discussed by Cochran.[17] The limit of detection was a penetration of 0.001%. This corresponds to a concentration of uranine dye in the extracted samples on the order of 10 ppb. Data points suspected of contamination were excluded when a measurement of inside concentration was more than 10 times the smallest observed value. Overall, 2.1% of the test samples met this criterion and were excluded from analysis.

RESULTS

Normal Valves

Figure 2 shows penetration of submicrometer aerosol for normal valves versus work rate. Penetration increases with increasing work rate, with a 10-fold difference between the lowest and highest work rate evaluated. This agrees well with previous work[2,4,5] and confirms the observation that exhalation valves in good condition permit negligible inward leakage.

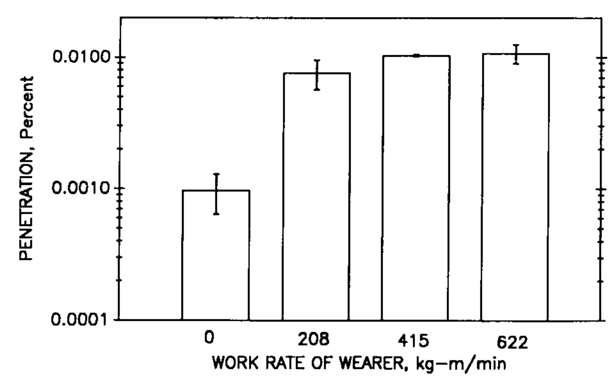

Figure 2. Submicrometer aerosol penetration through clean valves. Error bars represent one standard deviation (n = 4 or 5).

Effect of Flow Pattern and Flow Rate

Clean exhalation valves were challenged with submicrometer aerosol in three flow modes at 0 and 415 kg-m/min work rates. For each work rate, aerosol penetration through the exhalation valve was evaluated under (1) steady flow at the average inhalation flow rate; (2) inhalation only through the mask (i.e., exhalation flow diverted); and (3) normal breathing cycle through the mask. The results are shown in Figure 3.

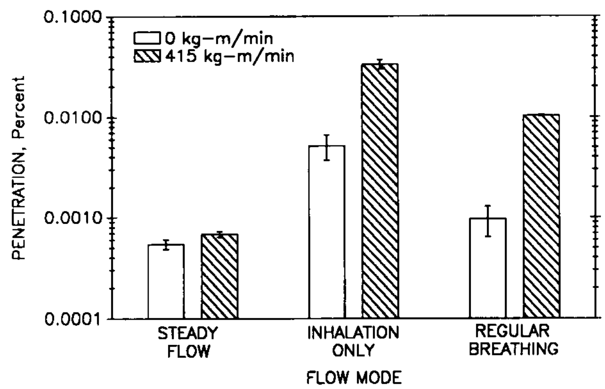

Figure 3. Penetration of submicrometer aerosol through clean exhalation valves in different flow modes (n = 3 or 4).

The penetration observed for full cycle flow was lower than that observed for inhalation-only flow. This is caused in part by the effect of mask dead space. For the authors' set-up, exhalation air was virtually particle free, having been filtered during inhalation. Mask volume in this test system was 270 cc, which is 38.6% of the 0 cam stroke volume and 21.3% of the 415 cam stroke volume. Assuming perfect mixing of exhalation valve leak flow, the penetration observed for inhalation-only flow (P_I) should be related to penetration observed for full cycle flow (P_F) as follows [11]:

$$\frac{P_I}{P_F} = \frac{100}{100 - DS} \qquad (1)$$

where DS is dead space volume expressed as a percent of inhalation volume. Equation 1 predicts the ratio P_I/P_F to be 1.27 (1.54 ± 0.24 observed) with the 415 cam and 1.63 (5.4 ± 0.5 observed) with the 0 cam. These measurements are made at the limit of detection for this method, accounting in part for the deviation from the expected values of P_I/P_F.

As expected, steady flow at the average inhalation flow rate was unreliable as an indicator of valve leakage under cyclic flow. This confirms previous research indicating that penetration through an exhalation valve at steady flow is not representative of that at cyclic flows. All other testing was conducted using the breathing machine to generate cyclic flow through the respirator.

Effect of Interference with Valve Seating

The presence of fine copper wires on the valve seat dramatically altered valve performance. Aerosol penetration increased by 100- to 1000-fold with the introduction of a 0.25-mm wire, as shown in Figure 4. For wire diameters greater than 0.08 mm, work rate was a minor consideration in valve perfonnance compared to the effect of work rate when the valves are clean. The penetration of 0.5-µm MMAD aerosol increased gradually to greater than 1% as wire thickness increased from 0.03 to 0.25 mm.

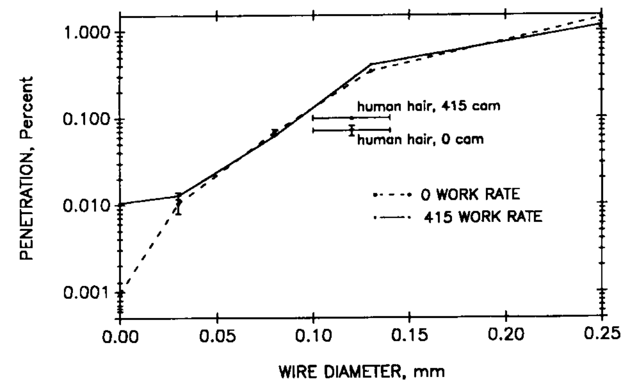

Figure 4. Penetration of submicrometer aerosol through normal and compromised exhalation valves, as a function of wire diameter.

The seating of the wire exerted a marked influence on aerosol penetration. If the wire was not in complete contact with the valve seat, the aerosol penetration was highly variable, as much as two to four times greater than carefully positioned wires. Nonetheless, for all conditions evaluated, the observed aerosol penetration did not exceed 5%. One human hair (diameter 0.1 to 0.15 mm) set loosely on the valve seat allowed penetration of the same magnitude as the wire leaks. The authors believe that other foreign objects of similar dimensions would cause similar leakage.

Effect of Aerosol Particle Size

The penetration of aerosol particles through leaky valves was strongly dependent on particle size. Particles of 1.5 to 2.5 µm aerodynamic diameter had a penetration half that of the 0.5-µm MMAD aerosol, as shown in Figure 5. Previous research on facial seal leaks indicated that facial seal leak penetration fell off less sharply with particle size, a 50% relative penetration being observed at approximately 4 µm.[18] Similar measurements could

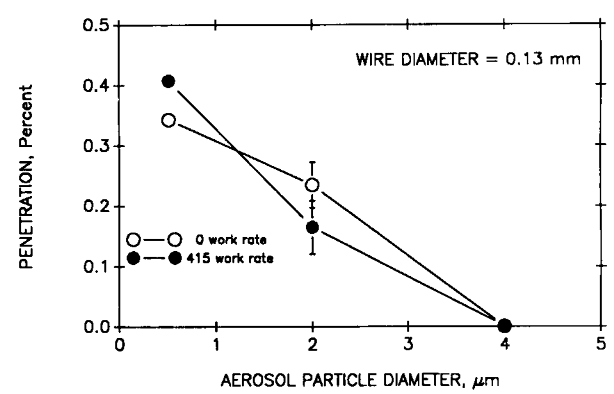

Figure 5. Penetration of exhalation valves with wire leaks versus particle size. The submicrometer aerosol is polydisperse, the others are monodisperse.

not be performed on clean exhalation valves because the penetration of the 0.5-µm MMAD aerosol was near the lowest detection limit for the experimental set-up.

Effects of Other Parameters

The exhalation valve cover offers mechanical protection to the valve and helps prevent the accumulation of paint overspray and other material on the valve and valve seat. It also provides a volume of relatively clean exhalation air that at least initially passes through valve leaks during inhalation. This effect is shown in Figure 6. Exhalation valve leakage showed a 1.5- to 2-fold improvement in valve performance with the valve cover in place compared to no cover. For nine test conditions evaluated, the average improvement with the exhalation valve cover was 2.0 (SD = 0.6).

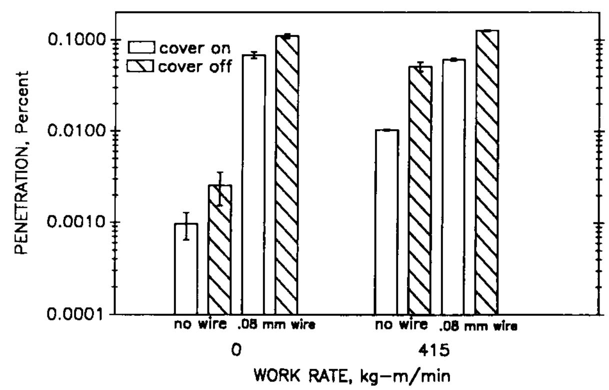

Figure 6. Effect of exhalation valve cover on submicrometer aerosol penetration through exhalation valves. Error bars are one standard deviation (n = 4 or 5).

The exhalation valve and valve seat can become coated with paint, even with the exhalation valve cover in place. An exhalation valve was coated with an even layer of spray paint, 10–20 µm thick. The valve was slightly stiffened and warped when seated on the valve seat. As shown in Figure 7, penetration of the 0.5-µm MMAD aerosol was 1.5% with the 0 kg-m/min cam and 0.75% with the 415 kg-m/min cam.

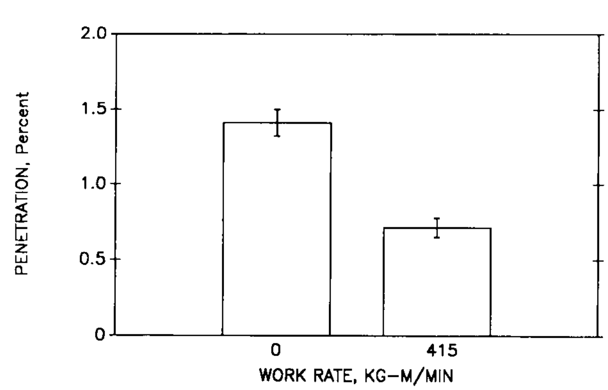

Figure 7. Submicrometer aerosol penetration through a valve compromised with spray paint.

The three valves obtained from discarded respirators were heavily coated with paint, although less so than the laboratory coated valve. Some paint was observed between the exhalation valve and the valve seat. Penetration through these valves ranged from 0.28 to 0.66%, comparable to the penetration found for a 0.13-mm wire on the valve seat.

The most severe exhalation valve defect is a missing valve or one stuck in the open position. When tested with a missing exhalation valve, the mask offered little protection, as shown in Figure 8. Penetration fell as aerosol particle size increased, but reached a plateau at about 30% penetration.

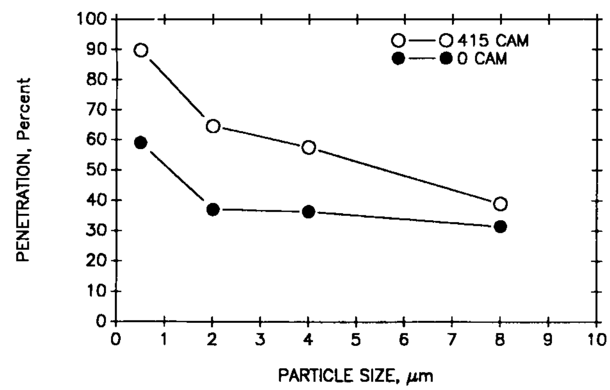

Figure 8. Penetration of aerosol through mask with no exhalation valve. The submicrometer aerosol is polydisperse, the others are monodisperse.

SUMMARY AND CONCLUSIONS

Properly functioning exhalation valves allow minimal leakage of contaminants into the mask, less than 0.01%. The exhalation valve is a relatively sensitive, but important, component of a respirator. Significant leakage can occur if exhalation valves are dirty or warped, or if fibers or foreign objects become trapped between the valve and the valve seat.

Penetration observed under laboratory conditions for wire-induced exhalation valve leaks was as high as 1.1%. While this amount of leakage is of concern for half-mask respirators, it is of greater significance for full-face mask respirators, which use the same kind of valves but have greater assigned protection factors. The magnitude of the leaks observed support the recommendation that the exhalation valves should be examined visually on a regular basis. Simple negative pressure tests may not detect problems with the exhalation valves, because the induced pressure may be sufficient to seal the valve around a foreign object.

Static or steady flow tests do not accurately reflect potential leakage through exhalation valves. The size of a foreign object required to produce a 1% leak is readily observable under good lighting conditions.

The effect of paint and/or dust accumulation on a valve is comparable to that of wire-induced leaks, 0.2 to 0.6%. Again, careful visual observation of the paint or dirt on the exhalation valve or seat can serve as a reliable indicator for valve replacement.

One can conclude that proper inspection of all respirator components, including the exhalation valve and its seat, is a necessary component of a respiratory protection program.

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