Manikin-Based Performance Evaluation of N95 Filtering-Facepiece Respirators Challenged with Nanoparticles

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Protection of the human respiratory system from exposure to nanoparticles is becoming an emerging issue in occupational hygiene. The potential adverse health effects associated with particles of ~1–100 nm are probably greater than submicron or micron-sized particles. The performance of two models of N95 half-facepiece-filtering respirators against nano-sized particles was evaluated at two inhalation flow rates, 30 and 85 l min⁻¹, following a manikin-based protocol. The aerosol concentration was measured outside and inside the facepiece using the Wide-Range Particle Spectrometer. Sodium chloride particles, conventionally used to certify N-series respirators under NIOSH 42 CFR 84 regulations, were utilized as the challenge aerosol. The targeted particle sizes ranged from 10 to 600 nm, although the standard certification tests are performed with particles of ~300 nm, which is assumed to be the most penetrating size. The results indicate that the nanoparticle penetration through a face-sealed N95 respirator may be in excess of the 5% threshold, particularly at high respiratory flow rates. Thus, N95 respirators may not always provide the expected respiratory protection for workers. The highest penetration values representing the poorest respirator protection conditions were observed in the particle diameter range of ~30–70 nm. Based on the theoretical simulation, we have concluded that for respirators utilizing mechanical filters, the peak penetration indeed occurs at the particle diameter of ~300 nm; however, for pre-charged fiber filters, which are commonly used for N95 respirators, the peak shifts toward nano-sizes. This study has confirmed that the neutralization of particles is a crucial element in evaluating the efficiency of a respirator. The variability of the respirator’s performance was determined for both models and both flow rates. The analysis revealed that the coefficient of variation of the penetration ranged from 0.10 to 0.54 for particles of 20–100 nm in diameter. The fraction of N95 respirators for which the performance test at 85 l min⁻¹ demonstrated excessive (>5%) penetration of nanoparticles was as high as 9/10. The test results obtained in a relatively small (0.096 m³) test chamber and in a large (24.3 m³) walk-in chamber were found essentially the same, thus, suggesting that laboratory-based evaluations have a good potential to adequately represent the respirator field performance.

Keywords: aerosol filtration; electret filter; N95 respirator; penetration

INTRODUCTION

Filtering-facepiece respirators are commonly used for personal protection from exposures to respirable aerosol particles. Fine particles are known to cause various respiratory health effects, including allergic alveolitis, asthma, pneumoconioses, cancer and others (WHO, 1999), as well as infectious diseases transmitted by bioaerosol particles, e.g. tuberculosis, Legionnaires’ disease, Q fever, mumps, measles and influenza (McCullough et al., 1997). Nanoparticles are believed to be particularly detrimental to human health since the inflammatory response depends on...
the total momentary particle penetration, fication criterion for N95 half-facepiece respirators/C24
the particle size of neutralized sodium chloride (NaCl) aerosol with after passing the tests performed using charge-
(NIOSH) regulations, 42 CFR 84 (NIOSH, 1997),
Institute for Occupational Safety and Health
facepieces are certified according to the National
and liquid aerosols that do not contain oil. The N95
properly fitted. They are recommended against solid
filtering-facepieces are widely used to reduce the
300 nm. The data collected by Brown (1993) indicate
2003), it lies primarily within the range of 100–
particles, if deposited in the upper airways, can be
translocated to the central nervous system and ganglia
axons and dendrites of olfactory neurons (Oberdörster et al., 2005). The N95 half-mask
filtering-facepieces are widely used to reduce the
inhalation exposure to particles, as these respirators are
inexpensive, convenient and highly efficient if
properly fitted. They are recommended against solid
and liquid aerosols that do not contain oil. The N95
facepieces are certified according to the National
Institute for Occupational Safety and Health (NIOSH) regulations, 42 CFR 84 (NIOSH, 1997),
after passing the tests performed using charge-neutralized sodium chloride (NaCl) aerosol with
the particle size of ~300 nm in diameter. The certifi-
cation criterion for N95 half-facepiece respirators is that the total momentary particle penetration, \( P \),
through the respirator cannot exceed 5% at 851 min\(^{-1} \), i.e. the filtration efficiency, defined as \( \eta = 1 - P \),
should be at least 95%. The value of 300 nm is pres-
ently accepted as the most penetrating particle size (MPPS) for particulate filters. However, numerous
investigations have demonstrated that the MPPS
can vary considerably from one filter model to
another and is dependent on the operational condi-
tions. For non-charged fibers, while the MPPS
increases with increasing fiber diameter (Grafe et al., 2001) and decreasing flow rate (Howard, 2003), it lies primarily within the range of 100–
300 nm. The data collected by Brown (1993) indicate that the MPPS may be even as high as 700 nm for very
low (0.001 m s\(^{-1} \)) air velocity through the filter.
For pre-treated respirator filter media, the MPPS
dependence on the fiber charge (Martin and Moyer, 2000) suggests greater uncertainty with respect to the most penetrating aerosol fraction.

To achieve high particle capture efficiency while
maintaining relatively low breathing resistance, the
N95 respirator filters are typically manufactured with
charged (pre-treated) fibers. These are further referred
to in this paper as electret filters. The certification
tests for N-series filters are carried out until minimum
efficiency is achieved or until an aerosol mass of
\( \geq 200 \) mg has contacted the filter, since, in contrast
to mechanical filters, the particle capture efficiency of
electret filters decreases initially with the filter
loading (Baumgartner and Löffler, 1987; Martin and Moyer, 2000; Ji et al., 2003). This effect depends on
the properties of aerosol particles, and, according to
Baumgartner and Löfler (1987), can be attributed to
the neutralization of fiber charges by the charges of
opposite polarity that are carried by aerosol particles
collected on the fiber. Walsh and Stenhouse (1996)
suggested an alternative explanation related to the
reduction of electrostatic effect as the layer of parti-
cles covering the fiber increases, which, in turn,
causes shielding of the electric field. Barrett and
Rousseau (1998) attributed the decrease of the elec-
tret filter efficiency with loading to the chemical
interaction between fibers and aerosol. Once the
loading has achieved a certain level, an electret filter
begins acting as a mechanical filter and its efficiency
increases. The pressure drop across the filter increases
during loading. Walsh and Stenhouse (1997) studied
how this increase is affected by the particle size,
charge and material properties, as well as by the filter
face velocity and the fiber charge. They developed
the computer simulation of the dendrite formation in two
dimensions utilizing the Kuwabara flow field
(Kuwabara, 1959). The theoretical study by Walsh
and Stenhouse (1997) suggests that the particle depo-
sition on the fiber surface is more uniform when it is
primarily driven by the electrostatic mechanism than
by inertia. Moreover, they found that more uniform
deposition is also associated with an increased fiber
charge. Similar results were obtained by Oh et al. (2002) using Brownian dynamics simulation. The
Kuwabara flow field was also used by Lathrache et al. (1986b) to calculate the penetration of charged
particles through charged fibers. The investigators
observed that under the charge equilibrium conditions
the particle charge distribution considerably affects
the particle deposition onto charged fibers and the
dependence of the penetration on the particle size is
bimodal. The results of theoretical study by Kanaoka et al. (2001) indicate that charged particles tend to
form taller dendrites that concentrate on a more lim-
ited area on the fiber surface than uncharged particles.

The performance of filtering-facepiece respirators
has been extensively tested using non-biological par-
ticles (Chen and Willeke, 1992; Qian et al., 1997b,
1998; Barrett and Rooseau, 1998; Huang et al.,
1998; Han, 2000: Martin and Moyer, 2000) as
well as biological particles (Brosseau et al., 1997;
McCullough et al., 1997; Qian et al., 1997a, 1998;
Reponen et al., 1999; Wang et al., 1999; Lee et al.,
2004a). However, these studies primarily addressed
the particle sizes >100 nm. Owing to increasing con-
cern about health effects associated with the pro-
duction of nanomaterials and other issues involving
nanoparticles, and because N95-type respirators are
widely recommended and used in occupational envir-
onments, there is a clear need to evaluate the perform-
ance of these respirators in the nano-sized range.

Other aspects of testing filtering-facepiece respira-
tors remain unresolved. Although, it seems important
to know the variability of the performance characteristics of filtering-facepiece respirators of the same model, we have not found any specific information on this topic in the literature devoted to N95 respirators. Also, while manikin-based protocols have been used for testing of the respirators’ performance in various test chambers (Lee et al., 2004b, 2005), the size of the test chamber needed to accurately predict the field performance of the respirator has not been adequately investigated. In this study, the performance characteristics of N95 respirators operating at different inhalation flow rates were tested at the initial moment of filtration (no loading factor was considered) using nano-sized and submicron NaCl particles (10–600 nm). The particle penetration was determined as a function of the particle size. The within-respirator-model variability was also determined. In order to validate the manikin-based testing protocol, similar measurements were conducted in small and large test chambers.

MATERIALS AND METHODS

Test system

The aerosol particle penetration through the N95 respirator filter was measured following a manikin-based protocol, in which the filtering-facepieces were sealed on the manikin face so that no leakage occurred between the face and the inner filter surfaces. To assure this, the leakage test was conducted using a bubble-producing liquid. The experiments were carried out in a test chamber utilizing sodium chloride aerosol (used by NIOSH in certification testing of N-series filtering-facepieces).

Figure 1 presents a diagram of the experimental set-up for measuring the particle penetration through an N95 respirator. Aspirated by fan (1), the ambient air was purified in the HEPA filter (2) and then supplied to the aerosol generator (3) (a six-jet Collison nebulizer, BGI Inc., Waltham, MA). The generated aerosol was diluted with the clean air supplied by pump (4), passed through dryer (6) and a $^{85}$Kr electrical charge equilibrator (7) (Model 3054, TSI Inc., Minneapolis, MN), and directed to the top part of the ‘small’ (0.096 m$^3$) test chamber (8). The design enabled us to achieve a good uniformity of the challenge aerosol in the test chamber. The manikin (9) was placed inside the chamber, and the test respirator (10) was sealed on its face by a silicone sealant. The manikin was equipped with a probe to sample the aerosol inside the facepiece. The outside aerosol was sampled at 5 cm from the respirator outer surface with a probe of approximately the same diameter and length as the in-facepiece sampling probe. The experiments were performed with a manikin at an inhalation air flow provided by a pump (13). The flow rate was controlled by a flow meter (12) (Model 4043, TSI Inc., Minneapolis, MN). In this study, two flow rates were tested: 30 l min$^{-1}$ representing light workload and 85 l min$^{-1}$ representing heavy workload (the latter is used in respirator certification tests). The inside and outside aerosol sampling probes operating at 1 l min$^{-1}$ were connected to the Wide-Range Particle Spectrometer (14) (WPS, model 1000 XP, Configuration A, MSP Corp., Shoreview, MI).

The WPS combines three measurement principles: the differential mobility analyzer (DMA), the condensation particle counter (CPC) and laser particle spectrometer (LPS). This allows measuring the diameter and the number concentration of aerosol particles in a wide size range, namely from 10 to 10 000 nm particle diameter. The DMA and CPC cover the range of 10 to 500 nm in up to 96 channels, whereas the LPS has a measurement capability from 350 to 10 000 nm in 24 channels. In order to remove

Fig. 1. Experimental set-up. 1, fan; 2, HEPA filter; 3, aerosol generator; 4, pump; 5, HEPA filter; 6, dryer; 7, $^{85}$Kr electrical charge equilibrator; 8, small chamber; 9, manikin; 10, N95 respirator; 11, tee valve; 12, flow meter; 13, pump; 14, Wide-Range Particle Spectrometer; 15, personal computer.
the particles larger than 500 nm from the DMA air stream, the instrument is equipped with the single-stage impactor. A built-in aerosol charge equilibrator ($^{210}$Po radioactive alpha source) imparts the Boltzmann charge distribution on the particles. After passing through the impactor and the charge equilibrator the aerosol enters the DMA where the particles of a narrow electrical mobility are extracted. The DMA operates in two modes: with the DMA voltage stepped (DMS mode) or scanned exponentially (SMS mode). The particles classified by the DMA according to their electrical mobility are subsequently transported to the CPC for counting. The CPC is of the thermal diffusion type, where butanol condenses on the sampled particles, making them grow to a size that is easy to detect with a light scattering detector (MSP, 2004). The aerosol concentration and particle size distributions measured by WPS inside and outside the respirator, respectively, was analyzed by the personal computer (15) and plotted against the particle size, $d_p$, represented by the mobility diameter for particles up to 350 nm and optical diameter in the size range of 350–600 nm.

For the method validation, selected experiments were repeated using a large (24.3 m$^3$), walk-in test chamber that simulates the field conditions in indoor work environments. In this case the manikin was placed in the center of the chamber and the challenge aerosol was evenly distributed in the chamber volume by a centrifugal fan.

**Test N95 respirators**

Two models of N95 filtering-facepiece respirators, commercially available from different manufacturers (further referred to as A and B) were selected for this study. Both of them consist of the charged fibers (electret media), and they are widely used in occupational environments. Respirator A is characterized by high fit factor value, while Respirator B has considerably lower fit factor (Coffey et al., 2004). Tables 1 and 2 summarize the physical parameters of respirators A and B, determined by the authors of this study (with the exception of the information on the fiber materials that was provided by manufacturers).

The thickness of each layer, $L$, was measured using a vernier caliper. The fiber diameter, $d_f$, was determined by analyzing the micrographs obtained under an optical microscope, connected to a digital camera and a personal computer. The surface density, $\rho_{SF}$, was obtained by weighing the samples of filters with a known surface area. Using these parameters and the available density of the fiber material, $\rho$, the packing density was calculated as:

$$\alpha = \frac{\rho_{SF}}{\rho}.$$  (1)

After deducting the areas covered by the silicon sealant, the overall surface area was determined for each facepiece. The above area was 0.0110 m$^2$ for Respirator A and 0.0134 m$^2$ for Respirator B. The face air velocities, $U_0$, calculated as the ratio of the volumetric flow to the surface area, were also different: at $Q = 301$ l min$^{-1}$, $U_0 = 4.5$ cm s$^{-1}$ for Respirator A and 3.7 cm s$^{-1}$ for Respirator B; at $Q = 85$ l min$^{-1}$, $U_0 = 12.9$ and 10.6 cm s$^{-1}$ for Respirators A and B, respectively.

**Penetration**

The aerosol penetration through the N95 respirator was determined particle-size-selectively, as a ratio of the aerosol concentrations recorded in each WPS channel inside, $c_{in}(d_p)$, and outside, $c_{out}(d_p)$, the facepiece:

$$P(d_p) = \frac{c_{in}(d_p)}{c_{out}(d_p)}.$$  (2)

The measuring cycle included three samples upstream of the filter, three samples downstream of the filter and then again three samples upstream of the filter (the last allowed us to assure that the aerosol concentration outside the respirator was consistent during each experiment). The fractional penetration,
was calculated based on the mean values of the aerosol concentration recorded in specific channels that were reckoned taking into account the second and the third samples of each cycle. The first samples were excluded as they could be contaminated by the aerosol remaining in the tube after prior measurement.

The measurement data were recorded in 48 channels of the DMA and 24 channels of the LPS. However, when the particle count in a channel was <50, the numbers from two or more channels were combined to achieve statistically representative data. The penetration of aerosol particles >600 nm was not calculated, because there were too few of those outside the respirator.

This study was initiated to primarily address the respirator protection against nanoparticles. The test particle size distribution is shown in Fig. 2. The highest aerosol concentration was observed in the particle diameter range of 20–40 nm. Overall, the test particle size range extended to as much as 600 nm, which allowed us to include \( d_p = 300 \) nm that is currently adopted for the respirator certification.

**Data analysis**

To determine the within-respirator-model variability of the penetration, 10 identical facepieces of each model were evaluated for both inhalation flow rates tested in this study. The mean value, standard deviation and the coefficient of variation of \( P(d_p) \) were calculated for each flow rate and each N95 respirator model using the complete data set obtained from ten experiments. The fraction of identical respirators that did not pass the N95 criterion (i.e. those that demonstrated the particle penetration in excess of 5%) was also determined.

To compare the penetration of sodium chloride particles through the N95 respirators obtained in the small and large chambers, the paired t-tests were run using Origin 6.0 (OriginLab Corp.).

**EXPERIMENTAL RESULTS AND DISCUSSION**

**The test chamber effect**

Similar to other manikin-based laboratory studies of N95 half-facepiece respirators, our tests were conducted in a relatively small test chamber (much smaller than a typical setting in which a worker wears the respirator). As part of the method of validation, we examined whether the performance characteristics obtained in this 0.096 m³ test chamber represent those expected in the field. Figure 3 depicts the comparison of the particle penetrations obtained for Respirator A using small and large (24.3 m³) chambers. The comparison was made for both inhalation flow rates used in this study. As it is difficult to achieve sufficiently high aerosol concentration level in a large volume, a greater number of the WPS channels were combined when analyzing the data collected in a large chamber. For consistency, the same channel-combining strategy was applied for the data obtained in the small chamber when applying the statistical testing. The paired \( t \)-tests ran for Respirator A revealed \( P \)-values of 0.397 and 0.053 for the inhalation flow rates of 30 and 85 l min⁻¹, respectively. This indicates that the respirator efficiency values determined in two test chambers were not significantly different. A similar conclusion was made for Respirator B.

The above finding suggests that the respirator performance tests carried out in a chamber of relatively small volume can be successfully used to predict the respirator performance in a workplace (this conclusion deals with face-sealed respirators and, thus, does not address the particle penetration through the leakage).

**Size selective penetration curve and variability of the respirator performance**

The within-respirator-model variability of the respiratory protection provided by Respirators A and B
at inhalation flow rates of 30 and 85 l min\(^{-1}\) is demonstrated in Fig. 4. Table 3 presents the values of the coefficient of variation that is defined as the ratio of the standard deviation to the mean and calculated in the particle diameter range of 20–100 nm. For the particles <20 nm and >100 nm, the penetration was close to zero (suggesting the respiratory protection level of almost 100%) so that there was no need to assess the N95 respirator performance variability.

It is seen that at \(Q = 85\) l min\(^{-1}\), the mean values of the penetration through Respirator A reached the 5% threshold for nanoparticles of 41 nm. Furthermore, for Respirator B, the mean penetration was >5% for \(d_p = 33–73\) nm, although it is expected to be below this level for all measured particle sizes (as B is an N95-certified respirator). It is acknowledged that N95 facepieces are certified on the basis of the total instantaneous penetration of 300 nm particles, and for this particle size our experiments showed the mean penetration values considerably <5%. However, the data presented in Fig. 4 revealed that the maximum particle penetration through both N95 facepieces tested in this study occurred not at \(d_p = 300\) nm but in the nano-sized range (when the particles mobility diameter is between 40 and 50 nm).

Table 3 also presents the fraction of identical respirators, among the 10 tested \((n = 10)\), which had the particle penetration in excess of 5% for some particle sizes. It is seen that at 30 l min\(^{-1}\), the particle penetrations through Respirators A and B were always <5% for all measured particle sizes. The increase of the inhalation flow rate to 85 l min\(^{-1}\) decreased the protection level provided by both respirators against particles of 20–100 nm. As a result, 6 of the 10 tested A-facepieces and 9 of the 10 tested B-facepieces showed penetration >5%. Further increase of the inhalation flow rate is anticipated to decrease the protection of N95 respirators against nanoparticles to an even greater extent. Although \(Q = 85\) l min\(^{-1}\) is a relatively high breathing flow rate (simulating human breathing at a heavy work load), much higher rates are believed to be achievable in the workplace. Janssen (2003) refers to the suggestion that respirators should be tested at flow rates exceeding 350 l min\(^{-1}\). The concern in this case is potentially excessive penetration of very small particles; thus, the higher penetration would be represented by the particle number rather than by the particulate mass. One could argue that the mass of penetrated nanoparticles is not sufficient to cause health problems. However, the health effects associated with nanoparticles may not necessarily relate to the particulate mass. Similarly, the effects caused by the human exposure to biological particles, such as viruses and bacteria, often depends on the number of inhaled bioparticles, for some of which the infectious dose is very low (McCullough and Brosseau, 1999).

With respect to the real life situation, the above findings represent the best-case scenario as the tested respirators were sealed to the manikin so that no particles penetrated through the face-seal leakage. The actual respiratory protection level provided by these respirators may be even lower if the respirator does not have a perfect fit. Coffey \textit{et al.} (2004) evaluated the fitting characteristics of 18 models of N95 half-facepiece respirators and determined the effect of the fit-testing on their protection level. They

### Table 3. Variability of the respirators’ performance

<table>
<thead>
<tr>
<th>Respirator</th>
<th>Inhalation flow rate, (Q) (l min(^{-1}))</th>
<th>Coefficient of variation of the penetration for particle diameter 20–100 nm</th>
<th>Fraction of respirators for which the test demonstrated penetration in excess of 5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30</td>
<td>0.21–0.48</td>
<td>0/10</td>
</tr>
<tr>
<td>A</td>
<td>85</td>
<td>0.10–0.29</td>
<td>6/10</td>
</tr>
<tr>
<td>B</td>
<td>30</td>
<td>0.32–0.54</td>
<td>0/10</td>
</tr>
<tr>
<td>B</td>
<td>85</td>
<td>0.16–0.26</td>
<td>9/10</td>
</tr>
</tbody>
</table>
showed that respirator wearer cannot expect to achieve the desired level of protection without a proper fit-testing. Moreover, the face-seal leakage increases with the filter loading owing to the pressure drop increase. According to Moyer and Bergman (2000), the penetration of NaCl particles through the face-seal leakage of N95 respirators can increase beyond 5% even at a low-level loading. Thus, given that the loading effect and a poor fit may increase the particle penetration above the levels found in this study, we conclude that the N95 respirators may not be efficient in providing the expected respiratory protection for workers exposed to nanoparticles.

**COMPARISON OF THE THEORETICAL CALCULATIONS WITH THE EXPERIMENTAL DATA**

Mathematical model of the particle penetration through an electret filter

In addition to the experimental data reported above, the theoretical calculations of the particle penetration through respirator filters were conducted using the classic theory of depth filtration (Pich, 1966; Lee and Mukund, 2001):

\[ P = \exp\left(\frac{-4\alpha E_t L}{nd_t(1 - \alpha)}\right), \]  

where \( E_t \) is the collection efficiency of a single fiber. Since the N95 respirator facepieces are usually multilayered, the total penetration through the respirator was determined as a product of the penetrations of each layer, calculated from equation (3).

The capture of particles ranging from 10 to 1000 nm by a mechanical fibrous filter is driven primarily by the diffusion and interception mechanisms. Assuming that these mechanisms are independent, the single-fiber collection efficiency can be obtained from the following equation:

\[ E_t = 1 - (1 - E_D)(1 - E_R), \]  

where \( E_D \) is the single-fiber efficiency due to diffusion and \( E_R \) is the single-fiber efficiency due to interception.

The single-fiber efficiency for the diffusion mechanism can be calculated (Payet et al., 1992; Gougeon et al., 1996) as:

\[ E_D = 1.6\left(\frac{1 - \alpha}{Ku}\right)^{1/3} \frac{Pe^{-2/3}}{1 + 1.6(1 - \alpha/Ku)^{1/3}Pe^{-2/3}}, \]  

Here \( Ku \) is the Kuwabara hydrodynamic factor calculated as

\[ Ku = \frac{-\ln \alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}, \]  

and \( Pe \) is the Peclet number defined as

\[ Pe = \frac{U_0 d_t}{D}, \]  

where \( U_0 \) is the face velocity and \( D \) is the particle diffusion coefficient

\[ D = \frac{k_B T C_C}{3 \pi \mu d_p}, \]  

\( k_B \) is the Boltzmann constant (1.3807 \times 10^{-23} \text{ J K}^{-1}), \( \mu \) is the fluid viscosity, \( T \) is the fluid absolute temperature, and \( C_C \) is the Cunningham slip correction factor. The latter is calculated as

\[ C_C = 1 + Kn[1.142 + 0.558 \exp(-0.999/Kn)], \]  

where \( Kn \) is the Knudsen number defined as the ratio of the gas free path (that is equal to 65 nm under normal conditions) to the particle radius.

The single-fiber efficiency for the interception mechanism was calculated as:

\[ E_R = \frac{0.6(1 - \alpha)}{Ku} \frac{N_R^2}{(1 + N_R)(1 + 1.9996Kn)}, \]  

where \( N_R \) is the interception parameter defined as the ratio of the particle diameter to the fiber diameter.

Figure 5 presents the results of the penetration calculated at \( U_0 = 12.9 \text{ cm s}^{-1} \) (Respirator A at \( Q = 85 \text{ l min}^{-1} \)) for the filter with characteristics, such as \( L, d_t, \alpha \) and \( \rho_{SF}, \) identical to those of Respirator A for two situations: when the fibers were not initially charged (mechanical filter, dotted curve) and when the fibers have a charge density, \( q, \) of 13 nC m\(^{-1}\) (electret filters, solid curve). The particle deposition is assumed to be driven by diffusion and interception for mechanical filter, with additional electrostatic interaction for electret. The difference between the two curves is clearly seen. The theory indeed predicts that if the filter fibers of Respirator A were not charged, the MPPS would be \( \sim 300 \text{ nm}. \) In that case, however, the particle penetration peak would reach as high as \( \sim 80\% \) (which considerably exceeds the experimental values). As the commercially available N95 half-facepiece respirators are made of fibrous electret filter media, the electrostatic mechanism plays an important role significantly enhancing the filter capturing efficiency. Below we describe the model that was employed to determine the particle penetration curve for the Respirator A with electret filter.

Neutral particles passing through the media made of charged fibers are polarized by the electric field and dipole charges are induced on the particles. The magnitude of the charge is proportional to the particle volume. The theoretical quantification of the particle deposition on charged fibers due to polarization forces is difficult because of uncertainty in the fiber charge density determination. We have failed to find
any specific information about ‘typical’ values of \( q \)
in the literature with few exceptions. The value of \( q = 34.2 \, \text{nC m}^{-1} \) was referred to by Brown (1979) and later used by Kanaoka et al. (1987) in their calculation of the polarization force. Much lower values, \( q = 0.5 \, \text{nC m}^{-1} \) (Walsh and Stenhouse, 1996) and \( q = 0.06 \, \text{nC m}^{-1} \) (Lathrache et al., 1986b) were predicted theoretically with no experimental confirmation.

To calculate the single-fiber collection efficiency due to polarization force, Kanaoka et al. (1987) used the following semi-empirical equation:

\[
E_q = 0.06 N_{Q0}^{2/5}.
\] (11)

The parameter \( N_{Q0} \) defined as the ratio of the electrostatic attraction force to the drag force is given for the case of a uniformly (unipolarly) charged fibers by:

\[
N_{Q0} = \frac{C C q^2 d^2_p}{3 \pi \varepsilon_0 \mu d U_0} \left( \frac{\varepsilon_p - 1}{\varepsilon_p + 2} \right),
\] (12)

where \( \varepsilon_p \) is the relative permittivity of the fiber and \( \varepsilon_0 \) is the permittivity of the vacuum.

In the present work, the efficiency of collection of neutralized particles on bipolarly charged fibers due to polarization force was calculated from the equation proposed by Lathrache and Fissan (1986a):

\[
E_q = B \left( \frac{1 - \alpha}{Ku} \right)^{2/5} \frac{\pi N_{Q0}}{1 + 2 \pi N_{Q0}^{2/3}}.
\] (13)

In the equation (13) the parameter \( N_{Q0} \) for a line-dipole charged fiber is defined as follows:

\[
N_{Q0} = \frac{C C q^2 d^2_p}{(1 + \varepsilon_f)^2 3 \pi \varepsilon_0 \mu d U_0} \left( \frac{\varepsilon_p - 1}{\varepsilon_p + 2} \right),
\] (14)

where \( \varepsilon_f \) is fabric dielectric constant and \( q \) denotes the charge of each sign per unit length of the fiber. The empirical constant \( B \) is introduced to allow for deviation of real filters structure from the ideal geometry of the Kuwabara cell model. At \( B = 0.21 \), the theoretical data on the particle penetration through the filter of Respirator A have a best fit with the experimental data. We found that for the above \( B \)-value, the single-fiber efficiencies predicted by equations (13) and (11) were not significantly different.

The overall collection efficiency of uncharged particles by a single charged fiber can be calculated based on the modified equation (4) as

\[
E_f = 1 - (1 - E_D)(1 - E_R)(1 - E_q).
\] (15)

As the fiber charge density was not known for Respirator A, we used \( q = 13 \, \text{nC m}^{-1} \) as the best fit for the theoretical and experimental data. Figure 6 depicts the comparison of experimental data and
Neutralization of particles

The certification test of an N95 filtering-facepiece respirator is carried out utilizing charge-neutralized particles in order to examine respirators’ performance under ‘worst-case’ scenario, representing the maximum penetration. Neutralization of aerosol particles is particularly important when testing electret filter.

In case both the fibers and the particles are charged, an emerging Coulombic force significantly enhances the capture of particles and, thus, reduces the penetration. The comparison of penetration values obtained with and without the particle charge equilibrator is shown in Fig. 7. For Respirator A operated at $Q = 85 \text{ l min}^{-1}$, the penetration decreased over 3-fold once the $^{85}\text{Kr}$ source was removed.

A similar experiment was conducted for a low efficient mechanical filter, in which case no significant difference between penetrations of electrically-neutralized and non-neutralized particles was observed. A charged particle polarizes the uncharged fiber and experiences an image force; however, unless the particle carries very high charges, this force is not strong compared with Coulombic or polarization forces.

Our results on the effect of the particle charge on the filter performance are in line with the findings of Chen and Huang (1998) and Fjeld and Owens (1988), who reported that the particle charging decreased the penetration through both the charged and non-charged filters. Kanaoka et al. (1987), who experimentally studied the particle collection by an electret filter media with rectangular fibers, achieved the maximum penetration at $d_p = 30–40 \text{ nm}$ for uncharged particles, whereas singly charged particles showed the peak at much larger sizes. These results are fully applicable when attempting to predict the performance of N95 filtering-facepiece respirators against nanoparticles.

CONCLUSIONS

The conventional wisdom is that the N95 filtering half-facepiece respirators are highly efficient for protecting the human respiratory tract against fine and ultrafine airborne particles if properly fitted. However, our manikin-based tests revealed that the
penetration threshold of 5% established for N95 facepieces could be exceeded when used against nanoparticles in the size range of ~30–70 nm. At the same time, the penetration of 300 nm particles (utilized as the most penetrating size for the certification of N95 respirators under 42 CFR 84 NIOSH regulations) was found to be considerably <5% for two N95 respirator models and two inhalation flow rates, 30 and 85 l min\(^{-1}\), tested in this study. The shift of the MPPS towards nano-sized particles is attributed to the electret filter media, which is conventionally utilized by the respirator manufacturers nowadays (the application of charged fibers considerably increases the filter efficiency, while the breathing resistance remains unchanged). The theoretical modeling of the particle penetration through mechanical and electret filters confirmed the experimentally observed shift. The modeling also confirmed that the particles captured by fibers only due to diffusion and interception go through the filter much more readily than those, which—in addition—are subjected to polarization force. It was quantitatively demonstrated that the particle electrical neutralization is a crucial element during testing the electret filters. If not neutralized, the particles can also be attracted to charged fibers owing to Coulombic force that significantly decreases the penetration, thus, resulting in the overestimation of the respirator protection characteristics.

The variability of the respirators’ performance was determined for both N95 models and both inhalation flow rates. The analysis revealed that the coefficient of variation of the penetration ranged from 0.10 to 0.54 for particles of 20–100 nm in diameter. At 85 l min\(^{-1}\), the fraction of N95 respirators for which the performance test demonstrated excessive (>5%) penetration of nanoparticles was as high as 9/10.

The test results obtained in a relatively small (0.096 m\(^3\)) test chamber and in a large (24.3 m\(^3\)) walk-in chamber were found essentially the same, suggesting that laboratory-based evaluations have a good potential to adequately represent the respirator field performance.

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