

Respirator Performance As a Function of Inhalation Valve Efficacy

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Abstract

Experimental studies were conducted to test the hypothesis that the protection provided by a respirator can be affected by the efficacy of the inhalation valve. Two models of full-facepiece respirators without nose cups were modified by replacing the standard one-way inhalation valves with one-way valves that eliminate backflow during exhalation. These respirators were evaluated using a headform and breathing machine with the inhalation valve functional and with the valve partially defeated to allow backflow during exhalation. Defeating the function of the inhalation valves was found to significantly decrease the provided protection against a vapor challenge.

Introduction

Experimental studies were conducted to test the hypothesis that the performance of a full-facepiece respirator can be affected by the efficacy of the inhalation valve. In conjunction with studies to measure the bias associated with various in-facepiece sampling methods (Myers and Hornung, 1989), an analytical model was developed to explain certain unexpected experimental observations (Campbell and Myers, 1989). This model has led the authors to hypothesize that the protection provided by a full-facepiece respirator can, under certain conditions, be compromised by an inhalation valve that allows backflow during the exhalation cycle. Specifically, it was envisioned that during exhalation contaminated air flows past the inhalation valve, becomes temporarily trapped downstream of the inhalation valve, and then reenters the facepiece during the next inhalation. This hypothesized mechanism is shown schematically in Figure 1.

The temporary trapping may result from two mechanisms: "volume trapping" or "sorbent

trapping." Volume trapping is the simple trapping of contaminant in the volume between the inlet valve and the sorbent. Sorbent trapping involves the temporary trapping on the surface of the sorbent bed. Volume trapping could conceivably occur with all contaminants (both aerosols and gases), while sorbent trapping could occur only for gases, and possibly only certain gases. We envision two possible cases: (1) volume trapping alone or (2) volume trapping in combination with sorbent trapping.

Experimental Procedure

The performance of two full-facepiece respirators without nose-cups was measured with a functioning inhalation valve and with a defeated inhalation valve in order to determine the effect of the inhalation valve efficacy on overall respirator performance. Each respirator being tested was mounted on a headform connected to a mechanical breathing machine, as shown in Figure 2. The exhaust from the breathing machine passes back through the facepiece and out the respirator's

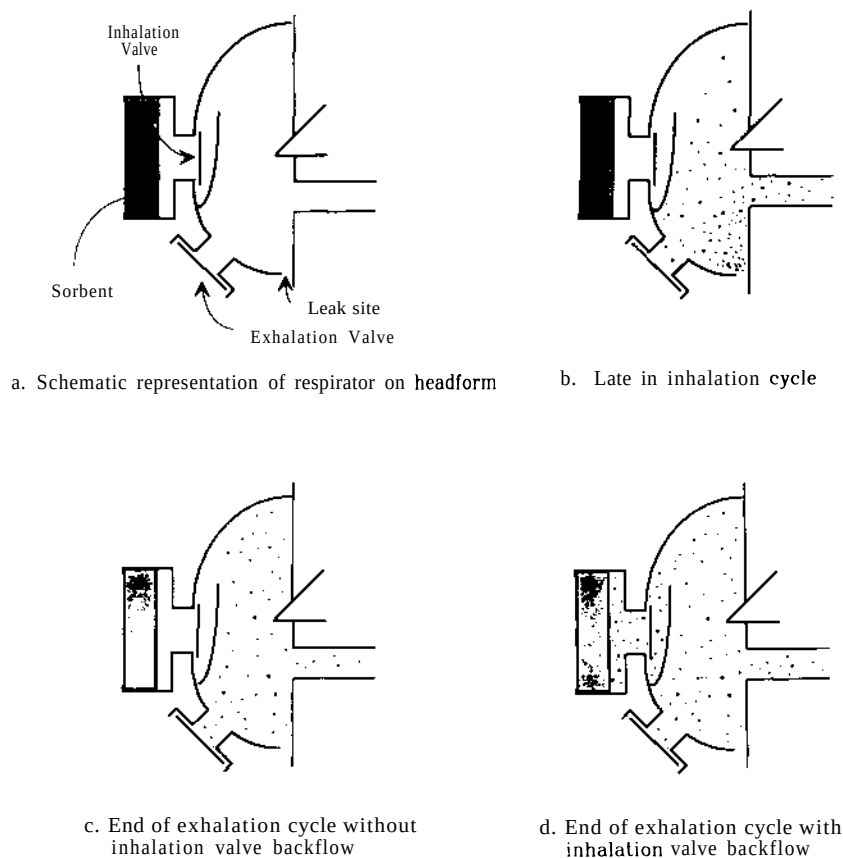


Figure 1. A schematic representation of the hypothesized mechanism by which inhalation valve backflow during exhalation can affect respirator performance. In 1(a), the basic respirator components are shown. In 1(b), relatively clean air is shown in the inlet path late in the inhalation cycle. In 1(c), clean air is envisioned in the inlet path at the end of exhalation when there is no inhalation valve backflow. In 1(d), contaminated air is envisioned in the inlet at the end of exhalation when there is inhalation valve backflow. This contaminated air, rather than clean air, is drawn into the respirator during the next inhalation.

exhalation valve. The breathing machine had a 1.58 liter tidal volume and was operated at a frequency of approximately 20 cycles/minute for a respiratory minute-volume of 30.2 liters per minute. Leaks were introduced through two 18-gauge needles through the facepiece seal, which is otherwise sealed to the headform. One needle was located through the facepiece near the right eye, the other at the right cheek. Acetone vapor is used as the challenge agent and is drawn from the reservoir through the two needles into the facepiece by the negative facepiece pressure during the inhalation cycle. A one-way valve prevents backflow through the needles due to the positive facepiece pressure during the exhalation cycle.

Three acetone concentrations were determined experimentally in this study:

- 1) The "pulmonary" concentration is measured between the headform and the breathing machine by sampling at a rate of 5 L/min. Of that 5 L/min, approximately 0.5 L/min is consumed by the flame ionization detector while the remainder is returned to the system through a port in the facepiece. This concentration corresponds to the concentration inspired by a respirator wearer and is, therefore, considered a good measure of overall respirator performance.

- 2) The "exhalation valve" or "exhaust" concentration is that exhausted through the exhalation valve. This concentration is monitored in our study because the analytical model, upon which the study hypothesis is based, predicts it will be equal to the "calculated" concentration defined below. In the

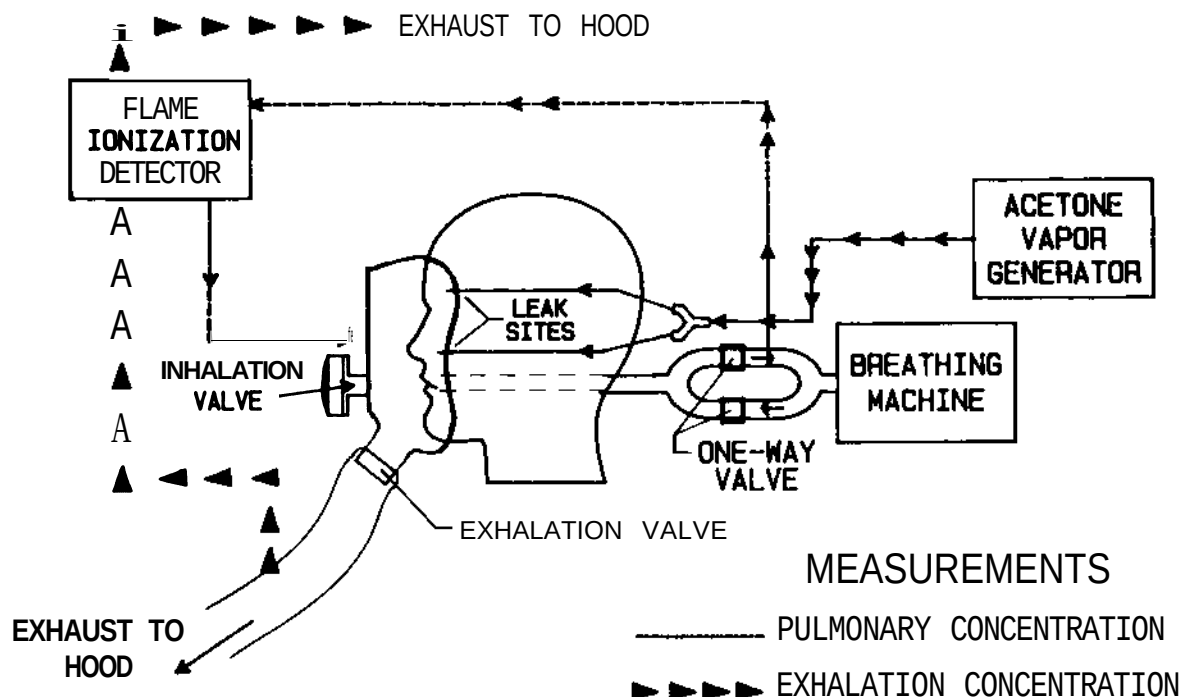


Figure 2. Experimental test system used to simulate the pulmonary-respirator system. A flame ionization detector was used to determine the "pulmonary" concentration (sampled from between the headform and the breathing machine) and the exhalation concentration (sampled from a trunk attached to the exhalation valve as shown).

experimental studies of Myers the exhalation valve concentration was significantly higher than the calculated concentration. It was suggested (Campbell and Myers, 1989) that this elevated exhalation valve concentration results from backflow through the inhalation valve, and that it would be reduced to the calculated value if the backflow were eliminated.

3) The "calculated" concentration is the inspired concentration calculated from

$$C_e = C_L Q_L / (Q_L + Q_i),$$

where C_L is the measured acetone concentration in the reservoir, Q_L is the measured flow rate through the two leak sites, and Q_i is the volumetric flow rate of clean air through the respirator inlet.

Neither of the two respirators used in this study were standard commercially available respirators; both were modified specifically for this study. Respirator A, a full-facepiece respirator without a nose cup, was modified by replacing the standard inhalation valves with valves having

superior sealing properties—valves originally * designed for use as exhalation valves. This modification was made to eliminate any backflow that may have been present with the standard inhalation valve.

Respirator B was identical to respirator A with two exceptions. First, the volume between the inlet valve and the sorbent bed was increased from the 30 cm³ of respirator A to 117 cm³ for respirator B. This modification was made in an effort to determine which of the hypothesized trapping mechanisms may be present. Secondly, respirator B used an organic vapor cartridge from a different manufacturer, which had a slightly higher inhalation resistance than the cartridge used on respirator A.

The performance of each of these respirators was then measured with the inhalation valves functional and with the inhalation valves defeated. The valves were defeated by inserting (with the cartridge temporarily removed) a wire to partially block the valve open and allow backflow during exhalation.

Results

The experimental results are presented in Table 1. Several observations can be made upon inspection of that table. First, within experimental error the measured acetone concentration exhausted out through the exhalation valve equals that calculated from the conservation-of-mass model when the inhalation valve is functional. For respirator A, the average measured exhalation valve concentration was 22.8 ppm, while the

average of the calculated exhalation valve concentration was 23.9 ppm. For respirator B the corresponding values are 28.7 and 29.8. In Table 1 the row labeled “ $\langle C_m \rangle / \langle C_e \rangle$ ” is the ratio of the averages of the measured concentration, C_m , to the calculated concentration, C_e . That ratio for the exhaust valve concentration with a functioning inhalation valve is 0.95 and 0.96 for respirators A and B, respectively. In both cases the difference between the measured and calculated is 5% or less and is considered to be within the range of experimental error.

Table 1. Measured acetone concentrations (C_m) in the exhalation valve discharge and in the "pulmonary" system are given for the case when the inhalation valve is fully functional and the case when the inhalation valve is defeated. The corresponding concentrations calculated (C_e) from a simple conservation of mass model are shown parenthetically. The row labeled $\langle C_m \rangle / \langle C_e \rangle$ gives the ratio of the average measured concentration to the average calculated concentration. The symbol " $\langle \rangle$ " indicates an average. The row labeled $\langle C_m \rangle_d / \langle C_m \rangle_f$ gives the ratio of the average measured concentration with inhalation valve defeated to the average measured concentration with the inhalation valve functional.

Respirator type	Exhaust (ppm)		Pulmonary (ppm)	
	Functional	Defeated	Functional	Defeated
	inlet valve C_m (C_e)	inlet valve C_m (C_e)	inlet valve C_m (C_e)	inlet valve C_m (C_e)
A				
trial 1	23.9 (23.9)	29.2 (22.0)	16.6 (24.1)	26.9 (22.0)
trial 2	23.6 (23.9)	27.3 (21.8)	16.0 (24.0)	26.3 (21.8)
trial 3	22.5 (24.4)	27.5 (22.6)	15.8 (24.2)	24.3 (22.6)
trial 4	22.4 (23.7)	28.5 (22.1)	15.6 (24.1)	25.3 (20.7)
trial 5	22.6 (24.3)	26.8 (21.6)	15.7 (23.9)	23.2 (21.5)
trial 6	22.0 (23.8)	26.3 (20.6)	14.7 (23.7)	24.2 (20.9)
trial 7	22.6 (23.5)	26.0 (21.1)	15.0 (23.6)	24.0 (21.4)
average	22.8 (23.9)	27.4 (21.7)	15.6 (23.9)	24.9 (21.6)
$\langle C_m \rangle / \langle C_e \rangle$	0.95	1.26	0.65	1.15
$\langle C_m \rangle_d / \langle C_m \rangle_f$		1.2		1.59
B				
trial 1	29.6 (29.8)	35.0 (29.2)	19.8 (30.6)	36.9 (29.2)
trial 2	28.5 (29.0)	33.6 (28.2)	18.6 (29.0)	34.3 (28.2)
trial 3	28.6 (30.4)	34.1 (29.4)	19.3 (30.2)	34.1 (29.5)
trial 4	26.2 (30.3)	34.8 (28.7)	17.4 (30.2)	34.0 (28.6)
trial 5	31.6 (29.9)	36.1 (28.7)	20.0 (30.0)	38.2 (28.4)
trial 6	28.1 (29.8)	29.5 (27.0)	16.5 (29.9)	29.4 (27.3)
trial 7	28.6 (29.6)	32.8 (23.6)	18.5 (29.6)	31.9 (28.3)
average	28.7 (29.8)	33.7 (27.8)	18.6 (29.9)	34.1 (28.5)
$\langle C_m \rangle / \langle C_e \rangle$	0.96	1.21	0.62	1.20
$\langle C_m \rangle_d / \langle C_m \rangle_f$		1.17		1.84

Secondly, we observe that defeating the inhalation valve significantly increases the exhalation valve concentration. For respirator A the average exhalation valve concentration increases from 22.8 to 27.4, an increase of approximately 20%. Similarly for respirator B, defeating the inhalation valve increases the exhalation concentration from an average of 28.7 ppm to 33.7 ppm, an increase of 17%. The ratio between average measured concentration with the inhalation valve defeated, $\langle C_m \rangle_d$, and the average measured concentration with the inhalation valve functional, $\langle C_m \rangle_f$, is shown in Table 1 in the row labeled " $\langle C_m \rangle_d / \langle C_m \rangle_f$ ". When the measured exhalation concentrations are compared to the calculated concentrations, we see that for respirator A the measured concentration of 27.4 ppm is 26% higher than the calculated concentration of 21.7 ppm. Similarly, for respirator B the increase is 21%. These increases are consistent with the experimental observations by Myers and Hornung (1989) that triggered this line of inquiry, as well as consistent with the hypothesis that backflow through the inhalation valve can affect respirator performance.

Third, we observe that the pulmonary concentration is dramatically increased when the inhalation valve is defeated. The average pulmonary concentration increased from 15.6 ppm to 24.9 ppm when the inhalation valve of respirator A was defeated—an increase of approximately 60%. For respirator B the concentration increased from 18.6 to 34.1—an increase of approximately 80%. These observations are particularly significant since the measured pulmonary concentration in this experimental system represents the concentration inspired by the respirator user.

We also note that the measured pulmonary concentration is significantly different from both the measured exhalation concentration and the calculated concentration. This is consistent with the flushing model we previously described (Campbell and Myers, 1989).

Finally, we observe that the behavior of the two respirators is not dramatically different. Recall that the inlet volume, the volume between the sorbent and the inhalation valve, was artificially increased in respirator B from 30 to 117 cm³. This was done to investigate the two different mechanisms that had been hypothesized to account for the effect of inhalation valve performance on overall respirator performance. The first

mechanism involves contaminated air that is temporarily trapped in the volume between the inhalation valve and the sorbent during the exhalation cycle and then reenters the respirator on the next inhalation cycle. The second mechanism involves contaminant that is temporarily trapped on the surface of the sorbent. If only the first mechanism were present, and if (as seems to be the case here) the inhalation valve backflow volume is greater than the inlet volumes, one would expect that increasing the inlet volume by a factor of four would increase the effect of defeating the inhalation valve by the same factor. Since no such increase was observed, these results suggest that the temporary trapping of contaminant on the sorbent is also involved and is to some degree responsible for the observed effects.

The generally overall higher concentration of B with respect to A is simply the result of the higher inhalation resistance of the organic vapor cartridges used in B resulting in a higher negative facepiece pressure, which increases the amount of acetone drawn into the facepiece during the inhalation cycle.

The above discussion slightly underestimates the effect of inhalation valve backflow because of a subtle experimental effect not taken into consideration: There are two competing effects associated with blocking open the inhalation valves. The first is the intended effect of induced backflow through the inhalation valve during exhalation. The second is a slight unintentional reduction of inhalation resistance of the valves, which reduces the negative facepiece pressure during inhalation. This in turn slightly reduces the amount of acetone drawn into the facepiece, which artificially enhances the apparent performance of the respirators when the inhalation valves are defeated (propped open). This second effect can be eliminated by normalizing the data with respect to the amount of acetone drawn into the facepiece. This is equivalent to normalizing the data with respect to the "calculated" concentration (indicated parenthetically as C_c in Table 1). The average computed concentration with functional inhalation valves was used as the reference concentration, C_{ref} (23.9 ppm for respirator A and 29.8 ppm for respirator B). The normalized concentrations of Table 2 were, therefore, computed from the measured concentrations, C_m , of Table 1 multiplied by the reference concentration, C_{ref} , divided by the calculated concentration, C_c . Table 2, therefore, presents the experimental data with the effect of

Table 2. The results of Table 1 are normalized to eliminate the effect of decreased faceseal leakage caused by the slight decrease in inhalation flow resistance when the inhalation valves are propped open. The normalized concentration is defined as $C_m(C_c/C_{ref})$ where C_m and C_c are as defined and tabulated in Table 1, and C_{ref} is the reference concentration selected as the average calculated concentration, C_c , of Table 1 (with functional inhalation valve). The ratio $\langle C_m \rangle_d / \langle C_m \rangle_f$ is as defined on Table 1.

Respirator type	Exhaust (ppm)		Pulmonary (ppm)	
	Functional inlet valve	Defeated inlet valve	Functional inlet valve	Defeated inlet valve
A				
[C _{ref} = 23.9]				
trial 1	23.9	31.7	16.5	29.2
trial 2	23.6	29.9	15.9	28.8
trial 3	22.0	29.1	15.6	25.7
trial 4	22.6	30.8	15.5	29.2
trial 5	22.2	29.7	15.7	25.8
trial 6	22.1	30.5	14.8	27.7
trial 7	23.0	29.5	15.2	26.8
average	22.8	30.2	15.6	27.6
$\langle C_m \rangle_d / \langle C_m \rangle_f$	1.32		1.77	
B				
[C _{ref} = 29.8]				
trial 1	29.6	35.7	19.3	37.7
trial 2	29.3	35.5	19.1	36.2
trial 3	28.0	34.6	19.0	34.4
trial 4	25.8	36.1	17.2	35.4
trial 5	31.5	37.5	19.9	40.1
trial 6	28.1	32.6	16.4	32.1
trial 7	28.8	41.4	18.6	33.6
average	28.7	36.1	18.5	35.7
$\langle C_m \rangle_d / \langle C_m \rangle_f$	1.26		1.93	

changes in inhalation resistance eliminated. The ratio of the average measured concentration with the inhalation valves defeated, $\langle C_m \rangle_d$, and with the valves functional, $\langle C_m \rangle_f$, is shown in Table 2 for each respirator. We see that the pulmonary concentration is increased by approximately 80% for respirator A and approximately 90% for respirator B.

Conclusions and Recommendations

These experimental observations are consistent with the hypothesis that the protection provided to respirator wearers can be affected by the performance of the inhalation valve. The experimental results suggest that backflow through the inhalation valve during exhalation can result in the

temporary trapping of contaminant, both in the volume of the inlet passage and on the inner surface of the sorbent bed. Volume trapping would apply to all contaminants while sorbent trapping would, of course, apply only to gases and vapors. These results further suggest that respirator manufacturers, as they continue to strive to increase respirator performance, should look toward

the inhalation valve as a possible way to increase the protection provided by their respirators. Toward that end, there is a need to determine how the effect of inhalation valve **backflow** varies from one challenge substance to another and to develop a reliable method of quantifying inhalation valve backflow.

References

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