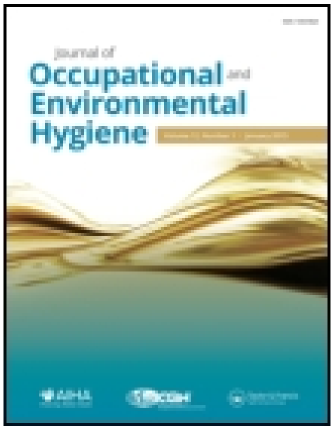




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# Protection of Firefighters Against Combustion Aerosol Particles: Simulated Workplace Protection Factor of a Half-Mask Respirator (Pilot Study)

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*The present pilot study investigated the penetration of ultrafine particles originated by combustion of different materials into elastomeric half-mask respirators equipped with two P100 filters. We determined the Simulated Workplace Protection Factor (SWPF) for 11 firefighters wearing elastomeric half-mask respirators and performing activities simulating those conducted during fire overhaul operations. The tests were performed in a controlled laboratory setting. A newly-developed battery-operated Portable Aerosol Mobility Spectrometer (PAMS) was used to measure size-resolved aerosol particle concentrations outside ($C_{out}$) and inside ($C_{in}$) of an air-purifying respirator donned on a firefighter, and the SWPF was calculated as $C_{out}/C_{in}$. Based on the total aerosol concentration, the "total" SWPF ranged from 4,222 (minimum) to 35,534 (maximum) with values falling primarily in a range from 11,171 (25 percentile) to 26,604 (75 percentile) and a median value being ≈15,000. This is consistent with the recently reported fit factor (FF) data base.[1] The size-resolved SWPF data revealed a dependency on the particle size. It was concluded that a portable device such as PAMS can be used on firefighters during overhaul operations (as well as on other workers wearing elastomeric half-mask respirators) to monitor the aerosol concentrations in real time and ultimately help prevent overexposure.*

**Keywords** combustion aerosol, elastomeric half-mask, firefighters, simulated workplace protection factor

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uoeh.

## INTRODUCTION

The US Bureau of Labor Statistics (BLS) has reported that firefighting ranks among the most dangerous occupations in the United States.[2] Coronary heart disease is the main cause of death among US firefighters during fire suppression.[3] Firefighters are often exposed to high concentrations of toxic, primarily ultrafine particles (<100 nm) aerosolized by combustion. First responders and first receivers are also exposed to ultrafine particles during emergency response activities. In general, exposure to ultrafine particles has been associated with impairment of cardiovascular function and other adverse health outcomes.[4–7]

Personal respiratory protection devices are widely used to reduce the inhalation exposure to particles of various sizes, including ultrafine, which account for more than 70% of particles (by number) released during fire knockdown (a flame reduction phase) and overhaul (late stage of the fire suppression process).[3] However, there is insufficient information pertaining to the protection level provided by these respirators against combustion aerosols during various activities, including, but not limited to, overhaul operations.

The present pilot study aimed at investigating the penetration of particles generated by combustion of different materials into elastomeric half-mask respirators worn by firefighters in a controlled laboratory setting. The simulated workplace protection factor (SWPF) was determined while the firefighters were performing activities routinely conducted in a fire overhaul situation. The data were compared to the findings of a recently published laboratory investigation on fitting identical half-mask respirators.[1] The study utilized a new prototype instrument, a Portable Aerosol Mobility Spectrometer (PAMS) (Kanomax USA Inc., Andover, NJ), for measuring total and size-resolved aerosol particle concentrations outside ($C_{out}$) and inside ($C_{in}$) of the half-mask respirator donned by a firefighter.

## MATERIALS AND METHODS

### Human Subjects

Eleven firefighters serving in the Cincinnati, Ohio, metropolitan area, including ten males and one female, were recruited to participate as subjects. Prior to recruitment, the investigators held a series of meetings with the Cincinnati District Fire Chief to develop an appropriate recruitment strategy. Recruitment flyers were sent to the area fire stations. Included in the flyer was a description of the study, the tasks to be performed by the subjects, and a list of the minimum requirements to qualify in the study, such as having recently not sustained any bodily injury, being able to provide and operate their turnout gear, and being clean shaven prior to the test (no beard, mustache, and so on). The study received an approval from the University of Cincinnati Institutional Review Board.

### Test Respirator, Pre-testing Procedures

Small, medium-, and large-sized elastomeric half-mask respirators (Model: 6000 Series, 3M, Minneapolis, MN) were offered to the subjects. Individuals were requested to select the same respirator size they would use on the job. While being worn by the subject, the respirator was visually examined to verify that it was not only suitable to the subject's facial dimensions but also provided a comfortable and snug fit. The respirator chosen for this study was of the same model that was tested in the recently published study[1]; this model is commonly used by firefighting personnel as well as by workers in other occupational environments such as foundry operators, fiber glass gunners and laminators, and shipyard workers.[8–10] The respirator was equipped with two new P100 pancake-shaped filters (Model 2091, 3M), which were attached onto the half-mask prior to each testing session. Before and after each test, respirators were cleaned with disposable Kimwipes (Kimberly-Clark Corp., Irving, TX) dampened with isopropyl alcohol.

Each respirator was thoroughly inspected for any damages it could have incurred during previous subject testing. While the subjects were experienced respirator users, for consistency, each firefighter was shown how to don the respirator and adjust the straps to ensure a suitable fit. After adjustments were made, a subject performed a positive pressure user seal check. Any faceseal leakages that were revealed during the positive pressure user seal check were remediated by adjusting the straps. Subject testing was initiated once the researchers verified that the mask was well adjusted so that no faceseal leakage was identified. No fit-testing was performed for this study (the firefighters have been fit-tested at work with the same model respirator).

### Test Conditions

During each test, a subject was asked to wear their turnout gear, which included boots, protective pants, and a jacket. Oxygen tanks and hard hats were not included as they would potentially interfere with Tygon (Saint-Gobian Corp., Valley Forge, PA) sampling tubes during testing. Subjects were evaluated to ensure that they were clean shaven. Additionally, each subjects' face was assessed to ensure no signs of moisture on their facial surface existed. While wearing the half-mask respirator, a subject entered a 24.3 $m^3$ exposure test chamber[11] and performed a series of five different activities representative of those executed during an emergency response situation such as the fire overhaul. These activities included: (1) stepping up and down a stepladder, (2) crawling back and forth, (3) squatting, (4) bending and touching their toes, and (5) picking up and moving an object. Each activity was performed for 2 minutes. As a subject was performing each activity, he/she was asked to occasionally turn their head from side to side and nod their head up and down. After the final activity, subjects were asked to remain stationary and breathe normally for 1.5 minutes. Thus, the total subject testing time was 11.5 minutes.

To mimic the smoke present in actual firefighting scenarios, wood combustion aerosol was generated in the test chamber by burning a wood pellet for approximately 15 minutes, followed by a waiting period of 10 minutes, which allowed for the stabilization of the challenge aerosol in the chamber prior to subject testing. The concentration level in the chamber was set to be 10–100 times lower than a typical knockdown level and within an order of magnitude of a typical overhaul level. The chosen ambient concentration allowed us to operate below the upper threshold of the aerosol measurement instrument deployed in this study (PAMS).

### Aerosol Measurement and SWPF

The total and size-resolved aerosol concentrations outside ($C_{out}$) and inside ($C_{in}$) the tested respirator were measured over the entire 11.5-min testing period. The aerosol measurement was performed using a prototype PAMS, an instrument developed at the National Institute for Occupational Safety and Health (NIOSH).[12] It is a battery-operated scanning mobility spectrometer, which neutralizes the sampled particles to a steady-state charging status using a dual-corona bipolar charger[13], then separates the particles according to their electrical mobility size in a differential mobility analyzer (DMA), followed by optical detection and counting with a condensation nuclei counter. The instrument is capable of real-time measurement of aerosol particle size distribution in the range of approximately 10 to 863 nm.[14] Given the typical size range of combustion particles, we focused primarily on the sizes between 20 and 200 nm. In addition to the PAMS, a P-Trak (TSI Inc., St. Paul, MN) was used in parallel to monitor the ambient particle concentration in real time.

Figure 1 presents the experimental setup. The outside (ambient) aerosol concentration was a subject for natural decay; therefore, the PAMS and P-Trak readings were acquired continuously during the test and an integrated value of $C_{out}$ was determined as a time-averaged. Similarly, an integrated value of $C_{in}$ was obtained (the inside concentration was determined exclusively based on the PAMS data). Each concentration value was recorded over a 2-min period, which was sufficient to complete three full scanning cycles for the PAMS; on the

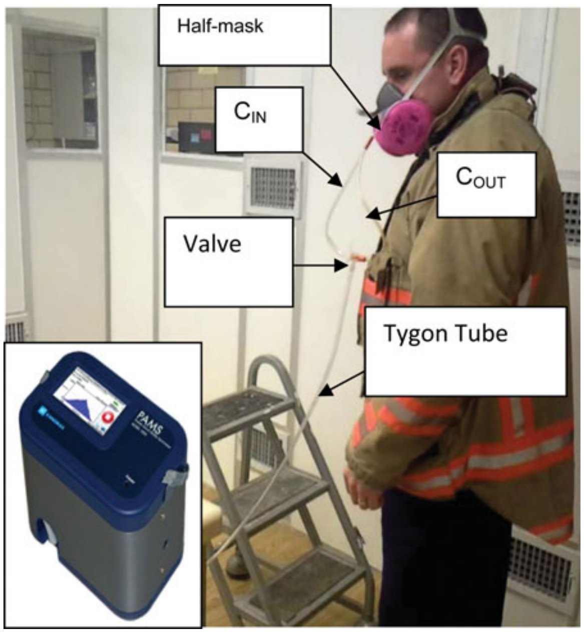


**FIGURE 1**. Test area inside the exposure chamber and PAMS

other hand, the time was short enough to essentially neglect the aerosol concentration decay factor. Each of these three cycles comprised of the eight channels making up the particle size range of interest. Upon completion of the given subject test, the SWPF was calculated as $C_{out}/C_{in.}$—size selectively and size integrated (based on the total concentration) for the PAMS data.

The sampling probes measuring the "outside" and "inside" concentrations were connected to the aerosol measurement devices via Tygon tubing so that the sampling lines were of the same length. The estimated particle losses in the sampling lines were below 10%. These were cancelled anyway in the calculation of the non-dimensional SWPF (same adjustment for losses for $C_{out}$ and $C_{in}$).

## RESULTS AND DISCUSSION

### Aerosol Particle Size Distribution

Figure 2 presents the size-resolved concentrations ($C_{out}$) of combustion-generated aerosol particles measured in the chamber with the PAMS during the 11 tests involving Subjects 1 through 11. The figure reveals a consistent pattern; the distributions covered primarily a size range of 20–200 nm expected for the tested combustion particle sizes.[15] In the quoted study 95% of particles generated by wood combustion under similar conditions were found to be within the referred size range. As seen from Figure 2, most of the curves reached their peaks at sizes slightly above 100 nm. The test with Subject 7 produced a different ambient particle distribution with the peak occurring at a higher level than in other tests. This may be associated with a different relative humidity in the chamber on the day of that test, which could cause more intense combustion

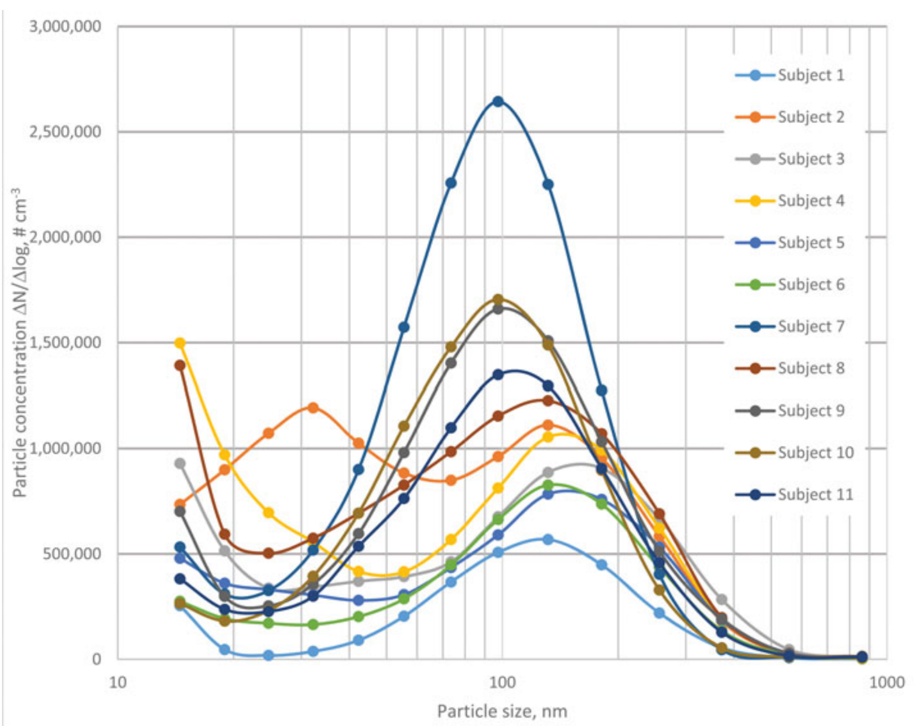


**FIGURE 2**. Size-resolved ambient aerosol concentration measured for Subjects 1–11

of the material and affect the post-combustion aerosol decay. The total ambient concentration data obtained with the PAMS were consistent with the P-Trak readings.

The particle size distributions measured inside the respirator were found to have consistent patterns (data not shown). Among the 11 subjects tested, the total counts inside the respirator ranged from 192 to 1276 particles during the entire reading time. In some particle size channels no particles were detected. For example, when testing Subject 1, the "inside" aerosol concentration was so low that particles were counted only in four PAMS channels. These low counts occurred because of high protection factor of the tested elastomeric respirator. Considering such low aerosol concentration levels and a short measurement time per particle size channel, the uncertainty of counting in PAMS, estimated from Poisson statistics, is relatively high (discussed below). This uncertainty could be reduced by increasing the "per-channel" measurement time; however, we did not choose to do so in the present investigation because it would require substantially longer overall measurement period (to scan over the entire particle size range).

## SWPF Based on Total Concentration

Figure 3 presents the SWPF values calculated for all tested firefighters based on the total concentration in the entire size range of interest. The "total" SWPF ranged from 4222 (minimum) to 35,534 (maximum) with "core" values falling in a range from ∼11,171 (25 percentile) to 26,604 (75 percentile). The median value was approximately 15,000 and the geometric mean (GM) value was 16,180. The geometric standard deviation (GSD) was 2.1. The SWPF results from this study fall within the fit factor (FF) data range reported by He et al.[1] for the same respirator (the data are also shown in this figure). The latter reported GM of 4779 and GSD of 9.1; the median FF value in the quoted study was 8140 (all numbers are given for the device that was referred to as a non-modified respirator[1]). A lower variability of the SWPF data and the higher median and GM as compared to FF can be attributed to the different representative group of subjects. The current study recruited professional firefighters who have been trained to use this respirator in their everyday practice while the quoted study[1] involved a random group of participants with a varying level of experience in using elastomeric respirators. Other factors (e.g., measurement equipment, ambient conditions, and activities) may have also contributed to the difference in data variability between the two studies.

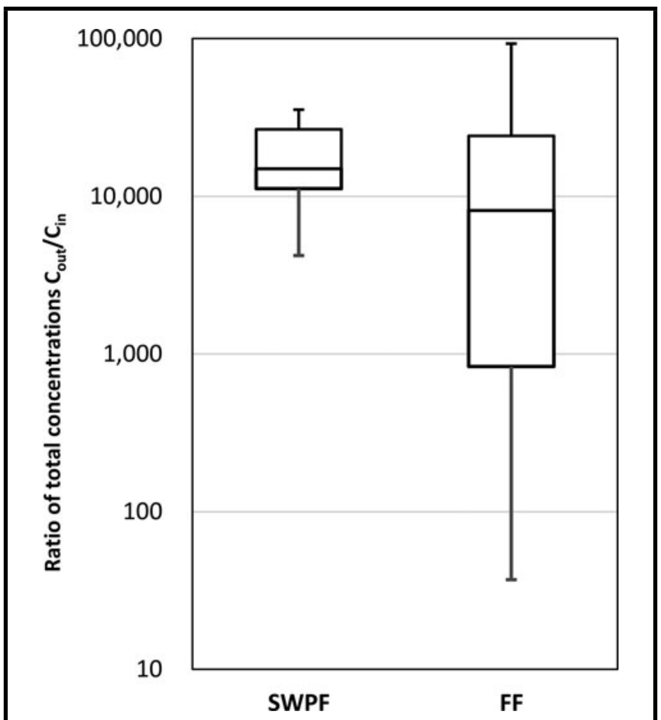


**FIGURE 3**. The "total" Simulated Workplace Protection Factor (SWPF) box plot representing the data collected from 11 firefighters and the Fit Factor box plot adopted from the 25-subject study of He et al.[1] The lines in the plot represent 5%, 25%, 50% (median), 75%, and 95%.

## Size-resolved SWPF

Figure 4 presents the size-resolved SWPF data. Each point represents the GM value obtained for a specific particle size with the error bars representing the corresponding GSD calculated for 11 subjects. The increasing trend was found statistically significant (t-test, $p<0.05$). It was unclear whether the observed trend was due to the filter penetration, or the faceseal leakage, or some other reason. To confirm there were no measurement artifacts, a separate experiment was conducted using a P100 filter (3M) housed in a filter holder under a cyclic flow (mean inspiratory flow rate = 40 L/min, breathing frequency = 0.25 Hz) produced by a breathing simulator (Koken Ltd., Tokyo, Japan). The ratio $C_{out}/C_{in.}$ obtained in this experiment ranged from ≈2,000 to >100,000, depending on particle size, which is consistent with the P100 (3M) industrial performance standard. By ruling out an unusual effect related to the filter, we surmise that the trend seen in Figure 4 can be attributed to one of the following effects: The first one is associated

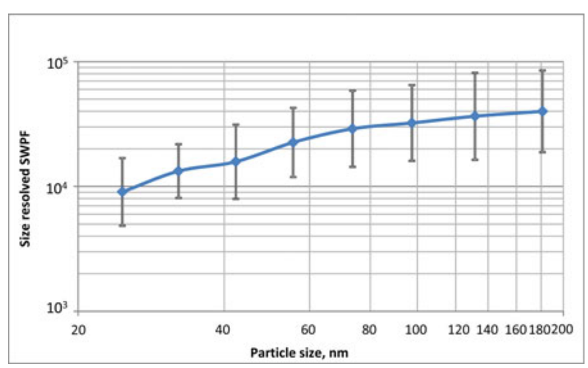


**FIGURE 4**. The size-resolved SWPF. Each point represents a GM value and the error bars represent a GSD calculated for 11 firefighters.

with the removal of particles from the respirator cavity during exhalation. Smaller particles subjected to diffusional motion may more likely be "trapped" inside the facepiece and not fully exit through the valve with effluent air. The second may be associated with small particles generated by subjects during exhalation. Both effects would artificially increase $C_{in}$ and thus decrease the SWPF. It is acknowledged that the trend found in this human subject study was not observed in our earlier manikin-based investigation(16) involving similar conditions (an elastomeric half-mask respirator fitted with two P100 filters (3M); wood combustion particles). Thus, the finding presented in Figure 4 is likely associated with the specifics of human breathing that may not be easily replicated when testing respirators on a headform. At the same time, a human subject study of elastomeric respirators published earlier(17) did reveal an increase of WPF with an increasing particle size, although it was reported for larger particles (0.7–10 $\mu$m).

The size-resolved SWPF data are influenced by the measurement uncertainty of the PAMS. The latter is primarily caused by the Poisson uncertainty associated with the condensation particle counter used in the PAMS. To conservatively estimate the measurement uncertainty occurred in this study, we selected the subject exposed to the lowest particle concentration. The measurement uncertainty of the SWPF was calculated as

$$\sqrt{\left(\frac{\Delta C_{in}}{C_{in}}\right)^2 + \left(\frac{\Delta C_{out}}{C_{out}}\right)^2}$$

where $\Delta C_{in}$ and $\Delta C_{out}$ are the Poisson uncertainty of the corresponding concentrations, which are calculated as

$$\Delta C = \sqrt{\frac{c}{Qt}}$$

Here Q is the PAMS flow rate (50 cm$^3$/min) and $t$ is the measurement time for each particle size channel adjusted to the "dead time" in the instrument. It was found that while the measurement uncertainty was relatively high, it provided only a moderate contribution into the overall data variability represented by the bars in Figure 4.

## LIMITATIONS

While the SWPFs found in this pilot study are believed to represent the "real world" condition reasonably well, the study has some limitations, including a relatively small number of subjects and only one model of a half-mask respirator tested. Besides, due to good fitting characteristics of the tested respirator, the particle concentration inside the facepiece was very low. A size-resolved, high-precision measurement of aerosol present at such low concentration levels is challenging (which is true for most aerosol instruments, including PAMS). However, in spite of high uncertainty, these measurements provide a valuable insight into the size-resolved SWPFs as demonstrated in this study. Lastly, it is acknowledged that the challenge combustion aerosol used in this study and the combustion aerosols produced during actual burning differ with respect to the particle shape, density, electric charge, and the concentration level, which may affect the protection characteristics of the respirator.

## CONCLUSION

Calculated based on the total aerosol concentration, the SWPF of an elastomeric half-mask respirator worn by firefighters was mostly above $10^3$ (Median = $15 \times 10^3$). The SWPF depends on the particle size. A portable mobility spectrometer such as PAMS can be used on firefighters during overhaul operations to monitor the size-resolved aerosol concentrations in real time and ultimately help prevent overexposure. The PAMS has a potential for a real-time assessment of the WPF in other occupational environments where the workers deploy elastomeric half-mask respirators. Unique portable aspects of PAMS provide new opportunities to conduct mobile, on-person measurements in real-world applications.

## ACKNOWLEDGMENTS

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