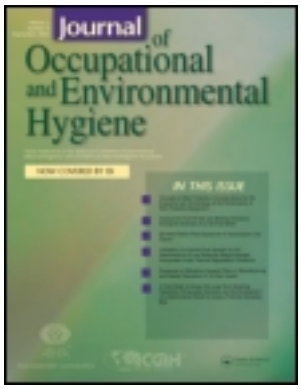


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# Nanoparticle Filtration Performance of Filtering Facepiece Respirators and Canister/cartridge Filters

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# Nanoparticle Filtration Performance of Filtering Facepiece Respirators and Canister/cartridge Filters

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*Respiratory protection offered by a particulate respirator is a function of the filter efficiency and face seal leakage. A previous study in our laboratory measured the filter penetration and total inward leakage (TIL) of 20–1000 nm size particles for N95 filtering facepiece respirators (FFRs) using a breathing manikin. The results showed relatively higher filter penetration and TIL value under different leak sizes and flow rates at the most penetrating particle size (MPPS), ∼45 nm for electrostatic FFRs,and ∼150 nm for the same FFRs after charge removal. This indicates an advantage of mechanical filters over electrostatic filters rated for similar filter efficiencies in providing respiratory protection in nanoparticle workplaces. To better understand the influence of the MPPS, the filtration performance of commonly used one N95 and one N100 FFR models, and four P100 canister/cartridge models were measured with monodisperse NaCl aerosols, and polydisperse NaCl aerosols employed in the National Institute for Occupational Safety and Health (NIOSH) certification test method. As expected, the polydisperse aerosol penetration was below 5% for the N95 FFR, and below 0.03% for the N100 FFR and P100 canister/cartridge filters. Monodisperse aerosol penetration results showed a MPPS of ∼40 nm for both the N95 and N100 FFRs. All four P100 canister/cartridge filters had a MPPS of ≥150 nm, similar to expectations for mechanical filters. The P100 canister/cartridge filters showed lower penetration values for different size nanoparticles than the N100 FFRs. The results indicate that a mechanical filter would offer a relatively higher filtration performance for nanoparticles than an electrostatic counterpart rated for the same filter efficiency. Overall, the results obtained in the study suggest that MPPS should be considered as a key factor in the development of respirator standards and recommendations for protection against nanoparticles.*

**Keywords** nanoparticles, filter penetration, filtering facepiece respirator, canister/cartridge filter, most penetrating particle size (MPPS)

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## INTRODUCTION

Nanoparticles are produced by natural sources and industrial processes.[1] A nanoparticle is defined as a nano-object with all three external dimensions in the size range from approximately 1–100 nm.[2] Engineered nanoparticles are materials deliberately synthesized for various applications because of their unique physical and chemical properties. The rapid growth of nanotechnology has increased the production of engineered nanoparticles in industrial workplaces. Tasks and processes such as cleaning engineered nanomaterials from dust collection systems, spills, and disposal can present a potential for inhalation exposure and a high level of risk. High concentrations of nanoparticles have been reported in some workplaces.[3,4] Inhalation of nanoparticles, the most common route of nanoparticle exposure, has been shown to produce adverse effects on pulmonary and systemic functions.[5,6] Nanoparticles have been implicated in human health and environmental effects.[7]

Results from the above studies suggest that respiratory protection is needed when engineering and administrative controls are not sufficient or are unavailable. Respiratory protection is used based upon professional judgment, hazard assessment, and risk management practices.[8] The Occupational Safety and Health Administration (OSHA) respiratory protection standard requires that NIOSH-approved respirators be used properly when needed to provide protection in industrial workplaces.[9]

The National Institute for Occupational Safety and Health (NIOSH) certifies N (not resistant to oil)-, R (partially resistant to oil)-, and P (oil proof)-series air-purifying particulate respirators, each at 95%, 99%, and 99.97% filter efficiencies for respiratory protection.[10] For NIOSH certification, N-series respirators are tested against polydisperse NaCl aerosols with a count median diameter (CMD) of 75 ± 20 nm while R- and P-series respirators are tested against polydisperse dioctyl phthalate (DOP) aerosols with a CMD of 185 ± 20 nm.

Penetration levels for both aerosol types are measured with charge neutralized particles at 85 L/min constant flow rate for filtering facepiece respirators (FFRs) using a TSI 8130 Automated Filter Tester (TSI, Inc., Shoreview, Minn.). A similar test method is used for canister/cartridge filters but the test flow rate is adjusted proportionately based on the number of canister/cartridges used in the respirator. A test flow rate of 85, 42.5, or 28.3 L/min is used when single, double, or triple canister/cartridge filters, respectively, are used in a respirator. NIOSH-approved N-series respirators contain electrostatic fiber media and have been found to have a most penetrating particle size (MPPS) of ~50 nm.[11] Many of the R- and P-series filter media and FFRs available in the market also showed a MPPS of ~50 nm indicating that they are also electrostatic type.[11–14]

To address the respiratory protection of workers against nanoparticles, government agencies and non-government organizations have developed standards and guidance for respiratory protection.[15–17] It is difficult to recommend respirators for these hazards because of the lack of occupational exposure limits for many types of nanomaterials.[18] NIOSH has demonstrated that current respirators on the market protect against nanoparticles.[15] NIOSH recommends respirator selection for particulates based on the assigned protection factors (APF).[19] The APF is defined as the minimum anticipated protection provided by a properly functioning respirator or class of respirators to a given percentage of properly fitted and trained users. Appropriate respirators can be selected based on the criteria described in the NIOSH Respirator Selection Logic (RSL).[20]

Other government agencies including Department of Energy (DOE) and the Environmental Protection Agency (EPA) have recommended specific respirator types for protection against nanoparticle exposures. For example, DOE recommends the use of half-mask respirators with P100 filters for airborne exposures of engineered nanomaterials.[16] The EPA has recommended the use of tight-fitting, air-purifying, full facepiece respirators with N100 filters for carbon nanotubes.[17]

This article is a continuation of the previous work in our laboratory that measured the filter penetration and total inward leakage (TIL) for N95 FFR models before and after removal of the electrostatic charge.[21] In that study, relatively higher TIL values for the N95 FFRs at 45 nm and for the charge removed N95 FFRs at 150 nm under different leak sizes and flow rates were obtained. The results indicated that the filtration performance of a mechanical respirator would be higher than an electrostatic respirator rated to have similar filter efficiencies when used for protection against nanoparticles. In this study, the filtration performance of N95 and N100 FFRs and P100 canister/cartridge filters against monodisperse and polydisperse aerosols was evaluated. The influence of the MPPS for the FFRs and canister/cartridge filters on the respiratory protection against nanoparticles is also discussed.

## MATERIALS AND METHODS

### Filtering Facepieces and Canister/cartridge filters

One model of a N95 FFR (3M 1800), one model of a N100 FFR (3M 8233), and four different P100 canister/cartridge filters (3M CN/CS CP3N, Draeger PH/CN/CS and 3M C2A1 canisters, and North OV cartridge) were purchased commercially and used in testing. Canisters and cartridges are similar in function and type of protection that can be provided. The difference is capacity. Gas masks are approved using canisters containing larger amounts of adsorbent compared to cartridges used on chemical cartridge respirators. Gas masks can be used for escape from immediately dangerous to life and health (IDLH) (not oxygen-deficient) atmospheres, while chemical cartridge respirators cannot be used for that purpose. Except for the 3M C2A1canister (used by the United States military), all these air purifying elements are NIOSH approved. 3M CN/CS CP3N, Draeger PH/CN/CS, 3M C2A1, and North OV filters were assigned labels C1, C2, C3, and C4, respectively. N95 and N100 FFR filter media contain electrostatic charge whereas all four canister/cartridge filter media are purely mechanical type as shown by the MPPS obtained from the penetration measured for different size monodisperse aerosols (Figure 1).

### Polydisperse Aerosol Penetration Test Method

Polydisperse aerosol penetration for FFRs was measured using the TSI 8130.[11] The TSI 8130 measures filter penetration based on particle mass. The TSI 8130 employs a photometer to measure the flux of light scattering from aerosol particles. The flux of scattered light is proportional to particle $(\text{mass})^2$ or $(\text{diameter})^6$. A test box made of Plexiglas (20 cm $\times$ 20 cm $\times$ 10 cm) with a top and bottom plate containing a hole (2.5 cm diameter) in the center was used for measuring penetration. A respirator with its concave side facing down was sealed to a bottom plate (20 cm $\times$ 20 cm $\times$ 0.5 cm). A silicon sealant was used to seal the top and bottom plates to make the Plexiglas box airtight. The Plexiglas box containing the respirator was placed in between the two filter chucks of the TSI 8130 and aligned to keep the top and bottom plate holes facing the upstream and downstream filter chucks, respectively. Penetration was measured under airtight conditions by closing the filter chucks.

Aerosol was passed through the outside to inside of the respirator during the test. The bottom outlet of the filter chuck was connected to a vacuum line and the flow rate was adjusted. Aerosol deposition onto the Plexiglas is possible, but it did not significantly change the challenge aerosol concentration. In the case of canister/cartridge filter testing, a bottom plate with an adapter was used to mount the canister/cartridge filter. The bottom plate was placed in the test box with the canister/cartridge filter facing the upstream aerosol. Penetration for N95 and N100 FFRs was measured using polydisperse NaCl aerosol (count median diameter 75 $\pm$ 20 nm, geometric standard deviation 1.86) and for P100 canister/cartridge filters using polydisperse DOP aerosols (count median diameter

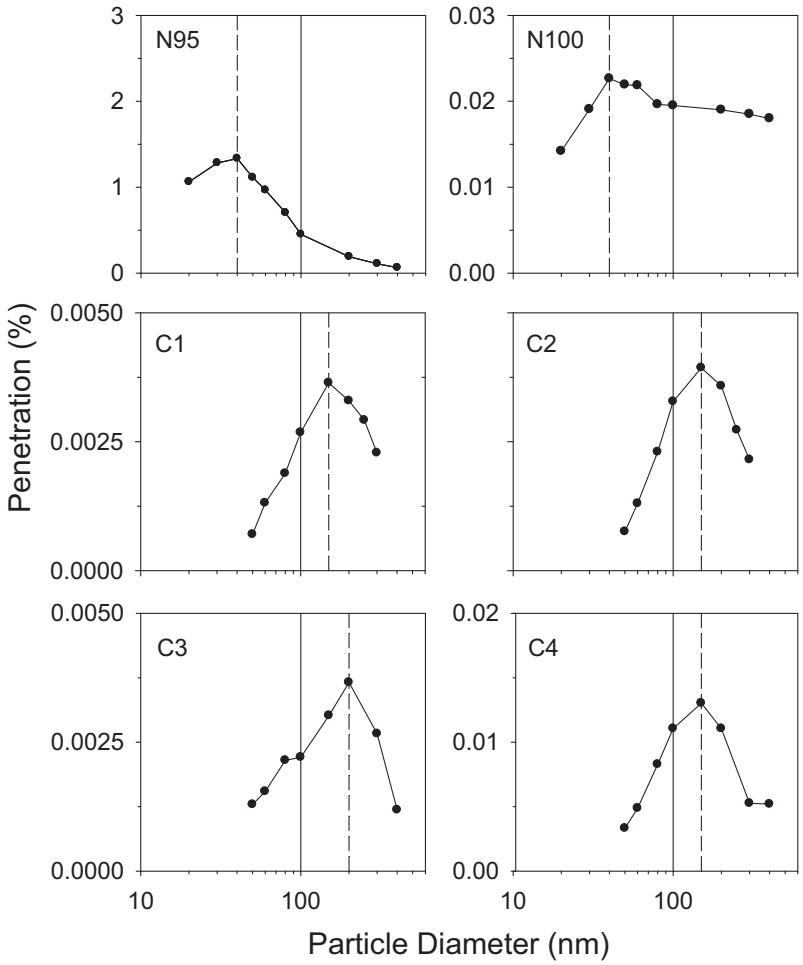


**FIGURE 1**. Typical penetration curves for N95 and N100 FFRs and four P100 canister/cartridge filters (C1, C2, C3, and C4) obtained for monodisperse NaCl aerosols using a TSI 3160 automated filter tester. Solid vertical line (100 nm) indicates the upper size range for nanoparticles and dotted line indicates the MPPS.

186 ± 20 nm, geometric standard deviation 1.60). Initial penetration for FFRs and for C1, C2, and C3 canisters was measured at 85 L/min and for cartridge C4 at 42.5 L/min for 1 min. Percentage penetration was obtained as the ratio of the particle concentration downstream of the respirator to upstream concentration multiplied by 100%. Average penetration for three samples from each model was obtained.

### Monodisperse Aerosol Penetration Test Method

Each FFR or canister/cartridge was tested against different size (20, 30, 40, 50, 60, 80, 100, 150, 200, 300, and 400 nm electrical mobility diameter) monodisperse NaCl particles using a Fractional Efficiency Tester (Model 3160, TSI Inc.) as described previously.[11] TSI 3160 employs condensation particle counters to measure the penetration based on particle number concentration. TSI 3160 can be programmed to generate different size monodisperse aerosols for the penetration test. N95 and N100 filters were tested with the above different size particles excepting 150 nm. The canister/cartridge filters were not tested with particles below 50 nm because of very low penetration levels. A test FFR or canister/cartridge filter was mounted on a Plexiglas plate as described above. The Plexiglas box containing the test filter was placed in between the two filter chucks of the TSI 3160 and aligned to keep the top and bottom plate holes facing the upstream and downstream filter chucks, respectively. Initial percentage penetration of FFRs was measured at 85 L/min for one minute. Canister/cartridge filters C1, C2, and C3 were tested at 85 L/min and C4 at 42.5 L/min for 1 min. Percentage penetration was obtained as the ratio of the particle concentration downstream of the respirator to upstream concentration multiplied by 100%. Average penetration for three test samples of each model was obtained.

## RESULTS AND DISCUSSION

Polydisperse NaCl aerosol penetration values for the N95 and N100 FFRs were 1.36% and 0.02%, respectively (Table I ). P100 canister/cartridge filters tested against polydisperse DOP aerosols showed penetration levels between

**TABLE I. Polydisperse and Monodisperse Aerosol Penetration for One Model Each of N95 and N100 FFRs and Four Models of P100 Canister/Cartridge Filters. Average of Three Samples (n = 3) and Error Represents 95% Confidence Interval.**

| | Initial Penetration (%) | | | | | |
|---|---|---|---|---|---|---|
| **Test Respirator** | **N95** | **N100** | **C1** | **C2** | **C3** | **C4** |
| Polydisperse NaCl aerosols | $1.36 \pm 0.30$ | $0.02 \pm 0.01$ | ND | ND | ND | ND |
| Polydisperse DOP aerosols | ND | ND | $0.001 \pm 0.001$ | $0.010 \pm 0.004$ | $0.008 \pm 0.003$ | $0.021 \pm 0.014$ |
| Monodisperse NaCl aerosols | $1.482 \pm 0.78$ | $0.027 \pm 0.010$ | $0.0022 \pm 0.002$ | $0.0031 \pm 0.001$ | $0.005 \pm 0.01$ | $0.014 \pm 0.01$ |
| MPPS | 40 nm | 40 nm | 150 nm | 150 nm | 200 nm | 150 nm |

ND = not determined.



0.001% and 0.021% (Table I ). Polydisperse aerosol penetration levels were below the NIOSH allowable maximum levels of 5% for the N95 FFRs, and 0.03% for the N100 FFRs as well as for the P100 canister/cartridge filters. Figure 1 shows filter penetration curves for the N95 and N100 FFR model respirators against different size monodisperse aerosols. The initial penetration level increased as the particle size increased from 20 nm, reached a maximum around 40 nm, and then decreased to produce a bell-shaped curve. Both N95 and N100 FFRs showed a MPPS of ∼40 nm. The results are consistent with the data obtained in previous studies.[11,22]

On the other hand, the four P100 canister/cartridge filters tested in the study showed a MPPS of ≥150 nm size (Figure 1). The MPPS for canister/cartridge filters obtained in the study agrees with the value reported previously.[23] In that study, two other P100 model canister/cartridge filters that were not tested in the present study showed a MPPS of ∼150 nm. The MPPS ≥150 nm obtained for P100 canister/cartridge filters indicate that these filters capture particles mostly by mechanical filtration. In general, the MPPS is >100 for mechanical filters and <100 nm for electrostatic filters. Increasing the electrostatic charge on fibers increases the collection efficiency and shifts the MPPS towards much smaller size particles.[22,24] Decreasing the fiber diameter is also known to decrease the MPPS.[24–26]

Engineered nanomaterials with unique properties are employed for various applications in nanotechnology workplaces. Some of the nanomaterials are toxic and require respiratory protection against nanoparticle exposure in workplaces to reduce potential health risks due to inhalation hazards.[6,15] Significant concentrations of different size range of nanoparticles have been generated in many industrial workplaces during various tasks/processes.[27] For example, significantly high concentrations of multi-walled carbon nanotubes (MWCNT) (∼20 nm) and metallic oxide nanoparticles of Ti (40 nm), Mn, Ag, Co, and Fe (20–50 nm) and aluminum (50–80 nm) have been produced during various work processes in manufacturing and research and development facilities. Although smaller size nanoparticles can aggregate, continuous generation of nanoparticles during work processes is not expected to change the size distribution.

Protection offered by air-purifying filtering devices is a function of filter efficiency and leakage through face seal and other pathways. The combination of filter penetration through filter media and leakage through face seal and any component interfaces is considered TIL. Excessive face seal leakage is known to compromise respiratory protection. The contribution of filter penetration to TIL is believed to be minimum when face seal leaks are introduced. To better understand this phenomenon, a previous study in our laboratory investigated the contribution of filter penetration and face seal leakage to TIL using a manikin.[21] Four N95 FFRs model sealed to the manikin were exposed to polydisperse NaCl aerosol and TIL values for different size particles were measured under different breathing flow rates and leak sizes. TIL values for the MPPS (50 nm) increased with increasing leak sizes and breathing flow rates and were significantly higher than the TIL for ∼400 nm size particles. Results from the above study indicated that the MPPS of respirators could influence the concentration of nanoparticles (<100 nm) inside the breathing zone (area inside the facepiece) of respirators.

Efficiency of respirators shows significant effect on the TIL for nanoparticles. Among the four N95 FFR models tested using the manikin,[21] the filter efficiency of two N95 FFR models was relatively higher than the other two models. TIL for the higher-efficiency models were found to be lower than the TIL values for the lower-efficiency models. The results indicate the filter efficiency dependence of TIL. The results are consistent with the TIL measured for 35 test subjects performing OSHA-prescribed fit-test exercises for five N95 FFR models in another study conducted in two test laboratories.

Filter penetration against ambient laboratory aerosol was measured for four of the models in that study. Filter efficiency of one of the four models was found to be relatively higher than the other three models. More than 80% of subjects passed the TIL test (TIL = <1) with the higher-efficiency model compared to only <7% of subjects with the three lower-efficiency models in both test laboratories. In the present study, N100 FFR and the four canister/cartridge filters are certified for similar filter efficiency (99.97%). Monodisperse aerosols penetration for nanoparticles (<100 nm) showed relatively higher efficiency for canister/cartridge filters than the N100

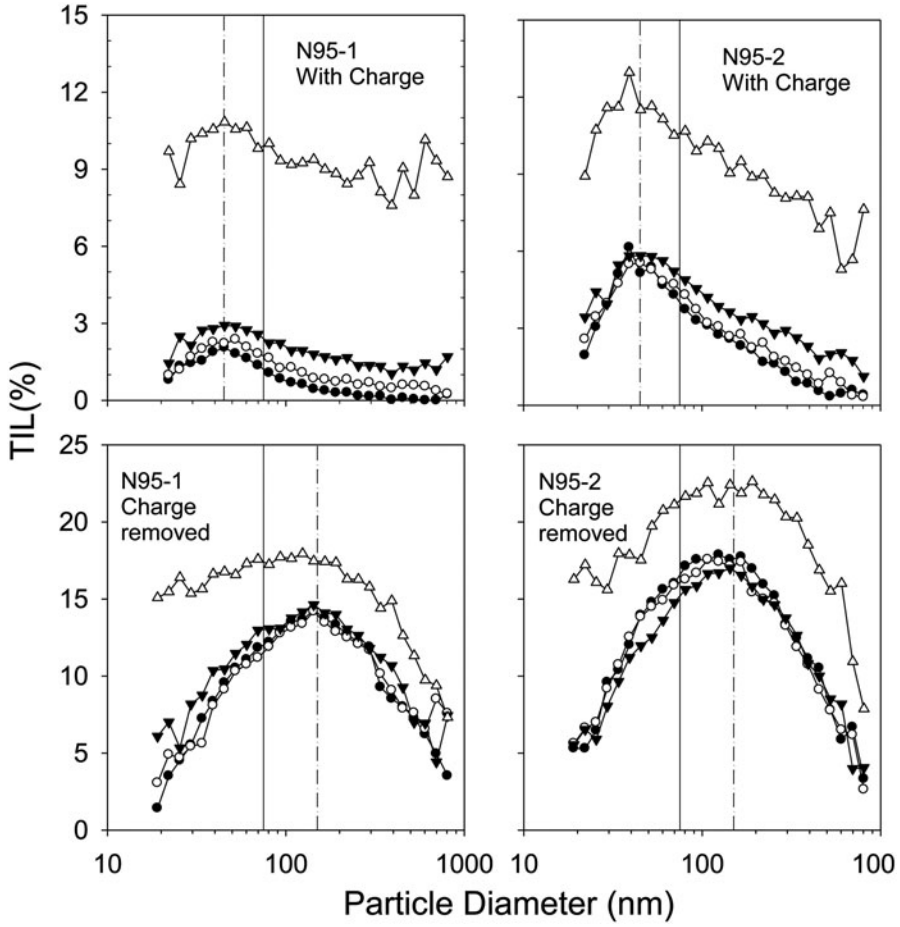


**FIGURE 2**. Typical TIL curves obtained for two N95 FFR models using a breathing manikin at sealed (filled circle) and with increasing leak sizes (2×1.19 mm, open circle; 2×1.8 mm, filled triangle; 2×3 mm, open triangle) at 40 L/min breathing minute volume. Solid vertical line (~75 nm) indicates the mode size of the test aerosols and dotted line indicates the MPPS.

filter. This indicates that the canister/cartridge filters may produce lower TIL values than the N100 filter when exposed to nanoparticles.

The difference in the MPPS for the electrostatic N100 filter and the mechanical canister/cartridge filters rated for similar filter efficiency may have significant impact on the respiratory protection for nanoparticles. TIL measurement using a breathing manikin indicated relatively higher concentration of nanoparticles inside the breathing zone of an electrostatic respirator than a mechanical respirator rated for similar filter efficiency.[21] In that study, TIL was measured for N95 FFRs before and after removal of electrostatic charge against polydisperse NaCl aerosols (mode size-75 nm). Artificial leaks showed a MPPS of ~45 nm and ~150 nm for N95 FFRs before and after charge removal, respectively, with the same test aerosol (Figure 2). TIL for nanoparticles (<100 nm) was higher for charge-removed N95 FFRs (mechanical filter) than with charge (electrostatic filter) at different leak sizes. This is because the filter efficiencies of the N95 FFRs with (top panels) and without charge (bottom panels) are not similar. This can be seen from the filter penetration measured at sealed condition (the bottom curve in each group).

In the present study, N100 FFRs and P100 filters certified for similar filter efficiency level (>99.97%) were tested for filter penetration against different size nanoparticles and compared. The MPPS for the N100 FFRs and P100 filters was ~40 nm and ≥150 nm, respectively (Figure 1). Results also showed that the mechanical P100 filters had lower penetration values for different size nanoparticles (<100 nm) than the electrostatic N100 FFRs (Figure 1). The results obtained in the study confirmed the outcome predicted previously.[21]

R- and P-series FFR models are recommended for protection against oil aerosols. Many of these FFR models are electrostatic with a MPPS in the nanoparticle size range which raises concern about their efficacy against oil nanoparticles. Several studies have reported the presence of oil aerosol particles and oil fumes in workplaces.[28,29] An oil mist is formed by condensation from the gaseous to the liquid state or by breaking up a liquid into a dispersed state, such as by splashing, foaming, or atomizing during cutting and grinding operations.

Respiratory protection may be needed against nanoparticles in these workplaces. While the electrostatic properties may not be removed by the oil aerosol atmosphere, the use of R and P-series filters with a MPPS >150 nm may be preferable for use in workplaces where an oil aerosol may be present to minimize the nanoparticle component in the respirator's inward leakage. Potential nanofiber filter media with lower penetration for particles <100 nm may also provide reasonable protection against nanoparticles.[26] It may be possible that manufacturers can develop filters with a MPPS >150 nm for oil nanoparticle workplaces and make them available to users.

Results obtained in the study have significant implications in the respirators' performance against nanoparticles. Results indicate that class 95 mechanical respirators with a MPPS of >150 nm may provide better protection against nanoparticles than class 95 electrostatic counterparts. The recommendation for respiratory protection against nanoparticles varies among the government agencies. For example, the NIOSH recommendation regarding respirators for nanoparticle workplaces includes the respirator selection logic.[15,20] DOE recommends the use of half facepiece respirators with P100 canister/cartridge filters for nanoparticle exposures[16] while EPA recommends the use of full facepiece respirators with N100 filters for both single-walled and multi-walled carbon nanotubes.[17]

None of the above recommendations for nanoparticles integrated the influence of the MPPS for respirators. The data obtained in the study indicate that MPPS for filters is an important factor to be considered in the respirator selection process for nanoparticle workplaces. Current respirator recommendations for nanoparticles lack a consensus approach and may present potential confusion to employers and workers. NIOSH has certified some N100 canister/cartridge filters but none is available in the market. Secondly, there is no scientific reason to believe that a N100 filter with a MPPS in the ~50 nm would be more efficient than a canister/cartridge filter with a MPPS in the ~150 nm to reduce the concentration of nanoparticles inside the breathing zone of respirators. The above factors should be considered in developing respirator recommendations for nanoparticle workplaces.

## CONCLUSION

As expected, polydisperse aerosol penetration was below 5% for the N95 FFR and below 0.03% for N100 FFR and P100 canister/cartridge filters. Monodisperse aerosol penetration results showed a MPPS of ~40 nm for both the N95 and N100 FFRs and ≥150 nm for the P100 canister/cartridge filters consistent with earlier studies. The P100 canister/cartridge filters had a MPPS of (≥150 nm), characteristic of mechanical filters, far from the nanoparticle region (<100 nm). The P100 filters showed relatively lower filter penetration values for different size nanoparticles than the N100 FFRs rated for the same filter efficiency (99.97%). Results similar to the performance of the mechanical P100 filters can be expected for a mechanical class 95 FFR. Based on the results obtained in the study, relatively lower concentration of nanoparticles inside the breathing zone can be expected for respirators with MPPS at ~150 nm than at ~50 nm. The use of R and P filters with a MPPS of >150 nm instead of ~50 nm may further reduce the inhalation of oil nanoparticles in workplaces. Overall, the results indicate that a mechanical filter would offer relatively higher filtration performance against nanoparticles than an electrostatic counterpart, rated for similar filter efficiency. The results obtained in the study suggest that MPPS should be considered as a key factor in the development of respirator standards and recommendations for protection against nanoparticles.

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