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Method Development for Measuring Respirator Exhalation Valve Leakage

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The wearing of respirators is an important means of protecting workers from excessive exposure to air contaminants. A proper-functioning exhalation valve is crucial for an effective respirator. A fast "Respirator Integrity Test" was developed to be used as a quality assurance test before field use of a respirator. The purpose of the test is to assure that no leakage occurs through the exhalation valve nor any other potential leak source in the respirator such as the seal between the respirator body and the air purifying cartridges. If a leak does occur through the respirator, its most likely cause appears to be the exhalation valve. Therefore, the new test method has been compared to a direct "Exhalation Valve Test." Exhalation valve leakage was measured in both new valves and field-used valves. Leakage through new valves was minimal in most cases, but one brand of new valves was found to leak significantly. Five percent of 67 field-used exhalation valves tested had unsatisfactory leakages indicating that dust or debris on the exhalation valve or valve seat may compromise the proper functioning of the valves. The cleaning of both new and field-used exhalation valves with water caused leakage to decrease significantly, thus supporting the importance of a good respiratory cleaning program for industries. **Brueck, S.; Lehtimaki, M.; Krishnan, U.; Willeke, K.: Method Development for Measuring Respirator Exhalation Valve Leakage: Appl. Occup. Environ. Hyg. 7(3):174–179; 1992.**

Introduction

Respirators are widely used in the workplace as a means of protecting workers from inhaling potentially dangerous or toxic airborne contaminants. Ideally, a proper-fitting and -functioning respirator will not allow the respirator wearer to inhale air contaminants having concentrations above the occupational exposure limits.[1,2] In practice, however, an undesirable amount of contaminants may enter the respirator cavity through inefficient air purifying cartridges, through leak sites between the face and respirator body and between the respirator body and air purifying cartridges, through open channels in damaged respirators, and through inadequately functioning exhalation valves.

Face seal leaks are the dominant pathways for air contaminant entry. Fit testing is, therefore, required for respirator wearers in industrial work environments to ensure that the selected respirator provides an adequate fit to the wearer's face.[3–7] Lack of respirator integrity may also allow air contaminants to enter the respirator through additional leak pathways. Among these, exhalation valve leakage appears to contribute the most. Laboratory tests with aerosols have shown that such leakage may be significant.[8–12]

Exhalation valves are simple flap-type valves that fit into an exhalation port on the respirator and allow for one-way flow of air. During inhalation, negative pressure inside the respirator cavity causes the exhalation valve to be pulled against the valve seat thus preventing outside air from entering. During exhalation, positive pressure unseats the valve and allows air to exit the respirator through the exhalation port with minimal resistance. If the exhalation valve does not completely seal against the valve seat during inhalation, unpurified air will leak into the respirator cavity and be inhaled by the respirator wearer, causing an exposure situation. Factors that affect the leakage of air through the exhalation valve during inhalation are physical damage to the valve or exhalation port, deterioration of the rubber through exposure to chemicals, and the presence of foreign material between the valve and valve seat.

The Occupational Safety and Health Administration (OSHA), in setting guideline requirements for a minimal acceptable respiratory protection program, requires respirators to be cleaned and disinfected regularly. Routinely used respirators must be inspected during cleaning and worn or deteriorated parts must be replaced.[5] If OSHA requirements are followed, then factors which cause improper exhalation valve function will be corrected and leakage will be kept to a minimum.

One of the first studies that examined exhalation valve leakage was conducted by Burgess and Anderson.[9] In their laboratory experiments, four different types of ex-

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halation valves were evaluated for leakage of submicrometer-sized uranine aerosols. The tests were conducted at ambient room humidity while the valves were connected to a breathing machine that simulated cyclic respiratory flow rates at a work rate of 830 kg-m/min. They found that new valves leaked the test aerosol from 0.002 to 0.071 percent, depending on the type of valve used for the test. In their studies of valves that had been discarded by users as malfunctioning, they found test aerosol leakage rates which were one to two times greater than leakage rates through new valves of the same type. In most cases, test aerosol leakage through humidified valves was lower than leakage through dry valves and aerosol penetration increased with an increase in work rate.

Held *et al.*[10] also used a breathing machine to measure exhalation valve leakage in studies at the Los Alamos Scientific Laboratories. Leakage of air through a clean exhalation valve during the inhalation cycle was measured to be 6 ml/min. When the valve was compromised by hairs placed between the valve and valve seat, the leakage increased nearly threefold.

Bellin and Hinds[11] measured aerosol penetration through exhalation valves for four different particle sizes using a mechanical breathing machine to simulate different work rates. As in previous studies, they also found that leakage increased with increasing work rate. Aerosol penetration through leaking valves was found to be particle-size dependent. A 0.25-mm copper wire placed on the valve seat increased aerosol penetration a hundred to a thousand times. Bellin and Hinds also found that paint and/or dust between the exhalation valve and the valve seat caused a penetration of test aerosols from 0.28 to 0.66 percent, which was similar to the penetration found when a 0.13-mm wire was placed on the valve seat. They concluded that proper-functioning exhalation valves should allow less than 0.01 percent leakage, but dirty or damaged valves may have significantly more leakage. Brosseau *et al.*[12] also found exhalation valve failure in tests with asbestos aerosols.

Contaminants such as aerosols, vapors, and/or gases are carried into a respirator by air flow through leak channels. Therefore, a relevant test for determining leakage is to measure the flow of air through leaks. Measurement of the air flow is a much less expensive and less elaborate test than any of the aerosol tests used in previous studies. The aim of this study was threefold:

1. To develop a fast and inexpensive quality assurance test that measures air leakage through any leak sites in the respirator body.
2. To compare this field compatible test to direct measurements of exhalation valve leakage.
3. To measure the leakage of air through new, unused exhalation valves and also through exhalation valves of respirators regularly worn and exposed to various workplace contaminants.

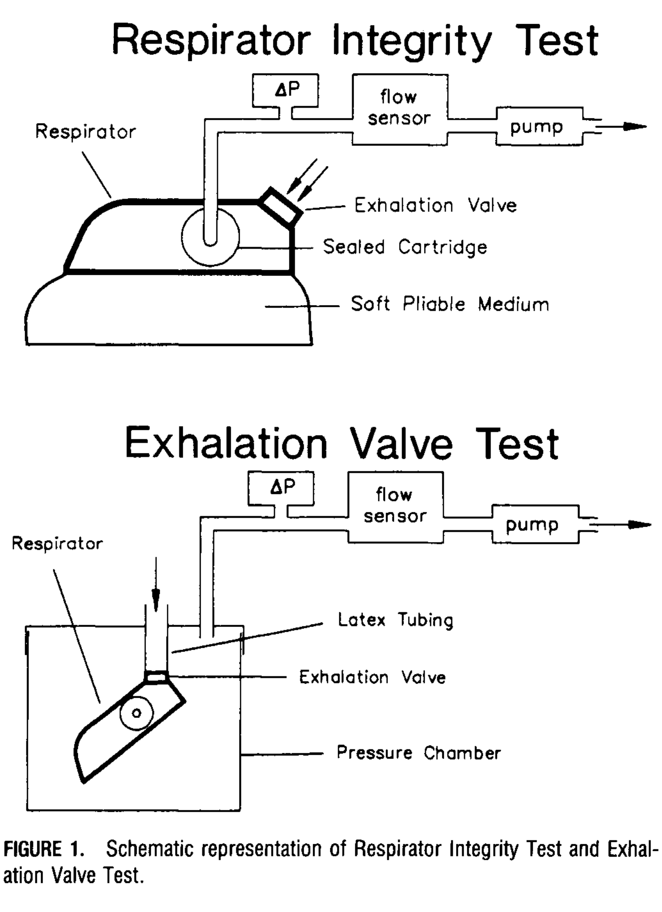

FIGURE 1. Schematic representation of Respirator Integrity Test and Exhalation Valve Test.

Methods

Two test systems, the Respirator Integrity Test and the Exhalation Valve Test, shown in Figure 1, were developed to determine respirator exhalation valve leakage in both the laboratory and in the field. The Respirator Integrity Test involves placing the respirator on a soft, pliable medium. A large, pliable prosthesis, used as a breast substitute, was found to be very suitable for this purpose. The prosthesis simulates the face of a respirator wearer and does not allow leakage between the respirator and the prosthesis. The test determines the integrity of the respirator by measuring leakage through all other sources, including through the exhalation valve. If leakage is found to be significant, the Exhalation Valve Test distinguishes exhalation valve leakage from other potential leak sources.

In order to confirm that there was no "faceseal leakage" between the respirator body and the prosthesis, the Respirator Integrity Test was compared to direct measurements of the flow through the exhalation valve. In this Exhalation Valve Test (see Figure 1), the backflow of air through exhalation valves into the respirator was measured at three different negative pressures, 0.5, 1.5, and 2.5 cm water gauge (w.g.). These negative pressures were experimentally chosen, based on our preliminary studies prior to testing the valves, to simulate the pressure difference that develops inside the respirator corresponding to resting, light, and moderate to heavy workloads. This compares to workload levels of approximately 208, 415, and 622 kg-m/min.[11] A small, high-volume sampling pump was used to generate the negative pressures. Leak flow, Q_l, through the exhalation valves was determined by a flow sensor. It consisted of a Magnehelic gauge that measured the pressure drop across a linear flow element. A bubble meter was used to calibrate the flow through the linear flow element. The regression equation, derived from the calibration curve, was used to convert pressure drop to leak flow.

The procedures required for each test are as follows:

A. Respirator Integrity Test
   1. Attach sealed cartridges, which have been modified for attachment of the flow sensor and pump, to the respirator.
   2. Position respirator on the pliable medium (prosthesis).
   3. Turn on the pump, adjust the negative pressure to the desired work level, and take the flow sensor reading.

B. Exhalation Valve Test
   1. Remove exhalation valve cover and carefully attach latex tubing to the valve seat assembly, making sure the exhalation valve is not disturbed.
   2. Attach latex tube assembly and respirator to the underside of the lid of the test chamber and close the lid of the chamber.
   3. Turn on the pump, adjust the negative pressure to the desired work level, and take the flow sensor reading.

Previous studies have indicated that aerosol penetration is reduced when the protective exhalation valve cover is in place when compared to measurements without the cover.[9,11] It should be noted that our tests do not measure aerosol penetration, but the flow of air through the leak. Therefore, removal of the valve cover does not affect the test.

Previous studies of exhalation valve leakage have used breathing machines to simulate the cyclic flow that occurs while a worker is wearing a respirator.[9–12] Bellin and Hinds[11] found that aerosol leakage at an average inhalation rate may be somewhat different from valve leakage occurring under cyclic flow conditions. Under cyclic flow conditions, instantaneous leakage may occur through the exhalation valve just before the valve closes reflecting the response dynamics of the valve. Steady flow was used in this study to produce negative pressures which simulate different work intensities. Exhalation valves were then evaluated for the leakage that occurs after the valve has closed in response to the negative pressure.

In this study, exhalation valve leakage was first evaluated in new, unused mushroom- and flap-type exhalation valves and then in exhalation valves from respirators used regularly in industry where they were exposed to workplace dusts and chemical vapors. Exhalation valve leakage was tested on 54 new respirator valves and 67 industrially used respirators. Test measurements were repeated five to ten times on a representative sample of randomly chosen respirators to determine variation in exhalation valve leakage for successive measurements.

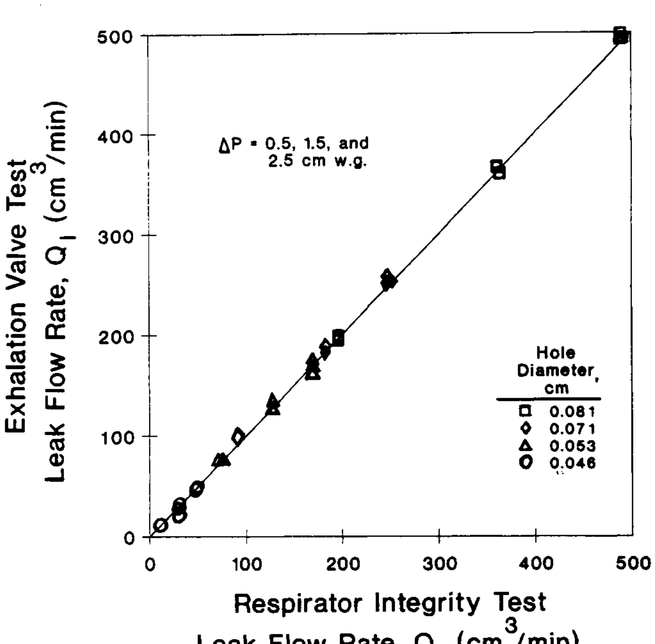

FIGURE 2. Comparison between leak flow measured by the Respirator Integrity Test and Exhalation Valve Test for fixed leakages.

Results

The Respirator Integrity Test and the Exhalation Valve Test will measure the same leakage if the respirator integrity is not compromised by leaks other than exhalation valve leakage. A comparison between leak flow rates, as determined by the Exhalation Valve Test and the Respirator Integrity Test, is shown in Figure 2. For this series of tests, the exhalation valve flap was replaced by 0.5-cm long fixed leak holes of 0.046, 0.053, 0.071, and 0.081 cm diameter. Three tests were conducted for each fixed leak-hole size and each negative pressure (0.5, 1.5, 2.5 cm w.g.). The data closely follow the 1:1 line which indicate that either test may be performed if the exhalation valve is the only source of leakage into the respirator. It should be noted that for each fixed leak-hole size the leak flow increases with increasing negative pressure.

Leak flow through new exhalation valves received directly from a supplier was tested using the Exhalation Valve Test. Once exhalation valve leakage rates were measured, a flow ratio, FR, could be determined by dividing the cartridge flow, Q_c, which is the air flow that enters a respirator through the air purifying cartridges, by the leak flow, Q_l.

$$FR = \frac{Q_c}{Q_l} \quad (1)$$

The flow ratio is equal to the fit factor if there is no aerosol removal in the leak channel and the aerosol particles mix well in the respirator cavity.[6,7] If aerosol particles are removed in the leak channels, the fit factor is higher than the flow ratio. For the calculation of flow ratios, 32,000 cm^3/min (32 L/min) was chosen as the cartridge flow because this is the minimum value required by the National Institute for Occupational Safety and Health (NIOSH) for performance testing of air purifying respirator cartridges.[13] This instantaneous inhalation rate corresponds

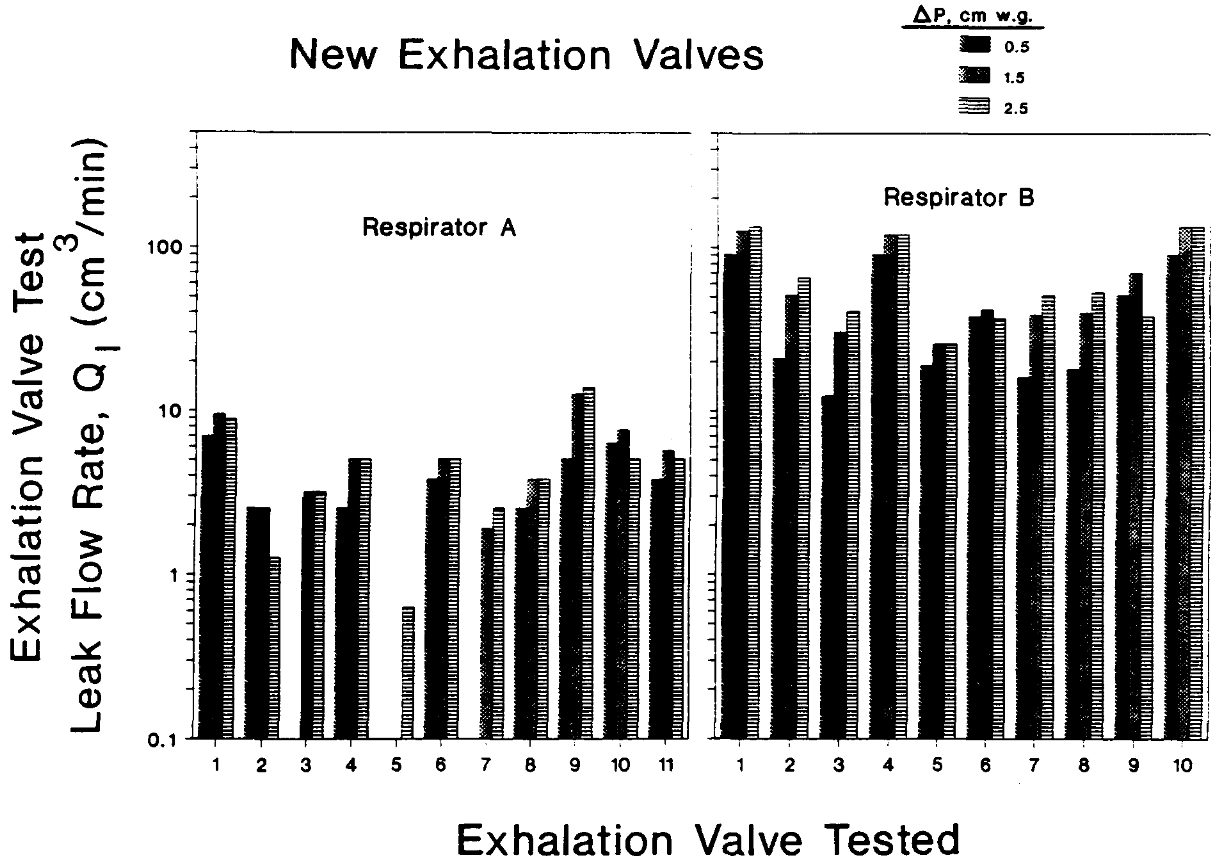

FIGURE 3. Exhalation valve leak flow rates for new valves.

to a breathing rate of approximately 16 L/min.

Four of the five brands of new exhalation valves had exhalation valve leak flow rates about 10 cm^3/min or less for all negative pressures, as seen for respirator A in Figure 3. The flow ratio for a leak flow rate of 10 cm^3/min is 3200. Aerosol studies have also shown very low leak flow rates through new exhalation valves.(9,11) For our evaluation of leak flow rates through exhalation valves, a flow ratio greater than or equal to 500 will be considered insignificant and acceptable, while flow ratios less than 500 will be considered unacceptable, indicating that the performance of the valves needs to be improved.

One of the five brands of new exhalation valves tested, brand B, had leak flow rates that were significantly higher, as shown for respirator B in Figure 3. Three of the valves tested had leak flow rates greater than 100 cm^3/min for negative pressures of 1.5 and 2.5 cm w.g. and nearly 100 cm^3/min for a negative pressure of 0.5 cm w.g.. The other seven valves tested had leak flow rates between 10 and 80 cm^3/min. It should be noted that Figure 3 shows exhalation valve leak flow rates on a logarithmic scale that tend to visually diminish differences between values. Leak flow rates of 100 cm^3/min give a flow ratio of 320 which can be considered significant and unsatisfactory when compared with leakage rates through the other brands of new exhalation valves. It was observed that exhalation valves from respirator brand B were flap-type with accordion-like folds. These were slightly different than those of the other respirator brands which were flat, mushroom- or flap-type valves.

New exhalation valves received from the supplier were packaged in small plastic bags or cardboard boxes. The valves did not include instructions, except for valves from one of the manufacturers which stated that the valves should be rinsed with cold water and dried before use. Ten exhalation valves from one of the manufacturers were tested before and after the valves were rinsed. Leak flow rates were lower after the valves had been rinsed and allowed to air dry.(14) The decrease in leak flow rates after washing and drying ranged from 0 to 70 percent, but for a majority of the valves, the decrease was 40 to 70 percent.

Leak flow through exhalation valves in respirators used in a dusty industry and in respirators used in a chemical industry was determined using the Exhalation Valve Test. Comparison of the results of these tests indicated that there was a tendency for greater exhalation valve leakage to occur in respirators used under dusty conditions. A likely explanation for this is that dust particles between the valve and valve seat may prevent the valve from completely sealing during inhalation.

The procedure for respirator care in the dusty industry required the respirators to be washed and disinfected after each use. Workers wore a respirator for approximately two to eight hours each day. Nearly half of the respirators were lightly to moderately covered with dust. Visual inspection of the exhalation valve assemblies found them to be free of physical defects; however, a majority had a light amount of dust on the outer surface of the exhalation valve. Two of the 26 brand C respirators tested had leak flow rates through the exhalation valves greater than 100 cm^3/min, which can be considered unsatisfactory. The remaining 24 respirators had exhalation valve leak flow rates between 0.1 and 50 cm^3/min, with most near 1.0 cm^3/min. One out of ten exhalation valves of respirator brand D had a leak flow rate greater than 100 cm^3/min, one had a nonmeasurable leak flow rate, and the remaining respirators had exhalation valve leak flow rates between approximately 1 and 20 cm^3/min.

The procedure for respirator care in the chemical industry also required respirators to be washed after each use. Visual inspection of these respirators and their exhalation valves found them to be clean and free of damage, except in a few instances where a very light amount of dust could be seen on the respirators. Respirator brand E had exhalation valves leak flow rates between 0.6 and 35 cm^3/min. Respirator brand F had exhalation valve leak flow rates between 15 and 30 cm^3/min.

Exhalation valves from four respirators used in the chemical industry were rinsed with cold water and dried after they had been initially tested for exhalation valve leakage. The decrease in exhalation valve leakage after cleaning the valves ranged from 45 to 91 percent. Although the leak flow rates before cleaning were not significantly high, the decrease in leakage was significant.

An exhalation valve from a respirator used in the dusty industry was found by the Respirator Integrity Test to have a very high leak flow rate, approaching 250 cm^3/min at a negative pressure of 2.5 cm w.g. A small piece of rubber debris between the valve and the valve seat, which prevented the exhalation valve from completely closing, was found upon visual inspection of the valve. After removal of this piece of debris, the leak flow rate through the exhalation valve decreased to less than 5 cm^3/min. This provides a good example of what happens when a foreign object between the valve and valve seat prevents the exhalation valve from completely closing.

The data for both new exhalation valves and field used exhalation valves shows that there is a tendency for the leak flow rate through an exhalation valve to increase with an increase in negative pressure. A probable explanation is that the increase in negative pressure causes an increase of air flow through the leak site, as has been previously shown.[6,7] In some cases, the leak flow decreased with increasing negative pressure. This is most likely caused by the exhalation valve sealing more tightly to the valve seat in response to the increased negative pressure, resulting in some of the leak holes becoming smaller or sealed.

Figure 4 shows the percent of respirator exhalation valves from industry (67 respirators tested) that had flow ratios less than a given flow ratio. Fewer than 10 percent of the respirator exhalation valves tested in this study had flow ratios less than 1000, and approximately 5 percent had flow ratios less than 500. Therefore, 95 percent of the respirators tested in this study had exhalation valve leakages that could be considered insignificant when a flow ratio of 500 or greater is considered insignificant.

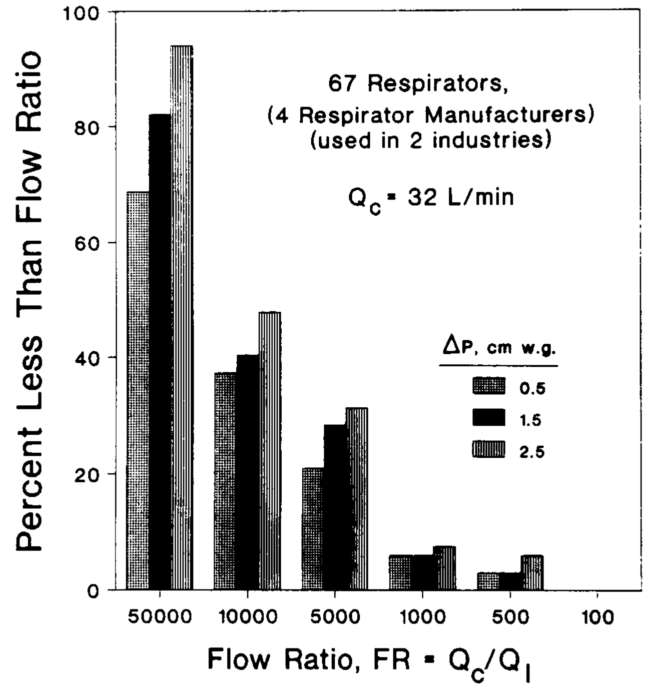

FIGURE 4. Percent of field used exhalation valves with flow ratios less than a given flow ratio.

Conclusion

Air flow through exhalation valves was measured at three different negative pressures. Two test methods, the Respirator Integrity Test and the Exhalation Valve Test, were developed to provide fast measurement of leakage in new valves and field-used valves. Comparison between the two test methods using fixed leak holes shows that each test gives similar results if leakage occurs only through the exhalation valve. Leakage in most of the new exhalation valves tested was less than 10 cm^3/min, giving a flow ratio of 3200 which was considered insignificant. One of the brands of new valves tested had leakages of 100 cm^3/min for some of the valves, indicating that significant leakage may occur. Leak flow rates of 100 cm^3/min give a flow ratio of 320 which was considered unsatisfactory. Some of the respirators used in a dusty industry had significant exhalation valve leakage. Respirators used in a chemical industry were found to have insignificant exhalation valve leakage. Leakage through both new and field-used exhalation valves decreased after the valves were cleaned with water and dried. Decrease in leakage ranged from 0 to 70 percent for new valves and 45 to 91 percent for field-used valves. Foreign debris between the exhalation valve and valve seat may prevent the valve from closing, causing significant leakage to occur. Overall, leakage through 95 percent of the field-used exhalation valves was minimal with flow ratios greater than 500. Visual inspection of the exhalation valve assembly allows the respirator user to identify problems that may cause significant exhalation valve leakage, but leakage may also be quickly and easily measured with the Respirator Integrity Test and the Exhalation Valve Test.

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