

The Effect of Internal Challenge on Exhalation Valve Performance

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Abstract

The presence of foreign objects, such as dust, in the exhalation valve of a respirator can contribute to leakage by preventing an airtight seal between the valve and the valve seat. Static test methods specified in the U.S. for evaluation of exhalation valve function may not detect leakage which would occur in actual use. Exhalation valves of seven identical half-mask **air-purifying** respirators were treated with dust and allowed to dry. The masks were sealed to a ceramic **headform** and evaluated with forward **light-scattering** photometry under dynamic flow conditions, and with an adaptation of the NIOSH-specified static method. Results in the 189 dynamic tests ranged from none detected to a maximum of 60 percent leakage. Additional tests showed up to 5.0 percent leakage with as little as 0.5 mg of dust. Static leakage measurements averaged across all factors exceeded the **15-mL/min** static leakage specified by the U.S. Army, and all but one exceeded the **30-mL/min** level cited by BOM-NIOSH. A poor correlation was observed between static and dynamic testing, suggesting that the use of static leakage measurements alone has a limited value and should be discontinued.

Introduction

Respirators are often worn to protect workers from inhalation of contaminants in dusty environments. This dust could find its way to the interior of the respirator and thus to the exhalation valve of the mask if the mask were improperly stored or allowed to lie interior-side up in a dusty area. (Although the probability is lower, the same flat phenomenon could also occur in a "clean" environment, particularly in one with improper respirator

maintenance and storage practices.) If the mask were then worn by a worker in a warm area, dust in the facepiece could be carried to the exhalation valve by perspiration, perhaps with additional dust particles from the face. Since the proper functioning of the exhalation valve requires it to position against the valve seat during the inhalation phase, the presence of foreign objects such as dust or facial hair could prevent the valve from making

a complete seal with the valve seat, thus allowing air to enter the facepiece through the exhalation valve rather than through the filters or chemical cartridges of the respirator. Workers wearing appropriately selected, correctly fitted, and otherwise properly functioning respirators would thus be inadequately protected. Recent experiments using small-diameter (0.03 to 0.25 mm) wires to prevent the exhalation valve from making complete contact with the valve seat have indicated leakage of 0.5- μm particles to be as high as 1.1 percent when the 0.25-mm wire was used (Bellin and Hinds, 1990).

Although test methods used in Japan (Myojo, 1989) specify dynamic test conditions (cyclical flow through the respirator, simulating actual use

conditions), current test methods in the U.S. call for static testing of exhalation valve function (QAD, 1967; 30 CFR 11, 1988; NIOSH, 1987a). Static testing, in which a constant negative pressure is exerted in the facepiece, may not detect leakage which would occur when the respirator is in actual use. The first purpose of this study was to investigate factors which could influence dynamic leakage through the exhalation valves of half-mask, air-purifying respirators. Specific objectives were to determine the effects of different dust types and quantities, saline (perspiration) quantities, work rates, and test duration on leakage through exhalation valves. The second purpose of this study was to compare the static and dynamic methods of leakage testing under clean and contaminated valve conditions.

Methods

The MSA Comfo® II Custom (neoprene) was chosen as being representative of half-mask, air-purifying respirators typically used in industrial applications. The masks were fitted with high-efficiency particulate aerosol (HEPA) filters, in which mode they have been certified by the National Institute for Occupational Safety and Health (NIOSH) for exposure to dusts, fumes, and mists having a Threshold Limit Value (TLV) less than 0.05 mg/m^3 , asbestos-containing dusts and mists, and radionuclides (NIOSH, 1991). The exhalation valve of this mask is manufactured of rubber, and attaches to the flat-beveled plastic valve seat via a stem in the center which slips through a mounting in the valve seat (Figure 1). Exhalation valves of seven MSA Comfo® II Custom probed masks were treated with three levels (25, 50, 75 mg) of three dust types (Table 1), each blended with three quantities of a dilute saline solution (0.25, 0.50, and 0.75 mL). The dust was applied with normal saline solution to simulate the effect of sweat washing the dust particles off the face down to the exhalation valve. (The masks were not tested with saline solution in the absence of dust; it is possible that the saline itself could leave a deposit on the valve, contributing to exhalation valve leakage.) Each mask received the 27 treatment combinations in random order, for a total of 189 exposure tests. Each mask was also tested in the clean condition at the beginning, the midpoint, and the conclusion of the study to determine baseline leakage and to detect any trends in valve performance with time. Including the clean mask trials, 210 tests were conducted.

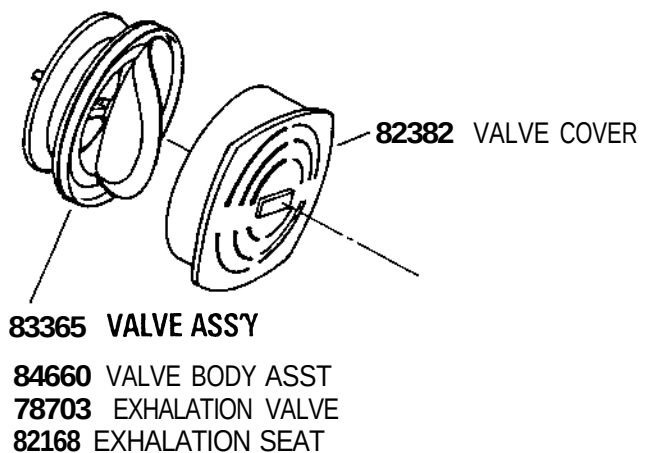


Figure 1. Exhalation valve assembly of the MSA Comfo® respirator. Drawing courtesy of MSA.

After the dust/saline slurry on the exhalation valve was dry, the mask was sealed with Patch Magic (a leak sealer formerly manufactured by Magic American Chemical Corporation) to a ceramic headform. To allow observation of the valve function and to minimize disturbance of the valve, the exhalation valve cover was not used. This has been shown to increase leakage by 0.04 percent or less when exhalation valves were tested by a similar method (Douglas et al., 1976). In preparation for static leakage testing, the HEPA filters were replaced with blocked-inlet filters, the quantitative fit test probe inlet was sealed, and an

Table 1. Particle size distributions of three test dusts.

Size range, μm	Percentage in Size Range		
	Lab dust ^a	ARD-Fine ^b	ARD-Coarse
0-5	91	39 $\pm$ 2	12 $\pm$ 2
5-10	5.5	18 $\pm$ 3	12 $\pm$ 3
10-20	3.5	16 $\pm$ 3	14 $\pm$ 3
20-40		18 $\pm$ 3	23 $\pm$ 3
40-80		9 $\pm$ 3	30 $\pm$ 3
80-200			9 $\pm$ 3

^a Lab dust was prepared in the laboratory from peat moss (52%), fuller's earth (16%), Kaolin clay (16%), and silica sand (16%). The particle size distribution was determined with a Leeds and Northrup Microtrac Analyzer, a laser light-scattering photometer (communication with David Jones, IITRI, Chicago IL, 1991).

^b Arizona Road Dust (ARD) is classified from natural Arizona dust. Particle size distributions were determined via sieving and gravimetric analysis (communication with Mark Nantau, AC Rochester, Flint MI, 1991).

exhalation valve cover modified to accept Tygon tubing was connected (Figure 2). (A hole was cut in the center of the exhalation valve cover so that a fitting could be attached, and the vent holes in the valve cover were sealed; the valve itself was not modified.) A personal sampling pump generated 2.5 cm (1 inch) of suction in the facepiece, and any resulting leakage through the exhalation valve was measured with a bubble meter (inverted burette and soap solution). It should be noted that this is an adaptation of the NIOSH test, in which the valve and valve seat are mounted in a holder independent of the respirator. Since static leakage was not detected when clean masks mounted on the headform were tested, it was assumed that other sources did not contribute to static leakage.

Following static testing, the respirator was prepared for dynamic leakage testing by replacing the blocked-inlet filters with the functional HEPA filters, attaching tubing to the fit test probe inlet, connecting a breathing pump to the back of the headform, and removing the modified exhalation valve cover (Figure 3). Both the exhalation and inhalation cycles were directed through the respirator. A heated flask containing distilled water was located in-line between the respirator and the breathing pump, although temperature and humidity measurements were not made in the facepiece. After the exposure chamber which housed the headform was sealed, an SG-20 Aerosol Generator (VirTis Co., Inc.), a Laskin-type nozzle, powered by 18 psi compressed air was used

to generate the dioctyl phthalate (DOP) polydisperse challenge aerosol, which had a light-scattering mean diameter of 0.72 μm (VirTis Co., Inc., 1977; VirTis Co., Inc., 1991). After allowing 15 minutes for chamber DOP concentrations to equilibrate, a JM-8000 Aerosol Dust and Smoke Photometer (VirTis Co., Inc.), which operates on the principle of forward white light scattering, was used to make leakage measurements at different work rates. Following dynamic leakage measurement, exhalation valve leakage was tested a second time with the static test method. The mask was then removed from the ceramic headform, cleaned, and dried in preparation for the next challenge test.

The breathing pump, which was built by U.S. Divers Corp., had two cylinders measuring 0.801 and 0.804 L, respectively. At rest, the average person breathes 12 times per minute at a tidal volume of 0.5 L, for a minute ventilation of 6 L/min (McArdle et al., 1981). Rest conditions were simulated by operating the smaller chamber of the pump at 8.33 cycles/min for a pump flow rate of 6.67 L/min. A medium work rate of 415 kg-m/min was simulated by operating both chambers at 21.5 cycles/min for a pump flow rate of 34.5 L/min. (Both inhalation and exhalation cycles were directed through the facepiece.) Each dynamic leakage test took 15 minutes, and consisted of five 3-minute periods, during which the breathing pump was (1) off, (2) operated at the resting rate, (3) operated at the medium work rate, (4) operated at the resting rate, and (5) turned off. (This order

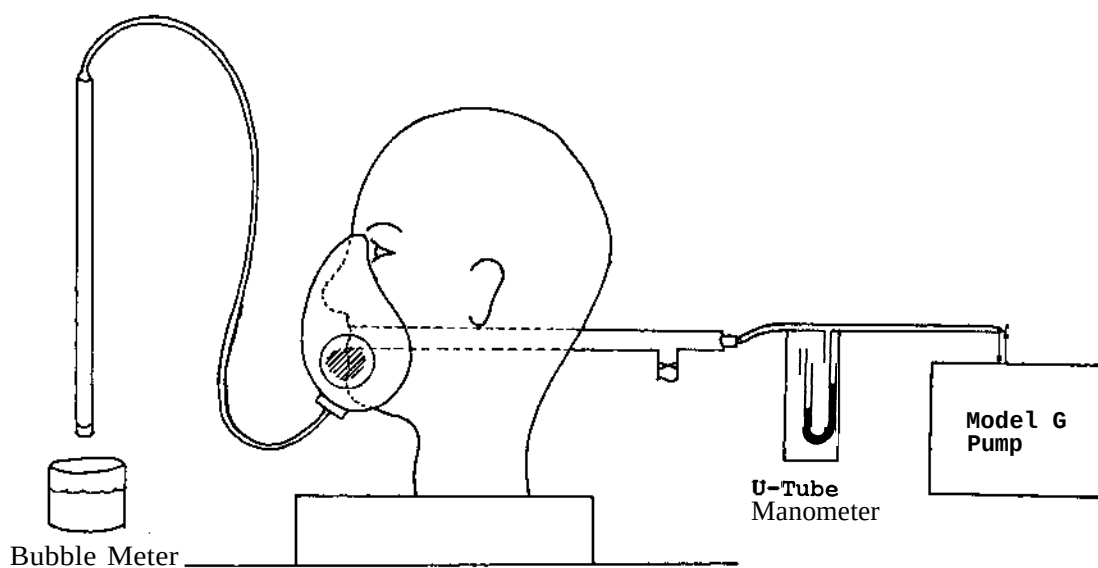


Figure 2. Static testing of the exhalation valve.

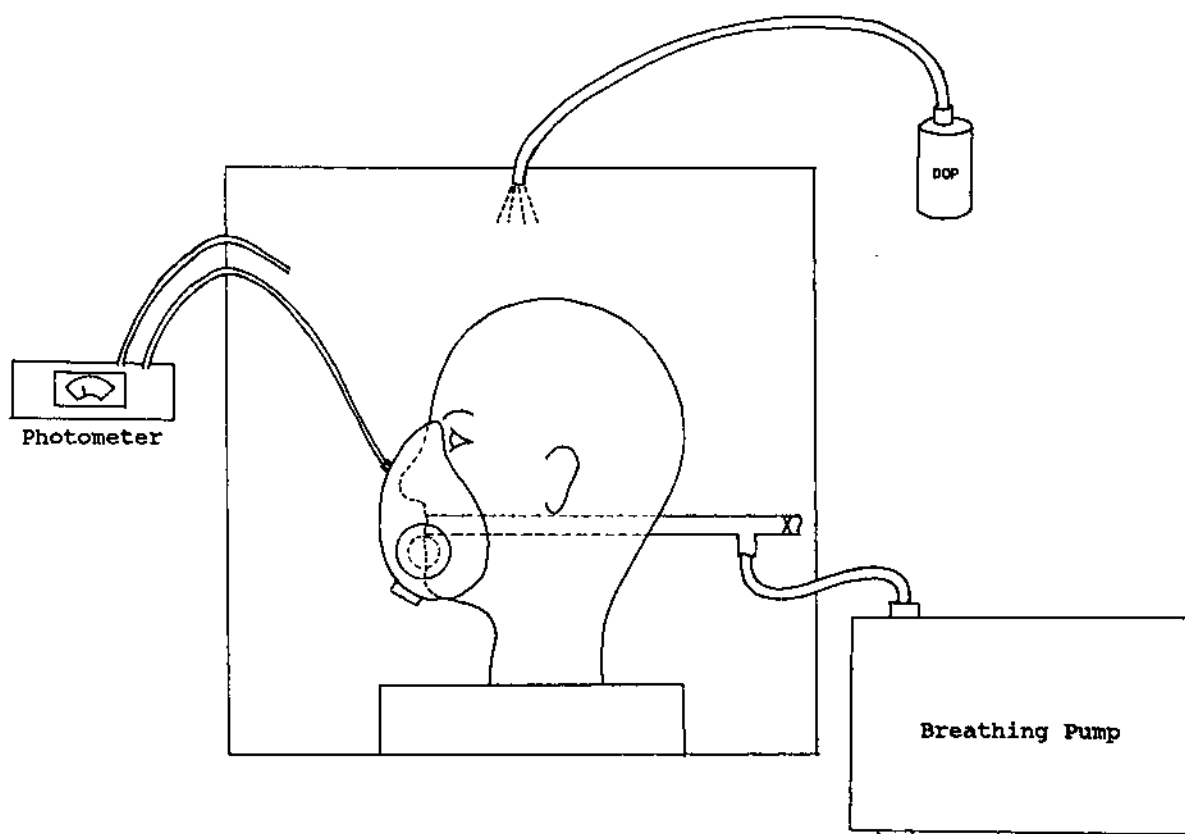


Figure 3. Dynamic testing of the exhalation valve.

was chosen to simulate an actual use cycle in which the breathing rate of the respirator wearer might begin at a low rate, increase as a task was performed, and decrease at completion of the task.) At the resting rate, the breathing pump exerted 0.4 cm (0.15 inch) water gauge of pressure (peak) on exhalation and -0.9 cm (-0.35 inch) water gauge suction (peak) on inhalation. At the medium work rate, these values increased to 1.9 cm (0.75 inch) on exhalation and -3.7 cm (-1.45 inch) water gauge (peak) on inhalation, in the same order of magnitude as the 2.5-cm (1-inch) suction exerted during the static test.

In-facepiece sampling was conducted through the standard probe provided by the manufacturer, which was a brass fitting with an internal diameter of 7 mm, projecting 9 mm from the front of the mask to allow a length of tubing to be connected to the photometer. Inside the respirator, the probe had an external diameter of 19 mm, and was virtually flush with the facepiece, extending 0.5 mm into the facepiece. The probe was located center line, about 25 mm above the exhalation valve. The photometer sampled continuously, resulting in minimum and maximum values (during the exhalation and inhalation cycles of the breathing pump) which were recorded 30 seconds into each minute. Since each work rate was maintained for three minutes, a new variable, "test duration in minutes" (TESTMIN) was created to describe the length of time at each of the work rates. For example, the leakage values at TESTMIN₁, TESTMIN₂, and TESTMIN₃ at the resting rate represent measurements made during the first, second, and third minutes of the resting rate cycle.

The leakage measurements were corrected both for baseline leakage and for variations in the exposure chamber DOP concentration. Respirator components supplied with the masks, including exhalation valves, inhalation valves, and filters, were not replaced throughout the study; therefore, static and dynamic leakage of clean exhalation valves were measured on all seven masks three times—at the beginning, the midpoint, and the conclusion of the study—to determine if there was any conditioning occurring as a result of mask use (21 tests). Analysis of variance (AOV) for repeated measures indicated no significant change in dynamic leakage ($p = 0.1792$); no static leakage was detectable on the clean masks. It was assumed that there was no "breaking in" effect in exhalation valve performance, at least within the

limits of this study, and each leakage measurement was corrected for baseline leakage determined for that mask at that point in time. As an example of how this was done, the three clean condition measurements obtained on Mask 1 during the first minute of the low work rate were averaged. The resulting value, approximately 0.74 percent, was then subtracted from each leakage measurement obtained on Mask 1 during the first minute of low work rate in each of the 27 exposure trials, in effect correcting the leakage value for leakage from sources other than the exhalation valve, including the face seal, filters, and filter—gasket interfaces. A similar correction was used by Douglas et al. (1976), who subtracted system leaks from test results when system leaks could not be sealed.

The JM-2000 Aerosol Dust and Smoke Photometer was designed primarily as an instrument to test HEPA filters in biological safety cabinets. While it is equipped with "upstream" and "downstream" sampling lines, the display is sequential; i.e., leakage must be determined by ratioing the in-facepiece and the chamber DOP concentrations. At the beginning of a 15-minute test, the instrument span was set so that sampling the chamber resulted in a readout of 100 percent. Due to the effect of the headform inhaling DOP-contaminated air through HEPA filters and exhaling filtered air, the chamber DOP concentration at the end of the 15-minute dynamic test typically dropped to 94 percent of its initial concentration. The results of six 15-minute chamber DOP concentration tests were used to correct the data from each measurement trial. For example, the average chamber DOP concentration during the first minute of testing was found to be 99.58 percent of the initial concentration; all leakage measurements recorded during the first minute were thus divided by 0.9958.

Computations were performed with the Statistical Analysis System (SAS) programs on an IBM 3081 computer. AOV for repeated measures was used to compare the effects of dust type, dust quantity, quantity of saline blended with the dust, work rate, and TESTMIN on dynamic leakage through the exhalation valves, and the effects of dust type, dust quantity, and saline quantity on static leakage. Duncan's multiple range test, a feature of the SAS AOV programs, was used to determine which means were significantly different. If AOV indicated a particular factor did not significantly affect the means, the Duncan's test assigned a value of "A" to all means. If it was

determined that a factor did significantly affect the means, means which were significantly different from each other received different letter values. Three means with assigned values of "A," "B," and "C" were thus significantly different from each

other; a mean with a value of "AB" was not significantly different from either of the means with a value of "A" or "B," but was significantly different from the mean with a value of "C."

Results

The arithmetic mean leakage obtained on all seven masks in the three clean condition tests was 0.73 percent, although the majority of values of leakages determined on the masks in the clean condition were lower (63 percent were ≤ 0.5 percent leakage, and 30 percent were ≤ 0.1 leakage). It should be noted that the mean leakages obtained are higher than those observed by other researchers who have observed valve leakage in clean exhalation valves to be ≤ 0.01 percent (Douglas, 1976; Bellin and Hinds, 1990), a value which is consistent with recent work we have conducted using a different experimental setup. The purpose of the experiments reported here was to determine the effect of contamination on exhalation valve function, rather than to evaluate exhalation valve performance per se on clean masks. As it is likely that the leakage determined on the masks in clean condition is greater than one would expect in a typical clean mask, subtracting this leakage from the values obtained in the contaminated valve tests should reduce the effect of the various factors tested. However, as discussed below, the statistical analysis did indicate significant effects of dust type, dust quantity, TESTMIN, and work rate.

Other researchers have reported poor performance of clean respirators under cyclic flow conditions, and have attributed the penetration to deformation of the exhalation valve (Brosseau et al., 1990). Used, concave exhalation valves from one manufacturer became convex, affecting the ability to close during the inhalation cycle. We did not observe this phenomenon; however, the flow rate in those experiments, 76 L/min mean flow and 100 L/min peak flow, was more than twice the highest flow rate we used. It was suggested that exhalation valve performance may at first improve due to conditioning, then degrade because of warping (Brosseau et al., 1990).

No trends in valve performance throughout the experiment were detected. The mean *dynamic* exhalation valve leakage in all the exposure tests was 5.5 percent (Table 2), over one-half of the total allowable leakage for a half-mask, air-purifying

respirator with a suggested assigned protection factor* (APF) of 10 (ANSI, 1980; NIOSH, 1987b; Hyatt, 1976). AOV for repeated measures (Table 3) indicated that significant factors influencing dynamic leakage were dust type, dust quantity, TESTMIN, and work rate. The Duncan's grouping indicated that there was a significant difference between leakage due to lab dust (10.6 percent) as compared to ARD-Fine (3.2 percent) and ARD-Coarse (2.6 percent). The tendency of leakage values to cluster by dust type can be seen in Figure 4, which presents leakage by work rate at each TESTMIN. The effect of the quantity of dust on the leakage rates varied with dust type. Overall, leakage was significantly higher at 75 mg than at 25 and 50 mg. Dust quantity was indicated as a significant source of variation for leakage due to lab dust (again, according to the Duncan's test, leakage was significantly higher at 75 mg than at 25 and 50 mg dust), with a similar trend of increased leakage with increased dust quantity observed with ARD-Fine (Figure 5).

The effect of TESTMIN (the length of time at a particular work rate) was statistically significant, but the slight reductions in leakage (approximately 4 percent total reduction from TESTMIN₁ to TESTMIN₃) had little practical effect on leakage, within the 3-minute period at each work rate. During the tests, it was observed that the leakage rate into the facepiece tended to drop off within the first several breaths at a given work rate, particularly at the medium rate, and then remain fairly constant during the remainder of the 3-minute period. (This indicates that while both the exhalation and inhalation cycles were directed through the respirator, a substantial amount of flushing was taking place within the facepiece.) As seen in Figure 4, there was a tendency for leakage to decrease as the work rate was increased from

*The 1989 proposed revision of ANSI Z88.2 suggested APFs of 10 and 100, respectively, for half-mask and full-face air-purifying respirators (ANSI, 1991). The APF represents the expected workplace level of respiratory protection that would be provided by a properly functioning respirator to properly fitted and trained users.

Table 2. Mean dynamic leakages by each factor.

Factor	Mean Leakages, Percentage	Duncan's Grouping
<i>Dust Type</i>		
Lab	10.625	A
ARD-Fine	3.159	B
ARD-Coarse	2.628	B
<i>Dust Quantity, mg</i>		
25	3.386	B
50	4.457	B
75	8.568	A
<i>Saline Quantity, mL</i>		
0.25	6.444	A
0.50	5.557	AB
0.75	4.111	B
<i>TESTMIN</i>		
1	5.595	A
2	5.465	B
3	5.352	C
<i>Work Rate</i>		
1 (off)	8.077	A
2 (resting)	6.868	B
3 (medium)	3.568	D
4 (resting)	4.269	CD
5 (off)	4.570	C
Mean Leakage	5.5	

Note: Duncan's groupings indicate significantly different means.

Table 3. Summary of analysis of variance of dynamic leakages.

Source	Degrees of Freedom	F Statistic	P
Dust Type	2	41.59	0.0001
Dust Quantity	2	38.58	0.0001
Saline Quantity	2	3.46	0.0651
TESTMIN	2	21.99	0.0001
Work Rate	4	42.30	0.0001

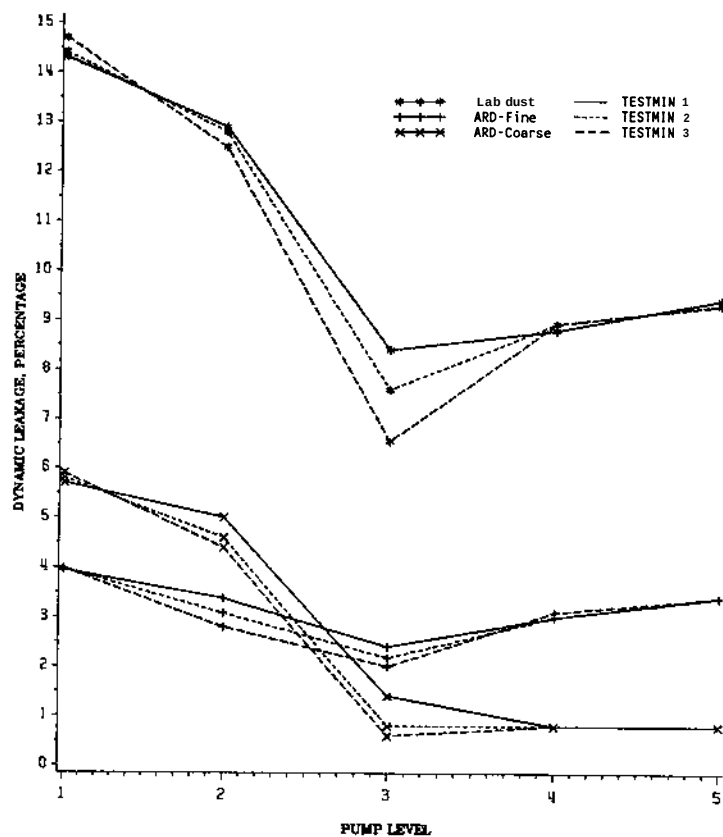


Figure 4. Mean dynamic leakage by work rate and TESTMIN.

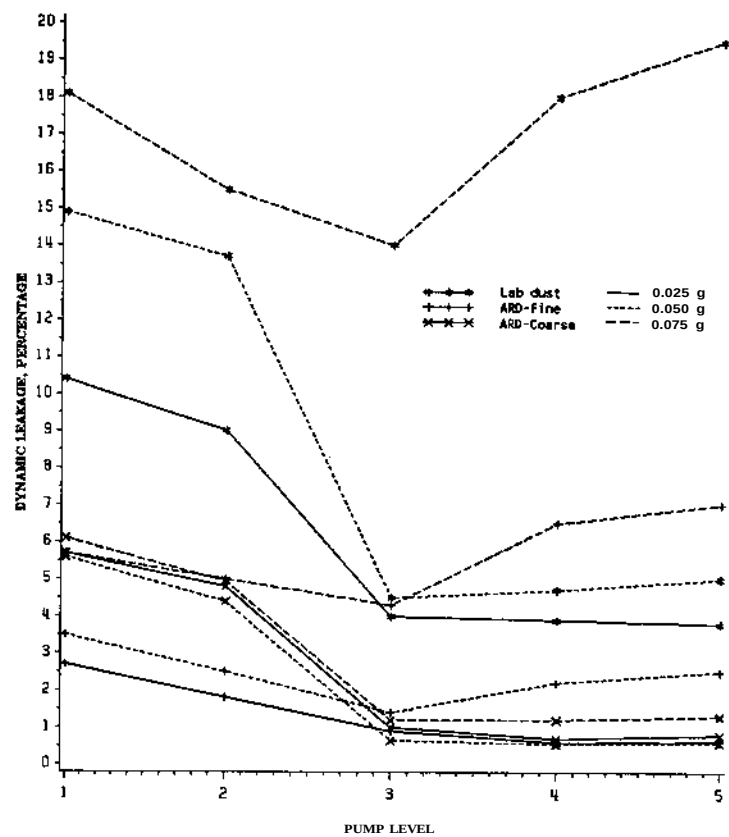


Figure 5. Mean dynamic leakage by work rate and dust quantity.

resting to medium. Two possible explanations for this decrease are valve clearing and valve molding. Removal of dust from the valve at the initiation of the medium breathing rate was seen in 52 of the 63 lab dust tests, 48 of the 63 ARD-Coarse tests, and 46 of the 63 ARD-Fine tests. If there is a level of negative pressure which causes the flexible valve to mold around any dust present and form a good seal, this would occur sooner in each breathing cycle at the medium rate, which had both increased frequency and volume as compared to the resting rate. Leakage tended to increase slightly or remain steady as the work rate was returned to resting or off, indicating interdependence of the valve-molding and valve-clearing mechanisms. The quantity of saline blended with the dust placed on the valve exerted no consistent effect on leakage (overall, 6.4, 5.5, and 4.4 percent with 0.25, 0.50, and 0.75 mL of saline). This result was not surprising since, in order to simulate actual use patterns, the dust was allowed to dry before testing.

Several additional tests were conducted using the resting breathing rate, 0.25 mL saline and smaller quantities of each dust type (0.5 to 20 mg lab dust; 1 to 20 mg ARD-Fine; 1 and 5 mg ARD-Coarse). Measurable leakage occurred with 0.5 mg lab dust (1.5 to 4 percent), 5 mg ARD-Fine (0 to 2.5 percent), and 1 mg ARD-Coarse (1 to 3.5 percent). When the data from these 27 additional tests were combined with the original 189 challenge trials, there were low correlation coefficients for dust quantity versus dynamic leakage ($r = 0.448, 0.423, \text{ and } 0.307$, respectively for lab dust, ARD-Fine, and ARD-Coarse); however, the quantity of dust did appear to affect leakage, as the probability of obtaining unacceptable leakage was higher for the larger dust quantities. The levels of leakage observed are higher than those reported for exhalation valve leakage caused by presence of a wire between the exhalation valve and the valve seat (Bellin and Hinds, 1990); a possible explanation is the limited area affected by a wire in the valve seat as compared to a valve contaminated with the dust-saline mixture.

While it was not possible to measure particle size distribution of the penetrating aerosol in these experiments, particle size distribution does have an effect on leakage through exhalation valves. Particles in the 1.5 to 2.5 μm aerodynamic diameter range have been shown to penetrate the valve at about half the rate of 0.5 μm particles (Bellin and Hinds, 1990). This may be due to the

geometry of an exhalation valve leak, which is probably more like a slit leak than a circular leak, and which may involve changes in airflow direction. For a slit leak (which may more nearly approximate an exhalation valve leak), the percent aerosol inside a facemask was found to be smaller than for a circular leak, for all particle sizes tested (Holton et al., 1987). It has been suggested that smaller particles, which have less inertia, may more easily follow the tortuous airflow paths around a valve and through the valve seat openings (Brosseau et al., 1990).

The standards of comparison for static leakage testing were 15 mL/min established by the U.S. Army (QAD, 1967), and 30 mL/min referenced in 30 CFR Part 11 (1988). Means of static leakage computed across dust type, dust quantity, and saline quantity all exceeded the 15-mL/min static leakage specified by the U.S. Army, and all but one (ARD-Fine) exceeded the 30-mL/min level cited by BOM-NIOSH (Table 4). AOV for repeated measures (Table 5) indicated that dust type was a significant factor in static leakage, with the same order observed as in the dynamic leakage measurements at the first resting rate, i.e., lab dust, ARD-Coarse, followed by ARD-Fine. The Duncan's test indicated significant differences among all means. Although not significant, increased dust quantity did tend to increase static leakage.

Static and dynamic leakage testing attempt to evaluate different parameters, e.g., flow of air into the mask versus penetration by aerosols. Because static leakage testing requires less time, skill, and instrumentation than dynamic testing, and is not subject to the biases introduced by aerosol sampling and measurement, including apparent particle-size selection at the exhalation valve (Bellin and Hinds, 1990), a good correlation between the two test methods would be advantageous to respirator performance testing. A recently proposed method, the controlled negative pressure technique (CNPT) (Crutchfield et al., 1989), is similar to the NIOSH technique in that a small suction is exerted on the facepiece and maintained at a constant level while the airflow required to maintain that level of suction is measured. This test, which could detect leakage from faceseal or exhalation valve, can be conducted on an actual wearer; however, it requires that airflow through the filters be blocked. The NIOSH method is intended to measure exhalation valve function only, and is not intended to reflect the fit factor provided by a respirator for a wearer. Because

Table 4. Mean static leakages by each factor.

Factor	Mean Flow, mL/min	Duncan's Grouping
<i>Dust Type</i>		
Lab	49.02	A
ARD-Fine	26.01	C
ARD-Coarse	40.80	B
<i>Dust Quantity, mg</i>		
25	33.65	A
50	39.32	A
75	42.85	A
<i>Saline Quantity, mL</i>		
0.25	37.62	A
0.50	36.96	A
0.75	41.24	A

Note: Duncan's groupings indicate significantly different means.

Table 5. Summary of analysis of variance of static leakages.

Source	Degrees of Freedom	F Statistic	P
Dust Type	2	30.79	0.0001
Dust Quantity	2	1.85	0.1995
Saline Quantity	2	0.66	0.5326

both the CNPT and the NIOSH test are conducted under static conditions, they may not reflect leakage through the exhalation valve under actual use conditions, in which flow and pressure are cyclic. It is possible that leakage rates measured under static conditions may represent leakage which occurs during a limited segment of the inhalation cycle, in which negative pressures vary.

Consistent with the findings of other researchers (Silverman et al., 1943; Burgess and Anderson, 1967; Douglas et al., 1976), a poor correlation was observed between static and dynamic testing. When dynamic leakage values from TESTMIN2 of the first resting rate were compared with static leakage values, the correlation coefficient R was 0.351 for the original 189 exposure tests, increasing to 0.436 when the 21 clean mask tests were also considered.

Table 6 summarizes the comparison between static and dynamic test results using a flowrate of

>30 mL/min as the failure criterion for static testing. The failure criterion for dynamic leakage was selected as 5 percent, as this level would account for half of the leakage occurring at a protection factor of 10. Using the dynamic test method as the basis for comparison, the Type I error, or probability of incorrect rejection by the static test of a valve which would have passed the dynamic test, was 39/108, or 36.1 percent. The Type II error, or probability of false acceptance by the static test of a valve which would have failed the dynamic test was 20/112, or 17.9 percent. Adapting terms defined in the literature (Hardis et al., 1983), the passing inadequate valve (PIV) percent, or percentage passing the static test which would have failed the dynamic test, was 20/89, or 22.5 percent. The percentage adequate valve rejected (PAVR), or the percentage failing the static test which would have passed the dynamic test, was 39/121, or 32.2 percent. If the only source of leakage into the respirator facepiece were a contaminated valve, e.g., the respirator

Table 6. Comparison of static and dynamic leakage values.

Static	Dynamic Leakage		
	Fail (> 5%)	Pass (< 5%)	Total
Fail (> 30 mL/min)	82	39	121
Pass (≤ 30 mL/min)	20	69	89
Total	112	108	210

$$X^2 = \frac{(b-c-1)^2}{b+c} = \frac{(39-20-1)^2}{39+20} = 5.49, p > 0.025$$

perfectly fit an employee's face, and if the only valve test performed were a static test, then the Type I error and the PAVR would represent the economic burden to the employer of rejecting or retesting adequate exhalation valves. The Type II error and the PIV represent the risk to the respirator wearer of selecting a mask with a poorly functioning valve. There are no established values for acceptable levels of Type II error or PIV; the levels would depend largely upon the risks of the chemical exposure, and should approach zero for maximum employee protection.

A McNemar analysis (Fleiss, 1981) of the data in Table 6 indicated that there were more masks which failed the static test but passed the dynamic test than there were masks which failed the dynamic test but passed the static test ($p < 0.025$). The fact that the static test showed more failures compared to the dynamic test (based on 5 percent leakage) on dirty valves, and no static leakage compared to an average of 0.73 percent on the clean masks, illustrates the lack of correlation between the two test methods. The 1-inch suction in the static test may be able to pull a clean valve against the valve seat, forming an airtight seal, while the cyclical variation in pressure from positive to negative in the dynamic test may allow a small amount of leakage through a valve as it begins to seat on the valve seat. This is supported by the fact that less leakage is seen at the high pump rate, in which greater negative pressure is reached sooner in the breathing cycle, seating the valve earlier.

As stated above, the purpose of these experiments was to determine the effect of contamina-

tion on exhalation valve function, rather than to evaluate exhalation valve performance per se on clean masks. As it is likely that the leakage determined in these experiments on the masks in clean condition is greater than one would expect in a typical clean mask, subtracting the arithmetic mean leakage from the values obtained in the contaminated valve tests should reduce the effect of the various factors tested. Despite this, the statistical analysis did indicate significant effects of dust type, dust quantity, TESTMIN, and work rate.

In recent years it has been recognized that sources of error affecting in-facepiece sampling include incomplete mixing of the test agent in the facepiece, sampling probe depth and location (Myers et al., 1986), particle size selection through face seal leakage (Holton et al., 1987; Hinds and Kraske, 1987), pulmonary deposition of particulates (Bollinger and Schutz, 1987), location of leak (Myers et al., 1986; Holton et al., 1987) and probe geometry (Liu et al., 1984). Given the difficulties of sampling aerosols from within a respirator under cyclic flow, it might be assumed that measurement of static leakage would be a more stringent test of respirator performance. The McNemar analysis performed on the data presented in Table 6 indicated that there was a higher probability of passing the dynamic test and failing the static test than vice versa. (This determination would be affected by the pass/fail criterion for each method.) Further research is warranted to determine whether static or dynamic testing is the more sensitive method of determining exhalation valve leakage; however, the magnitude of the Type II error suggests that static testing should not be relied upon as the sole test method of exhalation valve function.

Summary

It has been shown that there is a trend for increased leakage to occur through exhalation valves in the presence of increasing quantities of dust on the exhalation valve, resulting in unacceptable performance of the respirator. In addition to the quantity of dust, the type of dust involved affects the amount of leakage, as does the work rate of the wearer, with increased work rates resulting in less leakage through contaminated valves. To ensure that respirators are providing workers with the maximum protection possible, strong emphasis should be placed on effective management of the respirator program. Particular attention should be paid to respirator inspection and maintenance, cleanliness of workers' hands and faces, and storage of the respirator in a clean location. Workers must not be allowed to remove respirators in process areas, especially during or

immediately following dusty operations. As dusts of different compositions may produce widely varying leakage responses as a result of internal challenge, various dusts, including asbestos, should be investigated for effect on exhalation valve performance.

This study demonstrated a poor correlation ($r = 0.436$) between static and dynamic methods of exhalation valve testing. This, along with the apparent high rate of Type II errors in static leakage measurement as compared to dynamic measurement, suggests that the use of static leakage measurements alone has limited value and could result in a false sense of security by the respirator wearer. Based on the results of this study, continued use of static leakage measurement by itself is unjustified.

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