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Manikin-Based Performance Evaluation of Elastomeric Respirators against Combustion Particles

Xinjian He[1], **Michael Yermakov**[1], **Tiina Reponen**[1], **Roy T. McKay**[1], **Kelley James**[2], **Sergey A. Grinshpun**[1]

[1]Center for Health-Related Aerosol Studies, Department of Environmental Health, University of Cincinnati, Cincinnati, OH

[2]Department of Mechanical Engineering, University of Cincinnati, Cincinnati, OH

Abstract

Objective: To investigate the effects of faceseal leakage, breathing flow and combustion material on the overall (none size-selective) penetration of combustion particles into P-100 half and full facepiece elastomeric respirators used by firefighters.

Methods: Respirators were tested on a breathing manikin exposed to aerosols produced by combustion of three materials (wood, paper, and plastic) in a room-size exposure chamber. Testing was performed using a single constant flow (inspiratory flow rate = 30 L/min) and three cyclic flows (mean inspiratory flow rates = 30, 85, and 135 L/min). Four sealing conditions ("unsealed", "nose-only sealed", "nose & chin sealed", and "fully sealed") were examined to evaluate the respirator faceseal leakage. The total aerosol concentration was measured inside (C_{in}) and outside (C_{out}) of the respirator using a condensation particle counter. The total penetration through the respirator was determined as a ratio of the two ($P = C_{in} / C_{out}$).

Results: Faceseal leakage, breathing flow type and rate, and combustion material were all significant factors affecting the performance of the half mask and full facepiece respirators. The efficiency of P-100 respirator filters met the NIOSH certification criteria (penetration ≤0.03%); it was not significantly influenced by the challenge aerosol and flow type, which supports the current NIOSH testing procedure utilizing a single challenge aerosol and a constant air flow. However, contrary to the NIOSH total inward leakage (TIL) test protocol assuming that the result is independent on the type of the tested aerosol, this study revealed that the challenge aerosol significantly affects the particle penetration through unsealed and partially sealed half mask respirators. Increasing leak size increased the total particle penetration. The findings of this study point to some limitations of the existing TIL test in predicting protection levels offered by half mask elastomeric respirators.

Keywords

elastomeric respirator; combustion aerosol; manikin; total penetration

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Corresponding author: Sergey A. Grinshpun: sergey.grinshpun@uc.edu.

INTRODUCTION

While on duty, firefighters are exposed to a wide range of chemicals and particulate matter.(1) Smoke from a fire contains fine (< 1 μm) and ultrafine (< 0.1 μm) particle size fractions. In a large-scale fire test laboratory study, ultrafine particles were found to account for more than 70% of the total number concentration of particles during fire knockdown and overhaul.(2) Fine particle exposures at various workplace environments have been associated with impairment of cardiovascular function and other adverse health outcomes. (3–5)

There are approximately 1.1 million firefighters in the United States (including 300,000 career firefighters). Their leading cause of death is heart disease.(6) Sudden cardiac death is responsible for 50% and 39% of the on-duty deaths for volunteers and professional firefighters, respectively.(7) Firefighters have greater mortality rates associated with cardiovascular disease and elevated cancer rates than the general population.(8, 9)

Respirators used for structural firefighting should meet the certification requirements of the National Institute for Occupational Safety and Health (NIOSH) and the National Fire Protection Association.(10, 11) Ironically, there is very limited information on the efficiency of the full facepiece used by firefighters during actual firefighting. Furthermore, during fire overhaul (entering the structure after the fire has been extinguished), firefighters commonly use negative pressure elastomeric half mask or Filtering Facepiece Respirators (FFR) or no respirators at all.(12, 13) According to the Occupational Safety and Health Administration (OSHA), the assigned protection factors (APF) given for negative pressure air-purifying full and half mask respirators are 50 and 10,(14) which corresponds the equivalent penetration values of 2% and 10%, respectively (P = 100/APF, %).

Respiratory protection offered by negative pressure respirators significantly (and often primarily) depends on the faceseal fit.(15, 16) Very little data are available on faceseal aerosol penetration under the cyclic flow regime and even less is known about the filter versus faceseal penetration under actual breathing conditions. The early investigation carried out by Hinds and Kraske (17) addressed the performance of half mask and single-use respirators by measuring particle penetration through the filter and the artificially induced cylindrical leaks; the tests were conducted under a constant flow regime at rates between 2 to 150 L/min. Chen and Willeke,(18) who deployed a breathing manikin with artificially created slit-like or circular leaks to assess the faceseal versus filter penetration for 0.5 – 5 μm particles, also tested under the constant flow regime. However, artificial fixed leaks and constant flows are not representative of real world conditions. Workplace protection factor (WPF) studies are representative of real world conditions with human subjects wearing respirators (19–23) and thus, the WPF results include both filter and faceseal penetration. However, the contribution of faceseal leakage to total penetration cannot be calculated from WPF.

The above limitations were overcome in recent studies (15, 16, 19, 24, 25) either by inclusion of human subjects without induced fixed leaks or through partial sealing of respirators on a manikin tested under cyclic flow. Grinshpun *et al.*(16) found that the primary particle penetration pathway was faceseal leakage for both a N95 FFR and a surgical mask. Cho *et al.* (15) reported that despite having a well-fitted N95 FFR, the majority of particles penetrated through the faceseal leaks and the penetration decreased with an increase in respiration flow and in particle size.

Finally, most of the published data on the performance of respirators were collected using an ambient aerosol or nebulizer-generated NaCl particles. Some investigators utilized polystyrene latex (PSL) spheres as challenge aerosol in their tests.(26, 27) Others used fungal spores, bacteria or viruses.(20, 27–29) Eninger *et al.* (29) compared the effects of NaCl and three virus aerosols (all having significant ultrafine components) on the performance of fully sealed N99 and N95 FFRs. The authors concluded that filter penetration of the tested biological aerosols did not exceed that of NaCl aerosol, which suggests that NaCl may generally be appropriate for modeling filter penetration of similarly sized virions. However, particles used in the above-quoted studies are not representative of the exposures experienced by firefighters. The differences are concerned with the particle shape, density, electric charge, and possibly other properties. To our knowledge, the effects of combustion material on respirator performance have not been previously studied.

The present investigation was designed to examine the effects of faceseal leakage, breathing flow type and rate, and combustion material on the overall (non-size selective) aerosol particle penetration through elastomeric half and full facepiece respirators equipped with P-100 filters.

MATERIALS AND METHODS

Experimental Design

Two elastomeric respirators (one half mask and the other a full facepiece) were tested on a breathing manikin exposed to aerosols produced by combustion of three different materials. Testing was performed using two different flow patterns (constant and cyclic breathing regimes). Cyclic flow testing was conducted at three flows selected to represent breathing at different workload levels. Four facepiece sealing conditions were established to evaluate faceseal leakage. Total aerosol concentration was measured inside (C_{in}) and outside (C_{out}) of the respirator. Particle penetration (P) through the respirator was determined as C_{in} / C_{out}.

The experimental set-up for investigating particle penetration through the respirator is schematically shown in Figure 1. Inside the exposure chamber (142×95×102 inches, L×W×H), the tested respirator was donned on a manikin headform made of hard plastic (Allen Display^{SM}, Model: Full round molded male manikin display head). A copper pipe (1 inch diameter) was installed into the headform to simulate airflow through the upper respiratory tract. One end of the pipe was sealed between the upper and lower lips of the manikin. For cyclic flows, the other end was connected to an electromechanical Breathing Recording and Simulation System (BRSS) (Koken Ltd., Tokyo, Japan) with a HEPA filter placed in between to keep particles from re-entering into the respirator cavity with the exhalation air flow. The constant flow was created by a vacuum pump (Model: G272X, Doerr Electric Corp., Cedarburg, WI). The aerosol concentrations inside and outside of the respirator were measured with a condensation particle counter (TSI CPC, Model: 3007, TSI Inc., Minneapolis, MN) which detects particles in a size range from 0.01 to >1.0 µm.

Respirators and Test Conditions

Two types of respirators were tested in this study: (1) Half mask elastomeric respirator (size: medium) equipped with two P-100 filters and (2) Full facepiece elastomeric respirator (size: medium) equipped with the same type of P-100 filters.

Several studies have reported common facepiece leak locations as the nose, chin and cheek.(30–32) In the present study, four sealing conditions (“unsealed”, “nose-only sealed”, “nose & chin sealed” and “fully sealed”) were utilized when testing the half mask respirator. For the full facepiece respirator, only two sealing conditions (“unsealed” and “fully sealed”) were used because our pilot study revealed that these two conditions produced similar penetration levels, which made unnecessary to evaluate partially sealed conditions. Silicone sealant was applied in between the manikin’s face and the edge of the respirator to form seals. Sealing configurations for the half mask with “nose-only” and “nose & chin” sealing conditions are shown in Figure 2. Respirator straps were tightened and placed around the manikin’s head and neck as conventionally used. For each sealing condition, once the respirator was positioned, it was not removed until another sealing condition was evaluated.

Wood (BBQ long match, 0.23 ± 0.03 g), paper (Multifold brown paper towel, 0.25 ± 0.04 g) and plastic (Ziploc™ plastic bag, 0.24 ± 0.04 g) were selected for this study. Wood, paper and plastic are the most common materials encountered by firefighters during fire activities. All three materials were ignited by a long reach lighter and burnt separately inside the testing chamber. The aerosol measurements were initated15 minutes after burning to allow the combustion aerosol to reach a homogenous concentration. To assess the effect of breathing flow on the particle penetration through respirators, we selected three mean inspiratory flows (MIF) of 30, 85, and 135 L/min, with breathing rates of 15, 25, and 25 breaths/min (achieved by adjusting the tidal volume), respectively. These were established to simulate breathing at moderate, high, and strenuous workloads, respectively. The selection of the breathing rates was based on average respiratory rates reported in a healthy adult.(33, 34) In addition, one constant flow (30 L/min) was selected to investigate the effects of the flow type (constant vs. cyclic).

Three replicates were conducted for each condition, resulting in 144 and 72 measurements for the half and full facepiece respirators, respectively. The manikin breathing flow with three replicates was completely randomized throughout the entire study. A summary of experimental conditions is listed in Table 1.

Data Analysis

Collected data from the TSI CPC were entered into a spreadsheet, and descriptive and inferential statistical analyses were performed using SAS version 9.2 (SAS Institute Inc., Cary, NC). The total aerosol penetration was the sum of filter and faceseal penetration ($P = P_F + P_L$), where P_F is the penetration solely through the filter and P_L represents faceseal penetration. For each combination of experimental conditions, the average value of the overall penetration and the standard deviation were calculated from the three replicates. Analysis of Variance (ANOVA) with Tukey’s range test and paired *t*-test were performed to study effects of sealing condition, burning material, manikin breathing rate and respirator type on aerosol penetration value. *P*-values of < 0.05 were considered significant.

RESULTS AND DISCUSSION

Particle Size Distribution of Combustion Aerosols

Prior to the experiments involving respirators, challenge aerosols – produced by combustion of wood, paper and plastic, respectively – were characterized with respect to their particle size distributions determined with a Nanoparticle Spectrometer (Model: Nano-ID NPS500, Particle Measuring System, Inc., Boulder, CO). This instrument is capable of measuring particle diameter in a range of 5 to 500 nm. Particle size distribution curves obtained 30 minutes after burning are presented in Figure 3. The peak particle size for wood combustion aerosol was around 45 nm, and 95% of the particles fell within the size range of 20–200 nm. The peak size for paper and plastic combustion aerosols were 56 nm and 89 nm, respectively, with 95% of the particles falling in size ranges of 20–200 nm and 20–300 nm, respectively. In general, wood combustion produced smaller particles; all three peak concentrations were observed at particle sizes below 100 nm. More than 70% of particles generated by combustion of wood and paper and slightly more than 50% of particles generated by plastic combustion were ultrafine, which is consistent with the earlier findings. (2)

Half Mask Elastomeric Respirator with P-100 Filters

1. Respirator Donned on the Manikin (Unsealed)

a. Constant flow.: As shown in Table 2, for the constant flow 30 L/min, the overall particle penetration was very high: average values were 43.97 ± 2.44 % (wood aerosol), 48.37 ± 0.15 % (paper aerosol), and 50.67 ± 0.61 % (plastic aerosol). ANOVA revealed a statistically significant (p-value < 0.05) effect of combustion material, but from the practical standpoint it does not play an important role since all measured penetration values fell between 40% and 52%. The important finding is that the obtained penetration level is over three orders of magnitude higher than the one expected based solely on the filter efficiency. Indeed, the respirator was equipped with a P100 filter that has a collection efficiency 99.97% for the most penetrating particle size at a constant flow of 85 L/min, which corresponds to an overall penetration of ≤ 0.03% at 85 L/min and even lower at 30 L/min (no data are available for 135 L/min). This means that most of the penetrated particles entered through the faceseal leakage; only one out of thousands of the penetrated particles entered through the filter media. When testing with an unsealed respirator, a sizeable gap (~ 1 mm) located around the nose of the manikin was observed, indicating a poor fit for the tested respirator donned on the manikin, which could result in unexpectedly high penetration values. This was likely caused by the fact that the manikin was made of hard plastic. Softer human skin would likely form a better seal, resulting in lower penetration values for the elastomeric half mask respirator.

The total particle penetration results from two components: the filter penetration (P_F) at the corresponding flow through the filter (Q_F) and the leakage penetration (P_L) at the corresponding air flow (Q_L). It can be expressed as:

$$P = \frac{C_{in}}{C_{out}} = \frac{N_{in}}{N_{out}} = \frac{N_F + N_L}{N_{out}} = \frac{N_F}{N_{out}} + \frac{N_L}{N_{out}} = \frac{P_F N_{out} \frac{Q_F}{Q}}{N_{out}} + \frac{P_L N_{out} \frac{Q_L}{Q}}{N_{out}} \quad (1)$$

$$= P_F \frac{Q_F}{Q} + P_L \frac{Q_L}{Q} = P_F \frac{Q_F}{Q} + P_L \left(1 - \frac{Q_F}{Q}\right)$$

where: N_{in} – Particle numbers inside the respirator,

N_{out} – Particle number outside the respirator,

N_F – Number of particle penetrating through the filters,

N_L – Number of particles penetrating through the leakage,

Q – Breathing flow = $Q_F + Q_L$.

We concluded from Eq.(1) that it is crucial to determine the relative contribution of the air flow through the filter to the total air flow. Therefore, a separate experiment was conducted to measure Q_F when the half mask was donned on the manikin. A flow meter (Model: 4043, TSI Inc.) was placed between the filter and the respirator. Three breathing (constant) flows (30, 85, and 135 L/min) were selected. For each flow, the respirator was taken off from the manikin, and put back on. Then the filter flow was recorded after each re-donning the respirator. Seven replicates were performed for each flow (which makes the total number of runs equal to 21). It was determined that the fraction of the breathing flow entering through the filter (Q_F/Q) was 56.0 ± 7.2 % at 30 L/min, 61.7 ± 4.4 % at 85 L/min, and 61.0 ± 4.0 % at 135 L/min. Given that P_F of a P100 filter is negligibly low (<0.03%) compared to P_L, and Q_F and Q_L are comparable (according to the above experimental data), Eq. (1) can be simplified as:

$$P \approx P_L\left(1 - \frac{Q_F}{Q}\right) \quad (2)$$

The particle loss inside the gap (~ 1 mm) was estimated to be negligibly low according to a classic particle diffusion theory.(35) For these conditions, P_L is close to 100%, which allows further simplifying the equation for the overall particle penetration:

$$P \approx 1 - \frac{Q_F}{Q} \quad (3)$$

According to this assessment, the overall penetration values are expected to be slightly below 50% at 30 L/min and about 40% at 85 and 135 L/min, which is in a reasonable agreement with the penetration values experimentally obtained for an unsealed half mask tested against three combustion aerosols under constant flow of 30 L/min (listed in Table 2).

However, Eq. (3) is limited to constant flow only, and cannot be applied to cyclic flow conditions representing a much more complex two-direction flow regime.

b. Cyclic flow.: The data on the overall aerosol penetration through the *unsealed* half mask respirator obtained for different MIFs and different combustion materials are presented in Table 2.

b.1. Cyclic versus constant flow.: For wood combustion aerosol with a cyclic MIF of 30 L/min, the penetration was 8.27 ± 0.25 %, which is approximately 5-fold lower than the one obtained in the same experiment with constant flow (43.97 ± 2.44 %). Similar results were observed for paper and plastic combustion aerosols. Overall, P_{cyclic}-values were approximately 4 – 8 times lower than the corresponding $P_{constant}$-values. One reason for this difference is that with constant flow, aerosol particles continuously penetrate into the respirator (mostly through the leakage). However, under the cyclic flow regime, no particles enter during exhalation (half of the period). The return flow is particle-free since it is supplied back into the respirator through a HEPA filter installed between the manikin and the breathing simulator. This time factor causes a two-fold decrease in aerosol concentration inside the respirator with cyclic breathing compared to constant flow, which explains a 50% drop in the measured penetration. In addition, the returning clean air flow dilutes the particle-contaminated air inside the respirator by a volumetric factor of two, thus further decreasing the aerosol concentration C_{in}. Consequently, it should be anticipated that P_{cyclic} is at least 4 times below the corresponding $P_{constant}$. This explanation is valid when the majority of particles detected inside the respirator penetrate directly through facepiece leaks (not the filter). The situation is different when the aerosol enters solely through the filter (see Table 2 – fully sealed respirator). Additionally, with cyclic flow, the relative contribution of air flow through the faceseal leak and filter changes with time, which affects the difference between the penetration levels obtained in the two protocols (constant vs. cyclic flow). The large and consistent difference between $P_{constant}$ and P_{cyclic} found in this study points to a significant limitation of the existing respirator evaluation protocols that are based on the constant flow design.

b.2. MIF effect on P_{cyclic}.: As MIF of the cyclic flow increased, the particle penetration decreased. This was observed for all three combustion materials and was statistically significant (see Table 3). One possible explanation is changing leak size with increasing cyclic flows. Higher flows can generate higher negative pressures inside the respirator during breathing, which improves the sealing performance of the respirator. It should be stressed that P_{cyclic} values that ranged from a low of 5.37 ± 0.29 % (wood, 135 L/min) to a high of 11.4 ± 0.10 % (plastic, 30 L/min) are still well above the expected penetration level of P100 filters (< 0.03%). This suggests faceseal leakage was the primary penetration pathway for the unsealed half mask respirator.

b.3. Effect of combustion material on the particle penetration.: The data obtained with the three tested combustion materials revealed similar trends, with paper and plastic producing slightly higher penetrations than wood (see Table 4). There was no statistically significant difference in penetration between paper and plastic combustion aerosols. As this study is the first one of a kind dealing with combustion aerosols, no direct comparisons can be made with previous studies.

2. Respirator Partially Sealed on the Manikin (Nose-only Sealed and Nose & Chin Sealed)

a. Effect of partial sealing on penetration.: As seen from Table 2, penetration values obtained under these two conditions were significantly lower than those determined for the unsealed respirator (see Table 5). In most cases the decrease was almost two orders of magnitude. The data indicate that most of the leakage occurred around the manikin's nose.

b. Difference between two types of partial sealing.: There were no significant differences in penetration between the two partial sealing conditions labeled as "nose-only" and "nose & chin" regardless on the combustion material and the breathing air flow (see Table 5). This further suggests that sealing the nose area (rather than the chin area) reduced penetration on average from approximately 5 – 11% (unsealed) to 0.11 – 0.48% (nose-only sealed) for the cyclic flow regime, and from approximately 44 – 51% (unsealed) to 0.66 – 1.19% (nose-only sealed) for the constant flow regime. This finding is consistent with other studies (30–32) that suggest the nose is frequently the primary leak location.

c. Penetration pathway.: Although partial sealing reduced the total particle penetration to the levels below 1%, these levels are still much higher than that for a P100 filter alone (<0.03% or <<0.3%). Thus, although offering much greater protection against combustion particles, partial sealing still left a considerable opportunity for penetration through faceseal leakages so that full advantage could not be taken of the efficient P100 filter deployed in a half mask elastomeric respirator.

d. MIF effect on P_{cyclic}.: For nose-only sealed condition, we found that penetration remained at the same level at 30 and 85 L/min but was significant higher at 135 L/min (see Table 3). For nose-chin sealed condition, there were significant differences between the outcome observed at three MIFs (30, 85, and 135 L/min). Compared to the unsealed condition, the P_{cyclic} values obtained for the two partial sealing conditions were 10 to 100 times lower as determined at the same MIF. The results also show that increasing the flow does not always reduce the faceseal penetration. In another study, Cho *et al.* (15) reported that faceseal penetration was reduced significantly (p-value < 0.001) with increasing breathing flow. A different type of respirator (N95 FFR partially sealed on a manikin) tested in the quoted study may exhibit faceseal leaks of different sizes, which could cause the disagreement between the two studies.

e. Effect of combustion material on penetration.: Penetration values were higher for wood combustion aerosol as compared to paper and plastic combustion aerosols in both "nose-only" and "nose & chin" sealed conditions (see Table 4). In contrast, for an unsealed respirator, plastic combustion aerosol exhibited the highest penetration. The finding suggests that a better sealing may produce different effect on the respiratory protection level for different aerosols, e.g., be more beneficial for protecting against plastic combustion particles than against other materials. This seems to have a significant practical relevance, especially given that burning plastic generates more toxic combustion particles making their elimination by a respirator particularly important.

3. Respirator Fully Sealed on the Manikin—For a fully sealed half mask respirator, the total penetration should be equal to the filter penetration, which is supposed to be below 0.03% at 85 L/min for a NIOSH-certified P100 filter. In our experiments, no particle penetration was detected at constant flow rate of 30 L/min. For low to moderate cyclic flows, filter penetration was 0.002% or below. At the highest flow (MIF = 135 L/min), the average penetration was around 0.011%.

It is noted that the P-100 filter penetration values obtained in this study reflect the total particle count regardless of the particle size. The filter penetration generally depends on the particle size reaching the highest value for the most penetrating particle size (MPPS). One size-selective investigation revealed – for a specific P-100 FFR filter – that the penetration could be as high as 0.048% at the MMPS of 50–200 nm.(36)

Full Facepiece Elastomeric Respirator with P-100 Filters

1. Respirator Donned on the Manikin (Unsealed)

a. Penetration values.: As seen from Table 6, penetration values for unsealed condition were extremely low for all flows and materials. At 30 L/min, $P_{constant}$ ranged from 0.017% (wood) to 0.035% (plastic). The values of P_{cyclic} were even lower: from 0.003% for MIF = 30 L/min (all three combustion materials) to 0.025% (135 L/min, plastic). These levels were approximately three orders of magnitude lower than the penetrations obtained for the half mask elastomeric respirator. This difference is likely associated with the leak size. The nose has been identified as the primary leak location for half mask respirators (see the half mask section above), whereas full facepiece does not have a nose leak (thus penetration dramatically reduced). The difference between the cyclic and constant flow regimes for the full facepiece was not as big as we observed with the half mask. Again, this also can be explained by the leak size. As the full facepiece does not have nose leak, it is more comparable to a partially sealed half mask rather than a fully sealed half mask.

b. MIF effect on P_{cyclic}.: The lowest MIF (30 L/min) produced the lowest penetration; as the flow increased, the penetration increased (p-value < 0.05). Since the penetration values were so low and closer to those expected from the filter material, one would suggest that the role of faceseal leakage pathway is not as great for the full facepiece elastomeric respirator if compared to the half mask, and the particle deposition on the *filter* governs the process, at least to a significant extent. For ultrafine particles used in this study, the primary filtration mechanism is diffusion. As the flow increases, the residence time decreases, and the diffusion becomes less effective. This explains the experimentally observed effect of MIF on the particle penetration.

2. Respirator Fully Sealed on the Manikin—The data obtained with the fully sealed full facepiece were similar to those obtained with the fully sealed half mask. This is understandable because testing of a fully sealed respirator (both half and full facepiece) is essentially equivalent to examining the performance of the respirator filter (with an exhalation valve attached). As the same type of filter was used for the half and full facepiece respirators, there was no significant difference in the filter efficiency. The results are consistent with the fact that the efficiency of a P100 filter is 0.03% or below at 85 L/min.

CONCLUSIONS

Two elastomeric respirators (half mask and full facepiece) were evaluated as to the overall particle penetration with respect to faceseal leakage, breathing flow type and rate, and combustion material. All these factors were found to have significant impact on the performance of the respirators. The total penetration through the fully sealed half and full facepiece respirators did not exceed the NIOSH certification level established for P-100 respirator filters (<0.03%). Increasing leak size increased total penetration. Effects of combustion material and breathing flow were significant and heavily dependent on sealing condition. The results suggest that eliminating or minimizing the faceseal leakage is the key aspect for improving the efficiency of elastomeric respirators used by firefighters against combustion particles regardless of particle composition and size distribution.

Significant difference in penetration was found between cyclic and constant flow; however, this difference was mainly observed for the unsealed half mask. For the half mask (fully sealed) and full facepiece (unsealed or fully sealed), the penetration remained the same when challenged with three different combustion aerosols (wood, paper and plastic). While under sealing conditions such as “nose-only”, “nose & chin”, and “unsealed”, the combustion material did show a significant effect on the total penetration for the half mask. This effect was not consistent – plastic aerosol produced the highest penetration under the unsealed condition, whereas for the two partial sealing conditions wood aerosol was associated with the highest penetrations.

This study provides meaningful information related to the NIOSH respirator testing program in accordance with Title 42 of the Code of Federal Regulations, Part 84.(37) The results indicate that the efficiency of a P-100 respirator filter is not significantly influenced by the challenge aerosol and the flow type (constant versus cyclic). This supports the approach implemented in the current NIOSH respirator testing of P-100 filters that utilizes a non-combustion challenge aerosol and constant air flow. However, the NIOSH TIL test assumes that the result is independent on the type of the tested aerosol,(38) while this study revealed that the challenge aerosol significantly affects the particle penetration through unsealed and partially sealed half mask elastomeric respirators. The differences between the currently utilized challenge(s) and actual combustion aerosols are concerned with the particle shape, density, electric charge, and possibly other properties. The findings generated by the presently adopted TIL test protocol (utilizing ambient or NaCl model aerosols) may have limitations in predicting protection levels offered by half mask elastomeric respirators.

One limitation of this study is that a stationary (non-moving) manikin headform was used. It is acknowledged that this type of headform is not capable of mimicking human speaking, head movements, or facial expressions, which could affect the leak size. We believe that the next step in testing the elastomeric half mask and full facepiece respirators could involve robotically articulating headforms.

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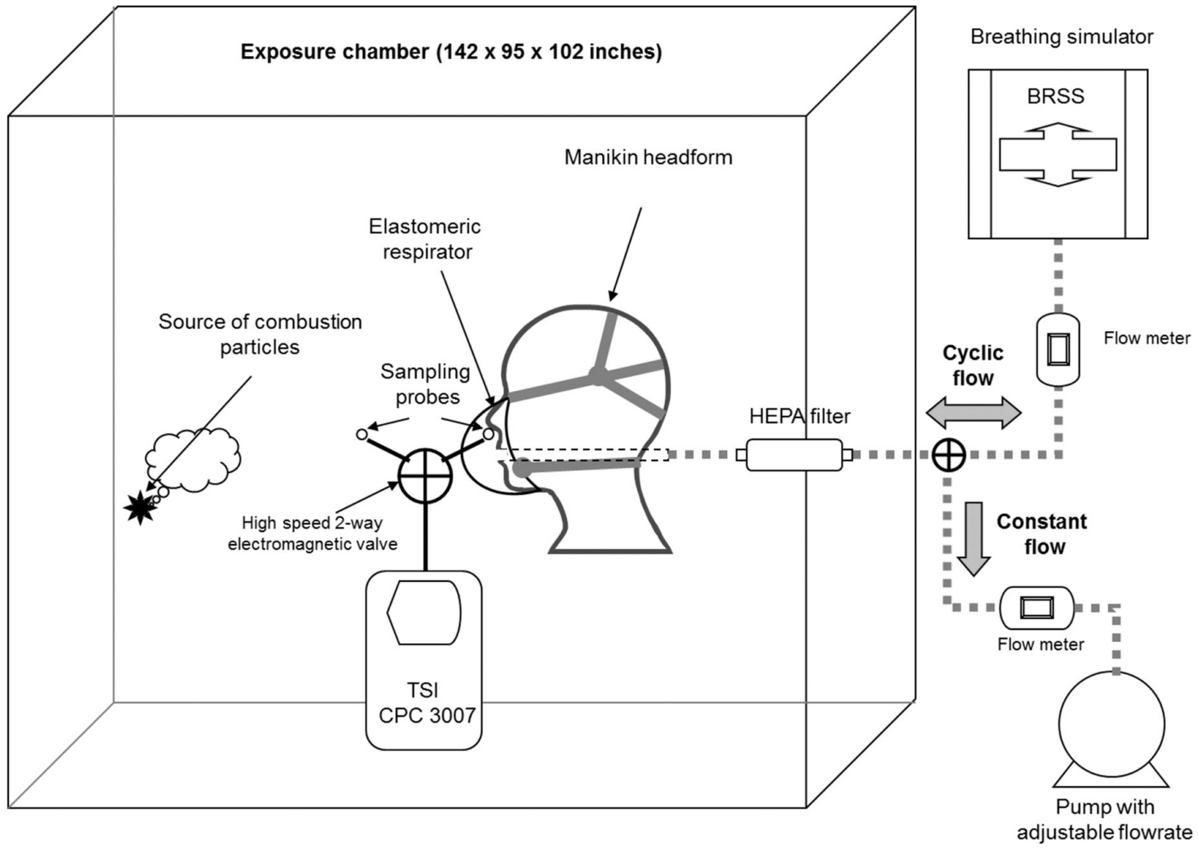

Figure 1.

Experimental setup

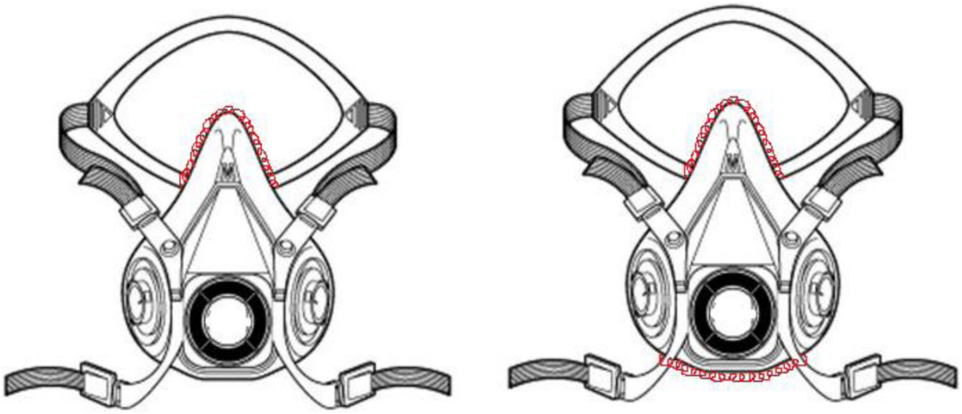

Figure 2.

"Nose-only" and "nose & chin" sealed half mask respirators. Respirator total length: 16 inches. Nose-only sealed length: 5 inches. Nose & chin sealed length: 4 inches.

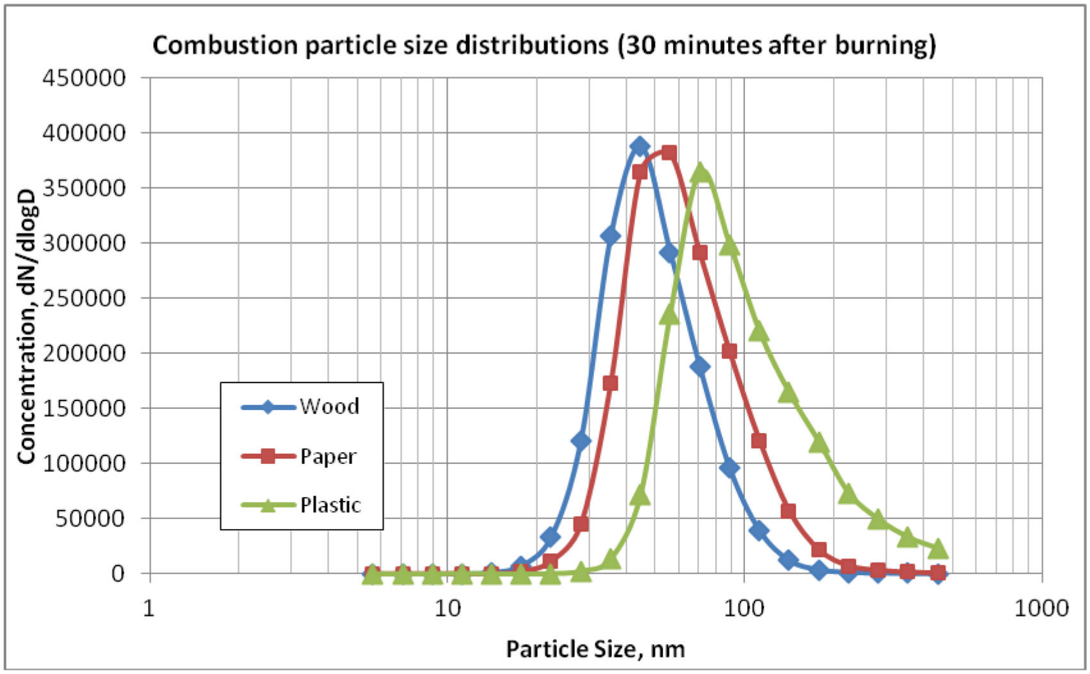

Figure 3.

Size distributions of particles aerosolized from combustion of three tested materials: wood, paper and plastic. The measurement with a Nanoparticle Spectrometer was initiated 30 minutes after burning.

Table 1.

Summary of Experimental Conditions

Variable	**Levels**	
Respirator Type	**Half mask**	**Full mask**
Sealing Condition	4 (unsealed, nose-only sealed, nose & chin sealed, fully sealed)	2 (unsealed, fully sealed)
Burning Material	3 (paper, wood, plastic)	3 (paper, wood, plastic)
Manikin Breathing Rate	1 constant (30 L/min) 3 cyclic (30, 85, 135 L/min)[a]	1 constant (30 L/min) 3 cyclic (30, 85, 135 L/min)[a]
Replicates	3	3
Total Runs:	3×4×4×3 = 144	3×4×2×3 = 72

[a]: The cyclic flows of MIF = 30, 85, and 135 L/min were applied at breathing rates of 15, 25, and 25 breaths/min, respectively.

Table 2.

Penetration values for a half mask elastomeric respirator

Material	Flow type[a], Flow rate (L/min)	Penetration, % (Mean ± SD)			
		Unsealed	Nose only Sealed	Nose & Chin Sealed	Fully Sealed
Wood	Constant, 30	43.97 ± 2.44	1.19 ± 0.08	0.33 ± 0.02	0.000 ± 0.000
	Cyclic, 30	8.27 ± 0.25	0.18 ± 0.01	0.23 ± 0.01	0.001 ± 0.000
	Cyclic, 85	6.63 ± 0.25	0.29 ± 0.01	0.34 ± 0.01	0.002 ± 0.000
	Cyclic, 135	5.37 ± 0.29	0.48 ± 0.01	0.29 ± 0.02	0.011 ± 0.003
Paper	Constant, 30	48.37 ± 0.15	0.66 ± 0.19	0.28 ± 0.11	0.000 ± 0.000
	Cyclic, 30	11.3 ± 0.26	0.11 ± 0.01	0.21 ± 0.02	0.001 ± 0.000
	Cyclic, 85	8.10 ± 0.44	0.19 ± 0.00	0.36 ± 0.01	0.002 ± 0.000
	Cyclic, 135	5.83 ± 0.06	0.25 ± 0.01	0.28 ± 0.01	0.011 ± 0.003
Plastic	Constant, 30	50.67 ± 0.61	0.69 ± 0.12	0.14 ± 0.04	0.000 ± 0.000
	Cyclic, 30	11.4 ± 0.10	0.12 ± 0.01	0.25 ± 0.00	0.000 ± 0.000
	Cyclic, 85	8.23 ± 0.25	0.20 ± 0.01	0.35 ± 0.02	0.002 ± 0.000
	Cyclic, 135	6.1 ± 0.10	0.25 ± 0.01	0.28 ± 0.01	0.011 ± 0.001

[a] For cyclic flow regime, the number represents Mean Inspiratory Flow (MIF).

Table 3.

ANOVA with Tukey's range test on the effects of the flow rate adjusted for material (half mask)

Tukey Grouping[a]	Mean Penetration[b] (%)	Flow type Flow rate (L/min)
Unsealed		
A	47.7	Constant, 30
B	10.3	Cyclic, 30
C	7.7	Cyclic, 85
D	5.8	Cyclic, 135
Nose-only Sealed		
A	0.85	Constant, 30
B	0.33	Cyclic, 135
C	0.23	Cyclic, 85
C	0.14	Cyclic, 30
Nose & Chin Sealed		
A	0.35	Cyclic, 85
B	0.28	Cyclic, 135
B C	0.25	Constant, 30
C	0.23	Cyclic, 30
Full Sealed		
A	0.011	Cyclic, 135
B	0.002	Cyclic, 85
B	0.000	Cyclic, 30
B	0.000	Constant, 30

[a] Means with the same letter are not significantly different (p-value > 0.05). The cyclic flows of MIF = 30, 85, and 135 L/min were applied at breathing rates of 15, 25, and 25 breaths/min, respectively.

[b] Calculated over all combustion materials.

Table 4.

ANOVA with Tukey's range test on the effects of the material adjusted for breathing flow (half mask)

Tukey Grouping[a]	Mean Penetration[b] (%)	Material
Unsealed		
A	19.1	Plastic
A	18.4	Paper
B	16.1	Wood
Nose-only Sealed		
A	0.53	Wood
B	0.31	Plastic
B	0.30	Paper
Nose & Chin Sealed		
A	0.30	Wood
A B	0.28	Paper
B	0.26	Plastic
Full sealed		
A	0.003	Paper
A	0.003	Wood
A	0.003	Plastic

[a] Means with the same letter are not significantly different (p-value > 0.05).

[b] Calculated over all breathing flow type and flow rate.

Table 5.

ANOVA with Tukey's range test on the effects of the sealing condition adjusted for material and breathing flow (half mask)

Tukey Grouping[a]	**Mean Penetration**[b] **(%)**	**Sealing Condition**
A	17.9	Unsealed
B	0.38	Nose-only Sealed
B	0.28	Nose-chin Sealed
C	0.003	Fully Sealed

[a] Means with the same letter are not significantly different (p-value > 0.05).

[b] Calculated over all combustion material and breathing flow.

Table 6.

Penetration values for the full facepiece elastomeric respirator

Material	Flow type Flow rate (L/min)	Penetration, % (Mean ± SD)	
		Unsealed	Fully Sealed
Wood	Constant, 30	0.017 ± 0.002	0.001 ± 0.000
	Cyclic, 30	0.003 ± 0.001	0.001 ± 0.000
	Cyclic, 85	0.010 ± 0.001	0.003 ± 0.000
	Cyclic, 135	0.019 ± 0.001	0.013 ± 0.002
Paper	Constant, 30	0.024 ± 0.000	0.000 ± 0.000
	Cyclic, 30	0.003 ± 0.001	0.000 ± 0.000
	Cyclic, 85	0.008 ± 0.000	0.002 ± 0.000
	Cyclic, 135	0.016 ± 0.001	0.010 ± 0.000
Plastic	Constant, 30	0.035 ± 0.001	0.001 ± 0.000
	Cyclic, 30	0.003 ± 0.001	0.001 ± 0.000
	Cyclic, 85	0.012 ± 0.001	0.002 ± 0.000
	Cyclic, 135	0.025 ± 0.002	0.011 ± 0.000