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# Performance of N95 FFRs Against Combustion and NaCl Aerosols in Dry and Moderately Humid Air: Manikin-based Study

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## Abstract

**Objectives:** The first objective of this study was to evaluate the penetration of particles generated from combustion of plastic through National Institute for Occupational Safety and Health (NIOSH)certified N95 filtering facepiece respirators (FFRs) using a manikin-based protocol and compare the data to the penetration of NaCl particles. The second objective was to investigate the effect of relative humidity (RH) on the filtration performance of N95 FFRs.

**Methods:** Two NIOSH-certified N95 FFRs (A and B) were fully sealed on a manikin headform and challenged with particles generated by combustion of plastic and NaCl particles. The tests were performed using two cyclic flows [with mean inspiratory flow (MIF) rates = 30 and 85 l min −1, representing human breathing under low and moderate workload conditions] and two RH levels (≈20 and ≈80%, representing dry and moderately humid air). The total and size-specific particle concentrations inside ($C_{in}$) and outside ($C_{out}$) of the respirators were measured with a condensation particle counter and an aerosol size spectrometer. The penetration values ($C_{in}/C_{out}$) were calculated after each test.

**Results:** The challenge aerosol, RH, MIF rate, and respirator type had significant ($P < 0.05$) effects on the performance of the manikin-sealed FFR. Its efficiency significantly decreased when the FFR was tested with plastic combustion particles compared to NaCl aerosols. For example, at RH ≈80% and MIF = 85 l $min^{-1}$, as much as 7.03 and 8.61% of combustion particles penetrated N95 respirators A and B, respectively. The plastic combustion particles and gaseous compounds

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CONFLICT OF INTEREST

None of the co-authors declared conflicts of interest.

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generated by combustion likely degraded the electric charges on fibers, which increased the particle penetration. Increasing breathing flow rate or humidity increased the penetration (reduced the respirator efficiency) for all tested aerosols. The effect of particle size on the penetration varied depending on the challenge aerosol and respirator type. It was observed that the peak of the size distribution of combustion particles almost coincided with their most penetrating particle size, which was not the case for NaCl particles. This finding was utilized for the data interpretation.

**Conclusions:** N95 FFRs have lower filter efficiency when challenged with contaminant particles generated by combustion, particularly when used under high humidity conditions compared to NaCl particles.

### Keywords

filtering facepiece respirator; N95; penetration; plastic combustion particles; relative humidity

## INTRODUCTION

Air-purifying respirators are commonly used in the USA for protection against job hazards. According to a voluntary survey conducted on US employers regarding the use of respiratory protective devices, 95% of the workers used air-purifying devices (BLS/NIOSH, 2003). The N95 filtering facepiece respirators (FFRs) are the most popular air-purifying respirators. They are expected to filter out at least 95% of airborne particles (‘N’ stands for non-oil resistant) (National Institute for Occupational Safety and Health, 1996). The National Institute for Occupational Safety and Health (NIOSH) estimates that 20 million American workers, including healthcare providers, firefighters, first responders, and construction workers use respirators every day for reducing exposure to airborne hazards (National Institute for Occupational Safety and Health, 2013). First responders such as emergency medical personnel and police—the first people who arrive at the scene of emergency and possibly exposed to elevated levels of hazardous materials present in flame and smoke—are often equipped with N95 FFRs (as evident from the response to the 9/11 terrorist attacks in New York and Washington). In various working environments, airborne combustion particles may be generated by burning plastic, wood, paper, cotton, and other construction materials, of which, open burning of plastic is particularly dangerous to the workers’ health.

Burning of plastic generates black smoke containing decomposition compounds, which contaminate the ambient air and cause harmful exposures (Tong *et al.*, 1984; Karasek and Tong, 1985; Fu *et al.*, 1997; Simoneit *et al.*, 2005). The chemical compounds generated by plastic burning include carbon monoxide, hydrogen cyanide, dioxin, acrolein, formaldehyde, etc. (Guidotti and Clough, 1992). These compounds may be present at the levels substantially exceeding their recommended exposure limits, which can cause health impairments and death (Milkovits, 2006). Some hazardous compounds have been shown to adhere to particles, which results in a deeper penetration into the respiratory tract, causing toxicological effects (Genovesi, 1980; Karasek and Tong, 1985; Kulkarni *et al.*, 2011). The health effects of exposure to smoke and fumes from plastic burning have been associated with various occupational diseases, including heart disease, lung cancer, asthma and emphysema, nausea, headaches, and damages in the nervous system (Timonen *et al.*, 2006; Schulte *et al.*, 2008).

NIOSH generates charge-neutralized sodium chloride (NaCl) particles of ~300-nm mass median aerodynamic diameter as the challenge aerosols to test the filtration efficiency of N95 FFRs (42 CFR Part 84; NIOSH, 1995), by using automated filter tester (TSI 8130; TSI Inc., Shoreview, MN, USA). The referred size was originally assumed to be near the most penetrating particle size (MPPS) for N95 FFRs, which has been questioned in several studies (Lee *et al.*, 2008). It has not been demonstrated that NaCl particles can be used as a universal aerosol that can accurately simulate aerosols produced by combustion for the filter/respirator testing purposes. Particles aerosolized from different sources feature different properties such as size distribution, charge distribution, and chemical composition, which can influence the filter performance (Lathrache and Fissan, 1986; Lathrache *et al.*, 1986; Martin and Moyer, 2000; Bałazy *et al.*, 2006; Eninger *et al.*, 2008; He *et al.*, 2013a). For example, Bałazy *et al.* (2006) who challenged two N95 FFRs with MS2 virus concluded that some N95 FFRs may not provide 95% filter efficiency against airborne virions that are smaller than the conventionally used 300-nm NaCl particles. Walsh and Stenhouse (1997) reported that factors such as size, charge, and composition of aerosol particles had significant effects on the filter performance; furthermore, these investigators stated that the charge of the test particles was a key factor affecting the electret filter performance. Our recent study (Gao *et al.*, 2015) conducted on the electret filter samples indicated that combustion particles penetrated more readily than NaCl particles, which could be attributed to different chemical properties of the two types (more details are provided below).

The NIOSH certifies FFRs by evaluating the filter performance under a constant flow of 85 l min$^{-1}$ (National Institute for Occupational Safety and Health, 2005). Numerous studies have been conducted to determine the filtration efficiency under constant flow regime (Chen *et al.*, 1990; Chen and Willeke, 1992; Qian *et al.*, 1998; Martin *et al.*, 2000; Eshbaugh *et al.*, 2009). However, the result obtained under constant flow may not accurately predict the filter performance under actual breathing conditions as a human breathing pattern is much more complex and features a cyclic nature. Therefore, in this study, we used a cyclic flow produced by a breathing machine to mimic human breathing.

A few studies have been published concerning the relative humidity (RH) influencing the respirator performance. The effect of RH on the filter efficiency varies depending on the aerosols type, particles size, and the filter material (Newnum, 2010). One study showed that the penetration of the non-hygroscopic particles increased as RH increased (Minguel, 2003). However, for hygroscopic particles such as NaCl, the penetration decreased with increasing the RH since the particle size increased by absorbing water from the ambient air. Kim *et al.* (2006) reported that the effect of RH on penetration of particles below 100 nm was not significant. At higher RH, the adherence between fibers and particles increases due to an increase in the capillary force. Consequently, the fibers are able to capture more particles from the air stream, i.e. the aerosol penetration decreases with increasing RH. However, this phenomenon has been shown to be pronounced specifically for coarse particles (with aerodynamic diameter >2.5 μm) at higher RH (Brown, 1993). While Yang and Lee (2005) reported that RH had no effect on the filter performance by comparing the filter penetrations of NaCl particles under RH = 30 and 70%, the effect was demonstrated at higher RH. Several studies (Ikezaki *et al.*, 1995; Lowkis and Motyl, 2001; Cheng *et al.*, 2006; Mostofi *et al.*, 2011; Haghighat *et al.*, 2012; Mahdavi *et al.*, 2015) have shown that the performance of electret filters decreases with increasing RH. For instance, Haghighat *et al.* (2012) tested N95 FFRs filters under three RH of 10, 30, and 70% at a constant flow rate of 85 l $min^{-1}$ and found that the penetration of the filters increased with the increasing RH. It should be noted that NIOSH certification testing program for FFRs includes preconditioning in a chamber at RH = 85 ± 5% and a temperature of 38 ± 2.5°C for 25 ± 1 h. We hypothesize that a humidity-associated partial or full discharge of the fibers of electret filters (material used in N95 FFRs) may significantly compromise the filter performance. The water vapor could condense on the electret fibers, which would produce a 'discharging' effect.

The present research effort is a follow-up to the study of Gao *et al.* (2015) performed using the same challenge aerosols. Similar to our earlier study, this investigation aimed at evaluating the penetration of particles aerosolized by combustion (plastic particles in particular) through filter samples of N95 FFRs and comparing the results to the penetration of the 'standard' challenge aerosol (NaCl). The main difference is that in the current effort we tested the whole facepieces and utilized a manikin-based protocol. The tested N95 respirator was fully sealed using silica adhesive on the plastic manikin headform in order to test the filter efficiency, whereas the previous investigation examined the performance of 76-mm diameter filter samples cut from the N95 FFRs. Additionally, this study was conducted under the cyclic (not constant) breathing condition. The main goal of this study was to investigate the particle penetration through N95 filters challenged with particles generated by combustion of plastic and compare the data to the penetration of NaCl particles. The second goal was to investigate the effect of humidity on the filtration performance of N95 FFRs.

## MATERIALS AND METHODS

### Respirators and challenge aerosols

Two widely used N95 FFRs labeled as N95 FFR-A and N95 FFR-B were tested in this study. The N95 FFR-B has a plastic mesh shell to support the physical structure of the filter media and prevent collapsing during regular use as well as under hot and humid conditions. Both the FFRs tested do not have exhalation valves, which results in the exhaled breath coming in full contact with the filter media. In an FFR equipped with an exhalation valve, the exhaled breath is essentially directed to the outside through the valve, which could reduce moisture build up inside the facepiece.

Two challenge aerosols including plastic combustion particles and NaCl particles were generated (one at a time). The plastic particles were produced by burning a plastic polypropylene straw (Home sense™; Kroger Co., Cincinnati, OH, USA) (19cm long and 0.5-cm diameter, 0.6 ± 0.01 g) held in a caliper. The plastic straw was ignited by a lighter and left for burning until completely consumed. The sampling devices were started to collect data 15 min after the completion of the plastic burning, which allowed the plastic particles to reach a spatial uniformity (He *et al.*, 2014a). We were specifically interested in testing the plastic particles as our previous study showed that they penetrated through the N95 FFR filters more readily than the other two types of combustion particles (wood and paper) (Gao *et al.*, 2015). Additionally, plastic aerosols were of interest due to adverse health effects associated with their exposure (Simoneit *et al.*, 2005). The NaCl aerosols were continuously generated using a particle generator (Model 8026; TSI Inc., Shoreview, MN, USA) from a water suspension with NaCl dissolved at 0.02 g $ml^{-1}$. A period of 20 min was allowed for NaCl particles to reach the homogeneous stage in the test chamber.

## Relative humidity

The respirators were tested against challenge aerosols at two RHs: ≈20 and ≈80%. These levels represent dry and moderately humid conditions, respectively. RH = 20% was the natural humidity inside the chamber. In order to establish the higher RH, a steam vaporizer (V150SG2UPC; KAZ Inc., Southboro, MA, USA) was utilized. The RH in the test chamber was measured using a digital psychrometer (SAM990DW; General Tools and Instruments, New York, NY, USA). Prior to testing, the N95 FFRs were placed under the tested RH for about 30 min before generating aerosol.

## Experimental design and test conditions

The experimental set-up shown in Fig. 1 has been described in detail elsewhere (He *et al.*, 2013c). All the tests were conducted in an exposure chamber (volume = 3.6 × 2.4 × 2.6 $m^3$, L × W × H). Table 1 summarizes the experimental conditions. The tested N95 FFR (either N95 FFR-A or N95 FFR-B) was properly positioned and fully sealed along the contact area of the manikin headform using the silica adhesive. The headform has a facial length of 11.43 ± 0.35 cm and width of 12.53 ± 0.25 cm, which is categorized into Cell 3 (small faces) of the NIOSH bivariate panel, developed by using the database of a total of 3997 respirator users (Zhuang *et al.*, 2007). A 1-in diameter copper pipe connected the nose and mouth area of the manikin with the breathing simulator. Two sampling probes were inserted: one in the breathing area inside the respirator cavity and one outside of the respirator. The two sampling lines were controlled by a high-speed two-way electromagnetic valve, which was manually operated to alternate measurements of the inside ($C_{in}$) and outside ($C_{out}$) aerosol concentrations.

The aerosol was measured with two devices. A P-Trak condensation particle counter (Model 8525; TSI Inc., Shoreview, MN, USA) counted particles across the size range measuring the total aerosol concentration. The mini wide-range aerosol spectrometer [a Nanoparticle Aerosol Monitor Model 1320 in combination with an optical particle counter Model 1.108, both from Grimm Technologies, Inc., Ainring, Germany] measured the particle size distribution and the total concentration. The concentration $C_{out}$ was measured during the first 5 min, followed by the measurement of $C_{in}$ for 10 min, and then $C_{out}$ was measured again over the last 5 min. In each test, the outside concentration was calculated as an average of the $C_{out}$ values measured over the two 5-min periods. Thus, the natural decay of the aerosol concentration in the chamber was accounted for; it was relatively small: 15% for NaCl particles and 35% for plastic combustion particles as measured over 20 min at no air exchange applied in the exposure chamber during the experiment. The particle penetration ($P_{total}$) was calculated as ($C_{in}/C_{out}$) × 100%. The air was supplied using the Breathing Recording and Simulation System (BRSS; Koken Ltd, Tokyo, Japan) via a high-efficiency particulate air filter. The BRSS is capable of establishing various breathing patterns by adjusting the flow rate and the breathing frequency. For this study, we selected two cyclic flows with mean inspiratory flow (MIF) rates of 30 and 85 l $min^{-1}$ and a breathing frequency of 25 breaths $min^{-1}$. These conditions represent human breathing under the low and moderate workloads, respectively (Tortora and Anagnostakos, 1990; Sherwood, 2006).

### Data analysis

Data analysis was performed using SAS version 9.3 (SAS Institute Inc., Cary, NC, USA). Paired *t*-test was deployed to evaluate the difference between plastic combustion particles and NaCl particles. Four-way analysis of variance (ANOVA) was used to evaluate the effects of challenge aerosol, RH, MIF, respirator type, and the interactions between RH and the other variables. Three-way ANOVA test was utilized to examine the significance of challenge aerosol, RH, and MIF after stratifying the data by respirator type. Paired *t*-test was used to examine the difference between the total particle penetrations obtained using the aerosol concentrations measured by the condensation particle counter and the aerosol size spectrometer. Correlation analysis was performed to evaluate the association between the two. For the size-specific particle penetration, the effect of particle size was analyzed by one-way ANOVA. The differences were considered significant if *P*-values calculated from the above statistical tests were below 0.05.

## RESULTS AND DISCUSSION

### Total particle penetration ($P_{total}$)

The total particle penetration obtained for the two tested N95 FFRs challenged with plastic combustion particles and NaCl particles is presented in Figs. 2 and 3 as measured using a P-Trak and a Grimm aerosol spectrometer, respectively. According to measurements conducted with the P-Trak, the total penetration values for combustion aerosol at RH ≈20% and MIF = 30 l $min^{-1}$ were 1.38 and 2.10%, respectively, for N95 FFR-A and N95 FFR-B. These values increase as MIF increased to 85 l $min^{-1}$. The penetration also showed higher values as the humidity was raised to 80%. The higher penetrations for combustion particles were observed for RH ≈80% and MIF = 85 l $min^{-1}$: 7.03% for N95 FFR-A and 8.61% for N95 FFR-B. The measurements using the Grimm instrument revealed similar trends with the maximum total penetration values of 6.05% for N95 FFR-A and 7.16% for N95 FFR-B measured at the highest tested RH and MIF. It is noted that these levels exceed the 5% NIOSH certification criterion established for N95 respirators. In all cases presented for the P-Trak measurements and all, but one, cases presented for the Grimm measurements, the results of paired *t*-test showed that the penetration of plastic combustion particles was significantly higher ($P < 0.05$) than that of NaCl particles, regardless of RH, MIF, and respirator type. The four-way and three-way ANOVA tests also showed that aerosol type was a significant factor ($P < 0.05$) affecting the filter performance (Tables 2 and 4). This finding is consistent with previous reports (Ji *et al.*, 2003; He *et al.*, 2013c). In our recent study (Gao *et al.*, 2015), we discussed why the plastic combustion particles may penetrate through an N95 'electret' filter material more readily than NaCl particles. In brief, we believe that the particles and gaseous compounds originated by burning plastic contain hydrophobic molecules, which, similarly to oil aerosols, are capable of degrading the 'electret' filter

(Tennal *et al.*, 1991; Teuten *et al.*, 2007; Gao *et al.*, 2015). Since the N95 filter material is not resistant to oil, it may be affected by the compounds produced from burning plastic. Whether the combustion gases affect filter performance was beyond the scope of this research, but is suggested as an area of future studies. The ‘oily’ particles generated by combustion may partially charge-neutralize the fibers and consequently reduce their collection efficiency, which, in turn, increases the aerosol penetration into the respirator. Unlike an N95 FFR, a P95 type (designed to protect against ‘oily’ aerosols) was found to feature the same collection efficiency for plastic combustion particles and NaCl particles (Gao *et al.*, 2015), which supports our interpretation. Other factors that could explain the significantly different penetration levels observed between plastic combustion particles and NaCl particles may include the difference in their particle size distributions (discussed below), as well as in the particle shape, density, charge, surface properties, and possibly other characteristics between the plastic combustion particles and NaCl particles. For example, Zhou and Cheng (2016) suggested that NaCl particles do not as readily penetrate the N95 FFRs as engineered nanoparticles due to their different electrostatic properties.

The total particle penetration values measured with a P-Trak when testing N95 FFR-A under the cyclic flow condition was compared to the results obtained with the flat filter samples made of the same material under constant flow (Gao *et al.*, 2015). Table 3 shows the results of this comparison. In the quoted study, the test conditions were established so that the face velocity for the flat filter sample was equal to the face velocity of the whole respirator under the constant flow. It was noted that the penetration of particles under cyclic flow (determined in this study) was 1.5- to 2.2-fold higher than that measured under the corresponding constant flow (the quoted study). This may be attributed to the differences in filter surfaces (cup like versus flat) and flow dynamics (cyclic versus constant).

**Effect of RH on $P_{total}$—**As shown in Fig. 2, the total particle penetration increased with the increasing RH. For NaCl particles, while $P_{total}$ increased significantly ($P < 0.05$) when RH was raised from 20 to 80%, it did not exceed the 5% NIOSH respirator certification criterion (except a minor excess observed for N95 FFR-B at MIF = 85 l $min^{-1}$). In contrast, almost all $P_{total}$ values obtained for plastic combustion particles exceeded 5%. The four-way and three-way ANOVA tests indicated that the effect of humidity was significant (Tables 2 and 4), which is in agreement with the results of other studies (Moyer and Stevens, 1989; Minguel, 2003; Newnum, 2010). Some older studies suggested that electrical discharge occurred on filter fibers at high RH (Ackley, 1982; Moyer and Stevens, 1989). As the charges decrease, the filter efficiency decreases as well, which results in a greater $P_{total}$. Other possible explanations for decreasing the filter efficiency with the humidity increase have been discussed in the literature. For example, Raynor and Leith (1999) indicated that humid air might help form small water droplets at intersections of fibers. These droplets could coalesce and cover the fibers, thus impeding their ability to collect. Haghighat *et al.* (2012) stated that at high RH salt particles such as NaCl might undergo deliquescence and interact with the filter as larger droplets. Gupta *et al.* (1993) speculated that the droplets could fill the interstitial spaces of the filter. This may negatively affect the filter performance. Our findings along with the above interpretation of the RH effect are consistent with the experimental investigation of Mahdavi *et al.* (2015) who suggested that

NaCl particles were partially or totally hydrated at high RH, which reduced their electrostatic attraction to the filter.

**Effect of MIF and respirator type on $P_{total}$—**Besides the challenge aerosol type and humidity, other factors such as MIF and respirator type were also evaluated in this study. As seen from Table 2, the effect of MIF on $P_{total}$ was significant ($P < 0.05$). Penetration increased with the increasing MIF, which is in agreement with previous reports (Eshbaugh *et al.*, 2009; He *et al.*, 2014b). Respirator type was found to be a significant factor as well. None of the three interactions between RH and other variables (RH and challenge aerosol, RH and MIF, RH and respirator type) had a significant effect on the respirator performance.

**$P_{total}$ data: aerosol size spectrometer versus condensation particle counter—** The total aerosol concentrations measured with the aerosol size spectrometer was obtained by combining all the channels between 15 and 900 nm. The particle size range in which P-Trak condensation particle counter measures the total concentration is ~20–1000 nm. In spite of the differences in the size range and operational principles, the paired *t*-test revealed that the $P_{total}$ values determined with the two devices were not significantly different ($P >$ 0.05). Additionally, as shown in Fig. 4, a significant correlation between the $P_{total}$ measured with P-Trak and Grimm was observed with the slope of 0.81 and the $R^2$ value of 0.87.

### Particle size-specific penetration ($P_{dp}$)

Figure 5 presents the size-specific particle penetration obtained with two tested N95 FFRs at MIFs = 30 and 85 l min$^{-1}$ and RH ≈20 and ≈80% while exposed to two challenge aerosols (plastic combustion and NaCl). For N95 FFR-A, data analysis revealed that particle size had a significant effect on penetration of both tested aerosols ($P < 0.05$), which was consistent with our previous results (He *et al.*, 2013b). For both types of challenge aerosols, the shapes of the penetration curves obtained in dry and humid air environments were about the same. Quantitatively, the difference between penetration levels found at two RHs decreased with increasing MIF (see the distances between two curves of the same color in Fig. 5a). Within the tested particle size range, the penetration under high RH exceeded that under low RH, regardless of MIF and challenge aerosol. The peaks were observed at 80 nm for NaCl and 35–46 nm for combustion particles, respectively. The difference in the MPPS likely reflects different physical proper- the particle shape, surface area, and effective density ties of the two types of aerosol particles relevant to the (Vaughn and Ramachandran, 2002; Boskovic *et al.*, particle–filter interaction, including, but not limited to, 2005). The MPPS data are comparable to the recently published results obtained for the N95 filter samples made of the same material (Gao *et al.*, 2015). The size-specific penetration values obtained for the N95 FFR-A device with NaCl particles were approximately between 0.01 and 7.69%; for plastic combustion particles, the range was 0.72–8.58%.

For N95 FFR-B, the trend was more complex. The penetration values were higher than those obtained for the N95 FFR-A, indicating that N95 FFR-B was not as efficient as N95 FFR-A. One-way ANOVA indicated that particle size was a significant factor affecting the penetration when the respirator was challenged with either of the aerosols. As shown in Fig. 5b, the curves representing the two challenge aerosols are closer to each other compared to the similar curves presented for the N95 FFR-A. The MPPSs obtained for the two challenge aerosols lay closer for both tested RH and MIF. The latter may be attributed to the electric charge on the fibers of the respirator filter. We believe that the bipolar charging of the N95 FFR-B filter is not sufficient to cause a pronounced size selectivity of $P_{\mathrm{dp}}$. This suggests a lower difference in penetration between combustion particles and NaCl. Similar to the results observed on N95 FFR-A, the filtration performance of N95 FFR-B decreased with increasing RH, except a few points obtained under MIF of 85 l min$^{-1}$.

### Effect of particle size distribution of the challenge aerosol on penetration

The information about the MPPSs obtained for the two challenge aerosols in relation to their particle size distribution helps interpreting the findings about the difference in total penetrations. Both size distributions—for NaCl and plastic combustion particles—were close to log-normal with a count median diameter and a geometric standard deviation of 80 nm and 5.9, respectively, for NaCl particles, and 59 nm and 4.8, respectively, for combustion particles.

It was observed that the peak of the particle size distribution was close to the MPPS value for combustion particles, which was not the case for NaCl particles. This suggests that the fraction of particles with sizes close to MPPS was greater for the plastic combustion aerosol as compared to NaCl aerosol, which contributes to the higher penetration level observed for the combustion particles versus NaCl.

### Limitations and future work

First, the findings of this study are limited to specific (although extensively used) N95 FFR models. Future efforts are needed to examine if the results of this investigation are fully applicable to other filter materials and respirator models. Second, this study is focused on the respirator filter efficiency (the tested device was sealed on the manikin), but does not address the role of the faceseal leakage, which may represent a prominent particle penetration pathway. Third, the study used the aerosol generated by burning plastic as an example of combustion particles. However, combustion aerosols can be generated by different materials, which vary from one another in terms of the particle size and charge distributions, chemical composition, and other factors that may affect the respirator filter performance. Thus, other challenge aerosols should be investigated in future research efforts. Finally, the interpretation of the findings of this study is of a limited utilization given that no chemical characterization of the gases/vapors generated by combustion was performed.

## CONCLUSIONS

This study evaluated the penetration of particles generated by combustion and NaCl particles through N95 FFRs sealed on a manikin headform and tested under simulated cyclic breathing flow. Filter penetration of N95 FFRs measured using particles generated by combustion of plastic was higher than the value determined with a NaCl challenge aerosol. This was most likely due to the compounds produced from burning plastic. A similar finding was reported in our companion study (Gao *et al.*, 2015), which was conducted with N95 filter samples at constant inhalation flow conditions. From this perspective, R95 or P95

FFRs should, probably, be considered as better alternatives for first responders since they may be exposed to similar combustion products in the air. Increasing the RH reduced the respirator filtration performance against both the NaCl and plastic combustion challenge aerosols. The findings presented in this study are limited to the respirators tested and may not necessarily be applied to all N95 FFRs and all plastic combustion aerosols.

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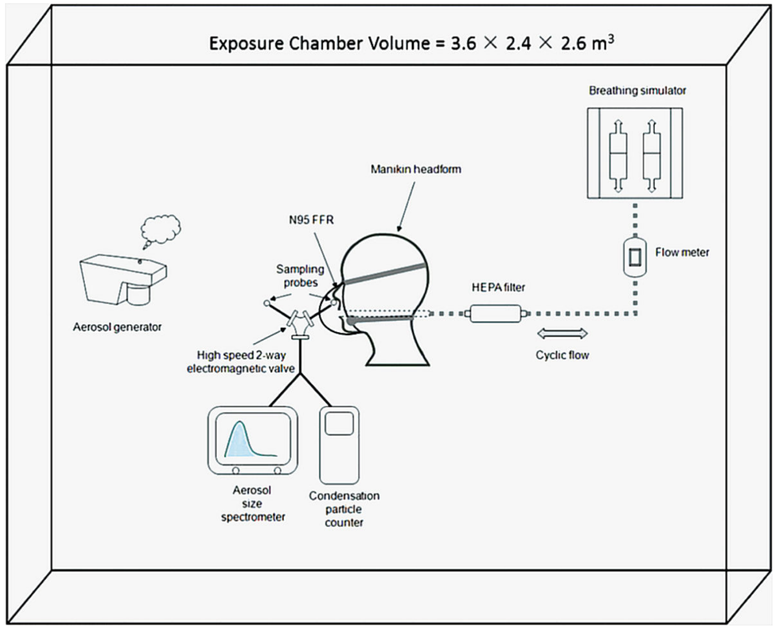


**Figure 1.**
Experimental set-up (modified from He *et al.*, 2013c).

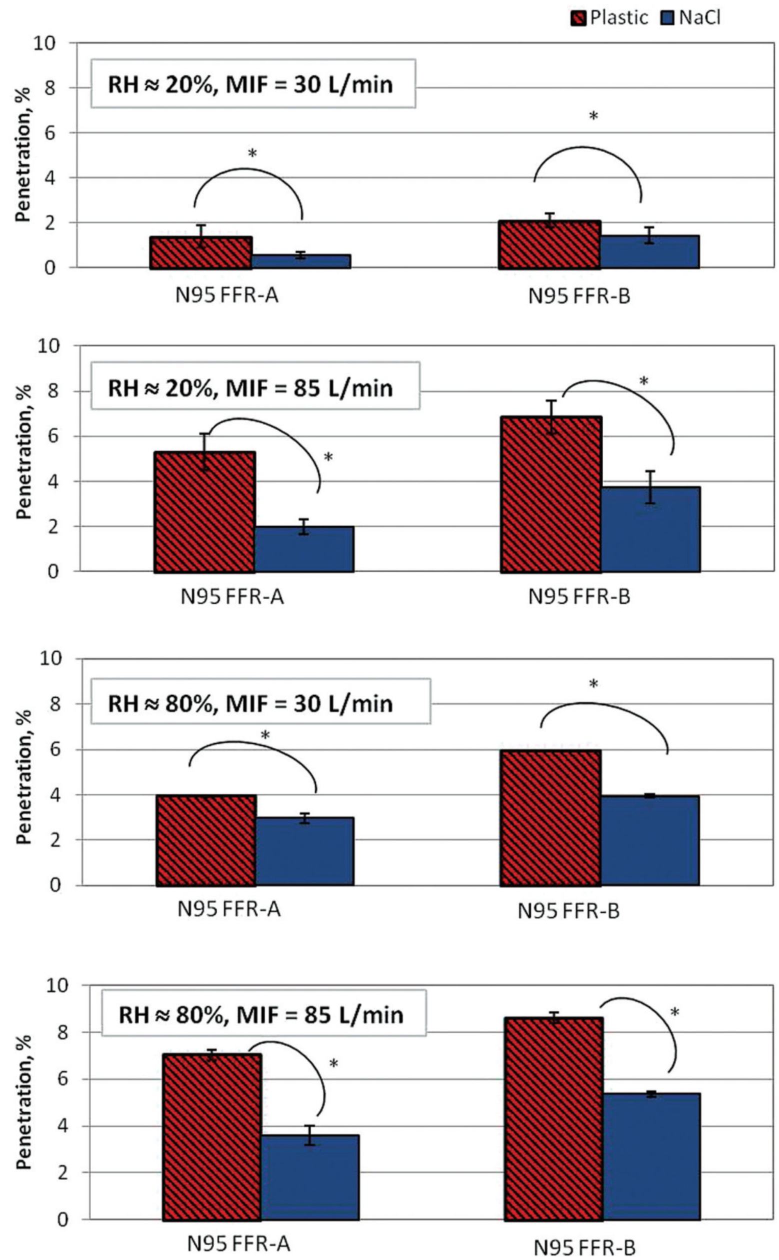


**Figure 2.**

Total particle penetration values (measured using a P-Trak condensation particle counter) for two N95 FFRs donned on a manikin headform while challenged with plastic combustion particles and NaCl particles. The error bars were obtained from six replicates (*$P < 0.05$).

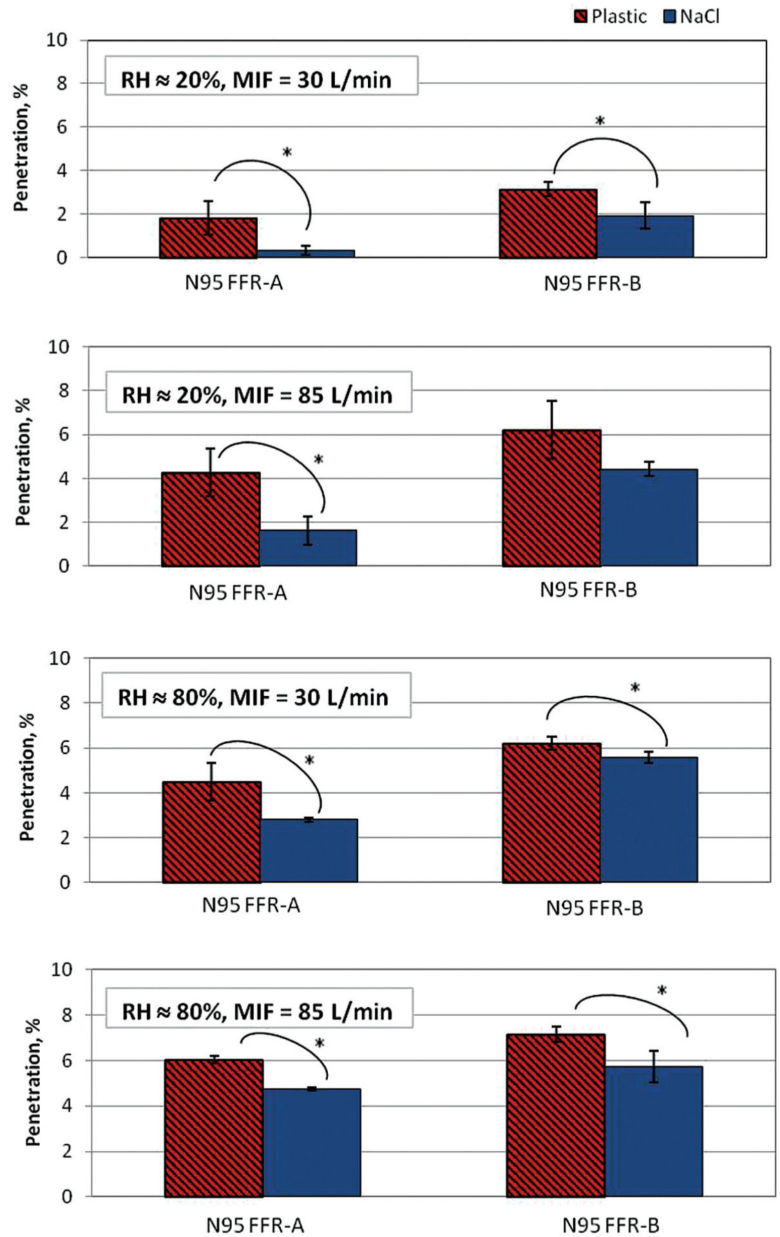


**Figure 3.**

Total particle penetration values (measured using a Grimm spectrometer) for two N95 FFRs donned on a manikin headform while challenged with plastic combustion particles and NaCl particles. The error bars were obtained from six replicates (*$P < 0.05$).

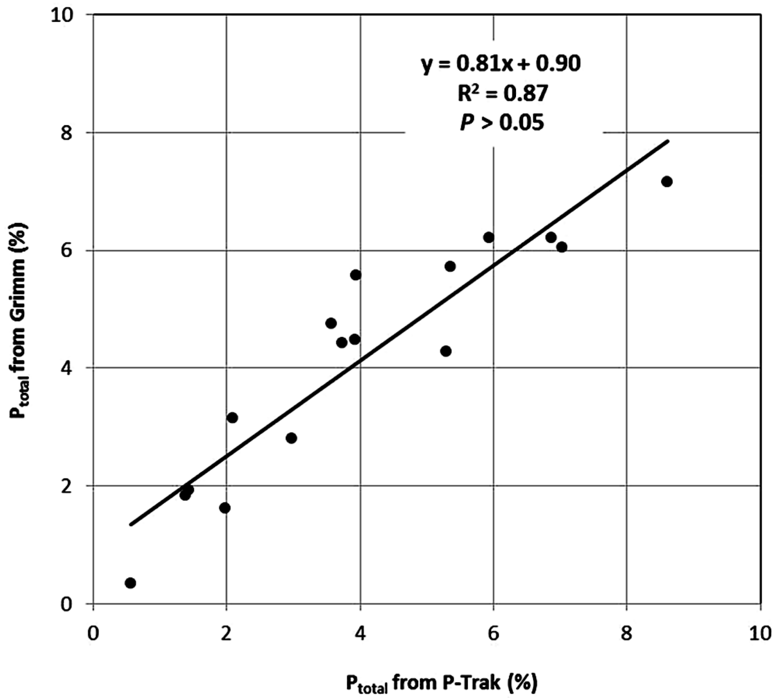


**Figure 4.**

Correlation between $P_{\text{total}}$ obtained from the P-Trak and Grimm measurement data.

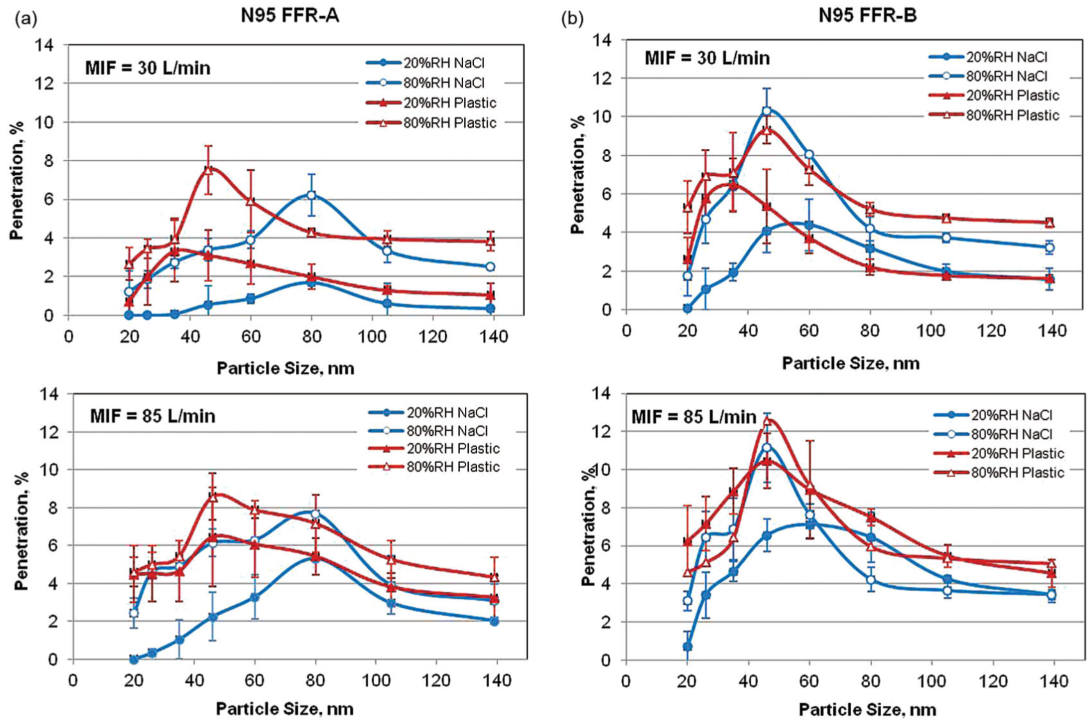


**Figure 5.**

Particle size-specific penetration values (measured using a Grimm spectrometer) for two N95 FFRs (a and b) donned on a manikin headform while challenged with plastic combustion particles and NaCl particles. The error bars were obtained from six replicates.

**Table 1.**

Summary of experimental conditions

| Variable | Levels |
|---|---|
| Respirator | N95 FFR-A and N95 FFR-B |
| Sealing condition | Fully sealed on the manikin |
| Challenge aerosol | NaCl; plastic combustion |
| Flow rate | Cyclic flows (MIF = 30, 85 $l\ min^{-1}$) |
| RH | ≈20%; ≈80% |
| Replicates | 6 |
| Total runs | 2 × 1 × 2 × 2 × 2 × 6 = 96 |

**Table 2.**

Significance of effects produced by the challenge aerosol,RH,MIF,and respirator type as well as by their interactions on $P_{total}$

| Source | DF | SS | MS | *F*-value | *P*-value |
|---|---|---|---|---|---|
| Challenge aerosol | 1 | 19.32 | 19.32 | 27.98 | 0.0007 |
| RH | 1 | 20.31 | 20.31 | 29.42 | 0.0006 |
| MIF | 1 | 25.49 | 25.49 | 36.92 | 0.0003 |
| Respirator type | 1 | 7.89 | 7.89 | 11.42 | 0.0096 |
| RH × challenge aerosol | 1 | 0.18 | 0.18 | 0.27 | 0.6188 |
| RH × MIF | 1 | 1.32 | 1.32 | 1.92 | 0.2037 |
| RH × respirator type | 1 | 0.13 | 0.13 | 0.18 | 0.6791 |

DF, degree of freedom; SS, sum of squares; MS, mean square.

**Table 3.**

Comparison of the total particle penetration values (%) obtained in two studies, while the N95 FFR-A respirator/filter was challenged with the same aerosols

| Aerosol | This study[a] MIF ($l\ min^{-1}$) | | Gao *et al.* (2015) study[b] Constant flow ($l\ min^{-1}$) | |
|---|---|---|---|---|
| | **30** | **85** | **30** | **85** |
| Combustion (plastic) | 1.38 ± 0.50 | 5.29 ± 0.80 | 0.76 ± 0.16 | 3.53 ± 0.53 |
| NaCl | 0.56 ± 0.13 | 1.98 ± 0.34 | 0.25 ± 0.07 | 1.29 ± 0.25 |

[a]Conducted with cyclic flows of MIF = 30 and 85 $l\ min^{-1}$.

[b]Conducted with constant flows of 30 and 85 $l\ min^{-1}$.

**Table 4.**

Significance of effects produced by the challenge aerosol, RH, and MIF on $P_{total}$ of the two tested FFRs

| Respirator | Source | DF | SS | MS | *F*-value | *P*-value |
|---|---|---|---|---|---|---|
| N95 FFR-A | Challenge aerosol | 1 | 9.12 | 9.12 | 10.59 | 0.0341 |
| | RH | 1 | 8.61 | 8.61 | 10.00 | 0.0341 |
| | MIF | 1 | 10.20 | 10.20 | 11.85 | 0.0262 |
| N95 FFR-B | Challenge aerosol | 1 | 10.22 | 10.22 | 12.43 | 0.0243 |
| | RH | 1 | 11.83 | 11.83 | 14.39 | 0.0192 |
| | MIF | 1 | 15.57 | 15.57 | 18.94 | 0.0121 |

DF, degree of freedom; SS, sum of squares; MS, mean square.