Published in final edited form as:

J Nanopart Res. 2012 May ; 14(5): .

Evaluation of environmental filtration control of engineered nanoparticles using the Harvard Versatile Engineered Nanomaterial Generation System (VENGES)

Candace S.-J. Tsai,

NSF Center for High-rate Nanomanufacturing (CHN), University of Massachusetts Lowell, One University Avenue, Lowell, MA 01854, USA, candace.umass@gmail.com

Manuel E. Echevarría-Vega,

Industrial Engineering Department, University of Puerto Rico Mayagüez, Mayagüez, PR 00681, USA

Georgios A. Sotiriou,

Particle Technology Laboratory, Department of Mechanical and Process Engineering, Swiss Federal Institute of Technology (ETH Zurich), 8092 Zurich, Switzerland

Christopher Santeufemio,

Campus Materials Characterization Laboratory, University of Massachusetts Lowell, One University Avenue, Lowell, MA 01854, USA

Daniel Schmidt,

Department of Plastic Engineering, University of Massachusetts Lowell, One University Avenue, Lowell, MA 01854, USA

Philip Demokritou, and

Center for Nanotechnology and Nanotoxicology at the Harvard School of Public Health, Boston, MA 02115, USA

Michael Ellenbecker

NSF Center for High-rate Nanomanufacturing (CHN), University of Massachusetts Lowell, One University Avenue, Lowell, MA 01854, USA

Abstract

Applying engineering controls to airborne engineered nanoparticles (ENPs) is critical to prevent environmental releases and worker exposure. This study evaluated the effectiveness of two air sampling and six air cleaning fabric filters at collecting ENPs using industrially relevant flame-made engineered nanoparticles generated using a versatile engineered nanomaterial generation system (VENGES), recently designed and constructed at Harvard University. VENGES has the ability to generate metal and metal oxide exposure atmospheres while controlling important particle properties such as primary particle size, aerosol size distribution, and agglomeration state. For this study, amorphous SiO₂ ENPs with a 15.4 nm primary particle size were generated and diluted with HEPA-filtered air. The aerosol was passed through the filter samples at two different filtration face velocities (2.3 and 3.5 m/min). Particle concentrations as a function of particle size were measured upstream and downstream of the filters using a specially designed filter test system to evaluate filtration efficiency. Real time instruments (FMPS and APS) were used to measure

particle concentration for diameters from 5 to 20,000 nm. Membrane-coated fabric filters were found to have enhanced nanoparticle collection efficiency by 20–46 % points compared to non-coated fabric and could provide collection efficiency above 95 %.

Keywords

Engineered nanoparticles; Aerosol emission; Filter; Engineering control; Silica; Environmental and health effects

Introduction

The aim of this study is to better understand how to effectively mitigate the environmental and health effects caused by nanoparticles in general (Ma-Hock et al. 2009; Shvedova et al. 2005, 2008). Of concern are a range of studies indicating ENP toxicity, such as those that found asbestos-like carcinogenic effects in mice (Poland et al. 2008; Takagi et al. 2008; Ryman-Rasmussen et al. 2009) from carbon nano-tubes (CNT) exposures and cardiopulmonary health effects in rats from acute exposures to nanostructured Fe₂O₃ (Sotiriou et al. 2011). Engineering controls such as filtration are essential for reducing ENP emission to the environment and minimizing occupational exposures during production or use of these nanomaterials.

Areas of active research include the assessment of the ability of currently available filters to capture ENPs and the development of new lower-cost filtration media for efficient capture of nanomaterials. A few recent studies have looked at the ability of commercial pollution control and respiratory protection filter media to collect nanoparticles (Japuntich et al. 2007; Kim et al. 2007). These studies have shown good agreement with the single fiber theory of filtration which predicts that particles below 100 nm in diameter will be collected more efficiently due to increased collection by the Brownian diffusion mechanism (Brown 1993; Hinds 1999). Recent publications (Golanski et al. 2010, 2008, 2009; Rengasamy et al. 2008) have documented that high efficiency particulate air (HEPA) filters have close to 100 % collection efficiency in the nanoparticle size range. However, due to their relatively high cost and lack of clean ability, researchers and companies may be tempted to use less sophisticated filters; this research investigates the performance of several fabrics commonly used in environmental air cleaning filters.

Other relevant studies testing respirator filters for nanoparticles, for example, N95 respirator cartridges generally showed expected penetrations of 5 % when challenged with nanoparticles. In these studies, the most penetrating particle size was about 40–50 nm (Shaffer and Rengasamy 2009; Rengasamy et al. 2008, 2009), which can be explained by the reliance on electrostatic forces in these filter materials. Most studies of filters other than HEPA filters did not use industrially relevant engineered nanoparticles, but rather fairly monodisperse standard test aerosols such as diethylhexyl phthalate (DEHP) (VanOsdell et al. 1990; Balazy et al. 2004; Japuntich et al. 2007), sodium chloride (Heim et al. 2005; Japuntich et al. 2007; Kim et al. 2007; Rengasamy et al. 2010), or silver (VanOsdell et al. 1990). Golanski et al. (2010) used laboratory-generated platinum, titanium dioxide, and carbon black nanoparticles to evaluate the collection efficiency of a HEPA and an electrostatic filter.

Environmental fabric filters using woven and non-woven fabrics have been commonly used for baghouses and filtration system since the late 1800s (Strauss 1975). Little research has been done on the performance of fabric filters for collecting submicrometer size particles. Needled felt (nonwoven) fabric filters have been widely used in Europe and held 85 % of

the market share of all fabrics used in dry filtration in the 1970s (Bergmann 1979). Culhane (1974) found that felted fabric filters operated at higher pressure drops compared to woven filters at the same filtration velocity. Needled felts are three-dimensional filter media where fibers are distributed randomly in three dimensions, and the active collection element is the single fiber; this is in contrast to woven fabrics, which rely on the formation of a dust cake on the fabric surface for high filtration efficiency. Research has found that felted fabrics provide high efficiency for fine and submicrometer particles (Bergmann 1979). Fabric filters are still commonly used in industry; this study selected woven and nonwoven fabric filters commonly used in baghouses to investigate the performance of such fabric filters for collecting nanoparticles.

Materials and methods

Filters

Evaluated filters include quartz (Whatman QMA quartz fiber, 47 mm D, BGI) and glass fiber (indicated as A/E) (Pall A/E glass fiber, 47 mm D, BGI) air sampling filters and six air cleaning fabric filters (Process Systems & Components, Inc.), i.e., woven polyester (WP), WP with Teflon® membrane coating (WP-TMC), polyester felt (PF), PF with Teflon membrane (PF-TMC), PF with Goretex® membrane coating (PF-GM), and filament polyester (FP). None of the eight filters have collection efficiency values claimed by the manufacturers for nano-size particles. These woven and nonwoven (felt) filters are typical of the sort used for baghouses in industry (Neundorfer Particulate Knowledge Baghouse 2011); and the tested fabric filters were selected to give a variety of filter media for this study. The quartz and glass fiber (A/E) filters were selected as being representative of standard high-efficiency air filters widely available on the market; although these filters are designed and marketed primarily for aerosol sampling, they can also be used for the filtration of small exhaust gas streams. The glass fiber filter is described by its manufacturer as a binder-free borosilicate glass fiber filter that is “recommended by EPA for high-volume air sampling to collect atmospheric particles and aerosols” (Pall Corporation 2011). The quartz filter is designed for air sampling in high temperature, high-acid environments, and for PM-10 testing (Whatman GE Healthcare 2011). The tested filter media can be considered in three groups, i.e., (1) the high efficiency quartz and glass fiber (A/E) sampling filters, (2) membrane coated fabric filters, and (3) non-coated fabric filters. The fabric filters were made and donated by the manufacturer, Process Systems & Components, Inc, Salt Lake City, UT, 84103, USA.

Nanoparticle generator: Harvard Versatile Engineered Nanomaterial Generation System (VENGES)

In this study, the Harvard VENGES (Demokritou et al. 2010) was used to generate the test aerosols. VENGES uses a flame spray pyrolysis (FSP) method (Madler et al. 2002) to generate ENPs. FSP is one of the most widely used industry methods for the generation of metal and metal oxide ENPs (Pratsinis 2010). Above 90 % by volume of the engineered nanomaterials in the market today are made using flame reactors (Pratsinis 1998).

Figure 1 illustrates the VENGES. A flammable liquid precursor, containing dissolved organometallic compounds, is pumped through a stainless-steel capillary tube. Immediately surrounding the capillary tube is a narrow annular gap of adjustable cross-sectional area that supplies oxygen, which is used to disperse the liquid precursor into fine droplets. A small pilot flamelet (premixed CH₄ and O₂ at 1 and 2 L/min, respectively) ignites the droplets so that the organic parts of the precursor molecules combust, while the metal atoms are oxidized, and form particles that grow by coagulation and sintering in the flame. In this study, a SiO₂ aerosol with a primary particle size of 15.4 nm was generated by the FSP of a

precursor solution consisting of hexamethyldisiloxane in ethanol (0.5 M) with a feed rate of 5 mL/min that was dispersed by oxygen with a feed rate of 5 L/min.

Filtration test setup

The layout of the specially designed filter test system is shown in Fig. 2. Filters were installed in a filter holder (F1 closed face filter holder, 47 mm D, BGI). Generated nanoparticles were diluted with HEPA-filtered air and passed through filter samples with areas of 17.34 cm² at two filtration face velocities [2.3 m/min (3.83 cm/s) and 3.5 m/min (5.83 cm/s)]. The recommended velocity range for woven-fabric baghouses is 0.3–3 m/min (1–10 ft/min) and for nonwoven baghouses is 1.5–3.7 m/min (5–12 ft/min) (Danielson 1973); the 2.3 m/min face velocity is thus within the recommended velocity range for baghouses using woven and nonwoven (felted) fabric filters and the 3.5 m/min face velocity is within the range recommended for nonwoven fabric filters.

Airflow meters were installed to monitor the velocity and airflow was adjusted by several adjustable switches installed inline. All tubing [6.35 mm (0.25 in.)] National Pipe Thread (NPT) and connectors (standard compression fittings) were stainless steel. Concentrations were measured upstream and down-stream of the filters (see monitoring below), and aerosol particles were collected for characterization by electron microscopy. Samples were collected for short time periods, so the measured collection efficiencies and pressure drops are those of the clean fabrics; collection efficiency may improve and pressure drop increase when the fabrics are well-conditioned in actual use, but this could not be tested in this study. The nanoparticles were generated continuously during each filter test and the generator was paused and the airflow bypassed the filter for all velocity or filter changes.

Monitoring and sampling procedure

Two instruments were operated simultaneously to record particle concentrations (5 nm to 20 μ m diameter range) and size distribution every second, i.e., the Fast Mobility Particle Sizer (FMPS®) spectrometer (Model 3091, TSI) (5–560 nm, 10 L/min), and the Aerodynamic Particle Sizer (APS®) (0.5–20 μ m, 5 L/min) spectrometer (Model 3321, TSI). Normalized particle concentrations were measured upstream and downstream of the test filters; for each filter, two sets of concentration measurements over a period of 2 min (120 data points) per measurement were carried out for each upstream and downstream measurement and for each velocity. Carbon-impregnated conductive silicone tubing (2 m) was connected to the air inlet of FMPS and APS to reach measuring locations. The total particle loss in the 2-m conductive tubing was previously evaluated using sodium chloride and ambient air particles and found to be about 8–15 % as measured by FMPS. The particle concentration was not adjusted by the loss for estimating collection efficiency. None of the particles generated from the VENGES system were found to have diameters >500 nm; therefore, the APS data were not used to calculate filtration efficiency. Aerosol particles were collected on TEM grids using sampling cassettes connected to the system as shown in Fig. 2. Transmission electron microscope (TEM)-copper grids (SPI 400 mesh with a formvar/carbon film) were taped onto 47-mm-diameter polycarbonate capillary-pore membrane filters (0.2 μ m pore size). Air was drawn through the filters at 1 L/min using a calibrated personal sampling pump, and aerosol particles deposited on the grid via Brownian diffusion.

Data analysis

Particle concentration data including number, surface area, volume, mass and total concentrations recorded by FMPS were exported to excel spreadsheets for analysis. The collection efficiency of each filter was calculated for each individual channel (except the efficiency based on the total concentration) using Eq. 1.

$$E = \frac{C_u - C_d}{C_u} \times 100 \quad (1)$$

where E is filter collection efficiency (%), C_u is the upstream particle number concentration (part/cm³), C_d is the downstream particle number concentration (part/cm³).

Each concentration used in Eq. 1 was the average of repeated 2 min samples (240 data points). Collection efficiency data profiles were statistically analyzed using SPSS. The Pearson correlation coefficient (γ) analyzed how collection efficiency profiles [E vs. particle diameter (d_p)] were associated with each other, e.g., PF versus WP or WP at 2.3 m/min velocity versus at 3.5 m/min velocity, the number (N) of data used for analysis is the number of diameter channels. The correlation coefficient is a number between +1 and -1, and is interpreted as the magnitude and direction of the association between two variables. The “magnitude” is the strength of the correlation. The closer the correlation is to either +1 or -1, the stronger the correlation. If the correlation is 0 or very close to 0, there is no association between the two variables. The “direction” of the correlation interprets how the two variables are related. A positive γ value means that the two variables have a positive relationship (as one increases, the other also increases), while a negative γ value means that the two variables have a negative relationship (as one increases, the other decreases). The paired sample t test analyzed the mean collection efficiency (E_{mean}) of the analyzed particle diameters. The p value measured the significance of the difference between the two E_{mean} values; a p value <0.05 means the compared efficiency profiles are significantly different. Analysis was applied to all 16 sets of efficiency data; data obtained at the same velocity were deemed “a group”, the analysis of efficiency profiles across two velocities was called “between groups” comparison, and the analysis of efficiency profiles at the same velocity was called “within group” comparison. In addition, data in the full range of particles sizes were used to calculate overall number, surface area, and volume collection efficiencies.

Sample characterization methods

Electron microscopy for filter and in-line aerosols analysis—Sampled particles were characterized using either a Philips EM400 TEM (Eindhoven, The Netherlands) operated at 100 kV or a Topcon 002B HRTEM (Tokyo, Japan) operated at 200 kV. Filter structure (pre- and post-test) and particle loading (post-test) were analyzed using a field emission scanning electron microscope (JEOL, JSM-7401F operated at accelerating voltages of 0.8–15 kV). The STEM images were obtained using a transmitted electron detector (TED) attachment to the scanning electron microscope and with the microscope operated at an accelerating voltage of 20 kV.

Off-line characterization of generated ENPs—The VENGENS generated particles are collected using a water-cooled, stainless-steel filter housing (Fig. 1) supporting a glass fiber filter (Whatman GF6, 25.7 cm in diameter), with exhaust gases drawn by a vacuum pump (Busch, Seco SV 1040C). Collected particles can be extracted from the filter as nanopowder, and used for off-line physico-chemical and morphological characterization. Off-line ENP characterization included N₂ adsorption (5-point isotherm, Micromeritic Tristar). ENP Samples were degassed under vacuum at 150 °C for 1.5 h. The average primary particle diameter (d_{BET} , in nm) was estimated from their specific surface area (SSA, in m²/g) measured for a given sample via the equation $d_{\text{BET}} = 6,000/(\rho \cdot \text{SSA})$, where ρ was the material's density (in g/cm³). The morphology of the generated ENPs was evaluated by transmission electron microscopy and scanning transmission electron microscopy (STEM, Tecnai F30). The samples were dispersed in ethanol and then placed on a carbon-coated copper grid, a typical STEM image is shown in Fig. 1a of the Appendix.

Porosity—Filter porosity was analyzed using a Quantachrome PoreMaster 33 mercury intrusion porosimeter, with data collected over a single intrusion/extrusion cycle. Filter samples were analyzed in glass cells with 0.5 cm³ stem volumes, with sample size of squares ~1 cm by 1 cm. The contact angle and surface tension of the mercury were set to the default values of 140° (on intrusion and extrusion) and 480 ergs/cm², respectively. For each sample, low pressure (pneumatic) data were taken from the minimum starting pressure of ~1.4 kPa (0.2 lb/in²) up to 345 kPa (50 lb/in²), with all low pressure data corrected versus a low pressure blank run to minimize artifacts at the low starting pressures used. High pressure data were taken from 140 kPa (20 lb/in²) up to 230,000 kPa (33,000 lb/in²), after which the two data sets were automatically merged using Quantachrome Poremaster for Windows 5.10; data from the intrusion cycle was used for calculation of average (volume median) pore size and pore size distribution in all cases. The overall range of analytical pressures used (~1.4 to 230,000 kPa) corresponded to an overall pore size range of ~1.1 mm to ~6.5 nm.

Pressure drop—The pressure drop across each filter at both filtration velocities was measured by attaching a Dwyer inclined-vertical manometer across the upstream and downstream TEM sampling ports (Fig. 2). The pressure drop across the filter housing with no filter sample mounted was subtracted from the measured pressure drops to determine the actual pressure drop across each filter sample. The pressure drops were measured when the filters were new, and did not increase appreciably during the relatively short periods of particle collection used here.

Results and discussion

Studied aerosols

The typical aerosol particle size distributions generated by the VENGES system for testing filter media at 2.3 and 3.5 m/min face velocity are shown in Fig. 3. Typically, when nanoparticles are dispersed as aerosols they form agglomerates instead of the single particles in the primary size. This was consistently seen for SiO₂ particles produced by the VENGES system, and the mode of such agglomerates was about 100 nm for this study. The particle concentrations of up to 2×10^6 particles/cm³ at a particle diameter of 100 nm were sufficient to allow the calculation of collection efficiency >99 % for the high efficiency sampling filters at 2.3 m/min face velocity. The same sampling period, 120 s, was used for every test at downstream and upstream to provide a stable number of particles passing through the filters. The size range cut-off used to calculate size-specific collection efficiency was selected such that each size range contained at least 90 % of the particles in the peak of the size distribution, which gave a range of 29- to 191-nm diameters for which collection efficiencies were calculated.

Performance of filter collection efficiency

Collection efficiencies of all filters using metrics of number in each size channel of 29–191 nm, total number, total surface area, and total volume of 5–560 nm are presented in Table 1. The total collection efficiencies were calculated based on the total particle count by FMPS (5–560 nm). Rengasamy et al.'s (2011) study suggests that a particle number-based test method would be more applicable to reasonably ensure a certain level of filtration performance for a wide size range of particles including nanoparticles. The collection efficiencies at two velocities based on number concentration over the chosen aerosol diameters are shown in Fig. 4. As shown in Table 1, the coated fabric filters, WP-TMC, PF-TMC, and PF-G, increased collection efficiencies by 20–30 % points versus the uncoated PF fabric filter and by 46 % points versus the uncoated WP filter, resulting in a collection efficiencies >95 % for the Teflon membrane-coated (TMC) fabric filters.

The collection efficiency based on total particle counts gave different results compared to average (mean) collection efficiency across the 29–191 nm channels due to the inclusion of the full FMPS size range of 5–560 nm. The efficiency of the sampling filters (quartz and A/E) increased for the full size range at 2.3 m/min face velocity, which indicates that the filters had higher collection efficiency for particle sizes above 191 nm and below 29 nm, but this increase was not seen at the 3.5 m/min face velocity. On the other hand, the efficiency of non-coated fabric filters tended to decrease for the full size range at both face velocities. However, the coated filters showed comparable collection efficiencies for the full size range and the selected size range and for both face velocities. The collection efficiency at 2.3 m/min was higher than at 3.5 m/min for all filters (except A/E); this was likely due to a longer residence time through the filtration region, giving more time for particles entrapment due to Brownian diffusion. At 2.3 m/min, for all fabrics except WP–TMC (which had a very high collection efficiency), the collection efficiency based on total number was higher than surface area, which was higher than volume; this indicates that the larger particles were collected with lower efficiency than the smaller ones, which is consistent with Fig. 4a. This trend was reversed at the higher velocity for all fabrics except PF–TMC; this indicates that impaction was relatively more important at this velocity, as larger particles were collected preferentially. In general, the differences among number, surface area, and volume collection efficiencies were not great, indicating that collection efficiency did not vary greatly with particle size; this result is consistent with the relatively flat size-dependent collection efficiencies shown in Fig. 4.

Statistical analysis of variability and similarity of filter performance

Collection efficiency data profiles were analyzed using statistical tools as introduced in the “Materials and methods”, “Data analysis”, to support and validate the results; the Pearson correlation and t test were used to statistically analyze data profile and the collection efficiency mean, respectively. The collection efficiency (number concentration) mean of each filter is shown in the “ $E_{\text{mean}}\%$ ” column in Table 1. Statistical results of the efficiency profile of E_{mean} , “within group” comparison (correlation and t test), among eight filters tested at the same face velocity are shown individually with superscript letters linked to the number collection efficiency data in Table 1. Statistical results of the efficiency profile comparison “between groups”, i.e., collection efficiency data obtained at 2.3 and 3.5 m/min velocities, are shown in the column entitled “ γ & t test” in Table 1.

Within group comparison

For the correlation among the eight filters within the group (in group), correlated filters are shown with the same superscript letter to indicate the same associated direction of particle collection corresponding to particle diameter. Quartz and AE filters were correlated to each other in group, noted with superscript “a”, but not with other filters within the group; a result that was consistently seen for both face velocities. Regarding other fabrics, for the 2.3 m/min face velocity, PF–TMC was correlated with PFG, noted with superscript “b” in Table 1a, and PF was correlated with WP, noted with superscript “c”, but they were not correlated with other filters within the group. For the 3.5 m/min face velocity, none of the fabric filters showed correlation with each other as shown in Table 1b.

When two efficiency profiles have a positive association, these two profiles can have values that differ in magnitude. Thus, the t test was used to test the magnitude of similarity. Regarding the significant difference among membrane-coated fabric filters (WP–TMC, PF–TMC, and PF–G), paired t test tested fibers are noted with superscript “t” in Table 1a, b, and results are noted below the table. When tested at the 2.3 m/min face velocity, t test values of the profile of E_{mean} (Table 1a) showed that there was no significant difference between the woven polyester (WP–TMC) filter and nonwoven (PF–TMC) filters with Teflon membrane

coatings ($p > 0.05$), and the Teflon membrane coating provided significantly higher collection efficiency than the Goretex membrane coating for the PF filter ($p < 0.01$). In other words, the two TMC filters provided higher collection efficiencies than the Goretex coated filter at the 2.3 m/min velocity. When tested at the 3.5 m/min face velocity, the WP-TMC, PF-TMC, and PF-G profiles of E_{mean} were all significantly different from each other ($p < 0.05$) (Table 1b), and the WP-TMC filter gave the highest collection efficiency.

Between group comparisons

The result regarding the correlation of efficiency profiles at different velocities using the same filter material are shown with γ value in “ γ & t test” column of Table 1a, b. The result indicated that the PF-TMC, PF, and WP filters but not others were alone in showing significant correlation at different velocities, indicating that such filter media gave the same associated direction of collection efficiency profile as a function of particle diameters. Quartz and A/E filters showed low correlation (low γ), but their collection efficiency data were not significantly different with a high p value resulting from the t test for both two different face velocities. The other six filter media were all significantly different with p values at 0.01 levels for two velocities and including the high correlated filters of PF-TMC, PF, and WP when used at the two test velocities. In other words, these filters’ efficiencies had different magnitudes, but the efficiency change versus the filtered particle diameter was in the same direction.

The correlation analysis results noted in Table 1a shows high correlations for quartz and AE, PF-TMC and PFG, PF and WP. As shown in Fig. 4, collection efficiency of these high correlated filters at the 2.3 m/min face velocity mostly was inversely proportional to particle diameter < 50 nm except the A/E filter. Therefore, the reduced efficiency of the A/E filter at particle diameters < 50 nm at the 2.3 m/min velocity might be due to experimental error as the collection efficiency profile of the AE filter was statistically tested and had a statistically significant high correlation ($\gamma > 0.9$) to the quartz filter. The trend of increased efficiency at diameter < 50 nm was not seen on most filters at the 3.5 m/min face velocity. The most dominant filtration mechanism for nanoparticles is Brownian diffusion, and the smaller the particle size the more Brownian diffusion will dominate the filtration mechanism (Hinds 1999). The higher velocity would reduce the particle residence time in the filter, thus reducing the chance for collection by diffusion. The stability of filtration performance at 2.3 m/min velocity is high for aerosols in the range of 29–191 nm. The WP-TMC filter tested at 3.5 m/min showed substantially reduced stability, while the nonwoven felted filters (PF-TMC, PF-G, and PF) gave comparable stability.

Material characterization and filter performance

The filter media were carefully characterized according to selected physical properties including fabric thickness, fabric weight, pressure drop, SSA, pore volume, and volume median pore size. Characterization results of all cleaned filter media and physical properties of selected filter media are shown in Table 2. Filter thickness and weight vary over a broad range; nonwoven fabrics were the thickest while the Teflon membrane coated and FP filter were the thinnest. WP filters had thicknesses in the same range as the quartz and A/E filters, but the weight was much reduced and the pressure drop was much lower than for the sampling filters. The SSA of the filters tended to increase when moving from clean to used filters for three filters whose SSA were measured, as shown in Table 2. The quartz filter consists solely of thin fibers and thus as expected has the highest SSA ($> 4 \text{ m}^2/\text{g}$), which is an order of magnitude higher than the SSA of WP-TMC and WP filters.

The particle collection time of all filters was the same so that comparable amounts of particles were collected by every filter. The SSA of the used WP-TMC filter increased

about $0.25 \text{ m}^2/\text{g}$ which was 74 % higher than the clean WP-TMC filter, from 0.34 to $0.59 \text{ m}^2/\text{g}$, and a similar increase in SSA was observed (about 19 % from 0.27 to $0.32 \text{ m}^2/\text{g}$) for the WP filter following use. On the other hand, the collected particles resulted to a $0.1\text{--}0.2 \text{ m}^2/\text{g}$ SSA increase which would be barely detected on a high SSA filter media, thus, the collecting time for such filter needs to be extended to obtain a significant SSA increase. Therefore, the SSA change between clean and used quartz, which was about a 3 % reduction, may not be significant due to the high overall surface area and could be due to a random variation between the measured areas. These increases are only observed when performing high pressure mercury intrusion pressures; the low pressure mercury intrusion data show no significant differences in the SSAs of the new and used filters, indicating that this difference comes from the presence of very fine pores or interstices between particles and consistent with nanoparticle entrapment in the filters.

In general, for fabrics the penetration can be expected to correlate directly with fiber diameter, pore volume, pore size, porosity, and air permeability and inversely with fabric thickness (Gao et al. 2011). The pore volume and pore size obtained in this study could not be correlated with filter efficiency. The fabric thickness affects the particle residence time, i.e., the thicker the fabric the longer the particle residence time. The FP woven filter was thinner than the other woven filters, and gave the lowest collection efficiency under all conditions. In addition, uncoated woven fabrics such as the FP and WP tested in this study have large openings in their weave when new and are known to have very low collection efficiency until a dust layer is created on the surface of the filter (Strauss 1975); this is consistent with the results found in this study. The uncoated PF had a much higher collection efficiency, which is expected as felted fabrics rely on in-depth particle collection on individual fibers rather than the formation of a dust cake and thus should have high initial collection efficiencies when compared to woven fabrics. This study has shown that fiber diameter plays an important role by demonstrating the strong influence of thin fiber diameter for collecting nanometer and submicrometer particles through Brownian diffusion. As Brownian diffusion is the dominant filtration mechanism for nanoparticles, collection efficiency should not be affected by the particle density (Kim et al. 2007). Therefore, similar results are predicted when nanoparticles of different densities are collected in the filter media studied here.

In-line aerosol samples collected upstream and downstream of tested filters were analyzed by TEM. No silica ENPs were found on the downstream side of the high efficiency sampling filters and the coated fabric filters. In contrast, many small ENP agglomerates were seen on the downstream side of the non-coated fabric filters with typical particles (TEM image is shown in Fig. 1b of Appendix) showing similar morphology to particles seen on the SEM images of used filters. Silica ENPs generated by VENGES were also collected for off-line characterization, the results indicating a SSA for the SiO_2 nanoparticles of $177 \text{ m}^2/\text{g}$, corresponding to an average SiO_2 primary particle size of 15.4 nm with agglomeration clearly visible in STEM images as shown in Appendix.

The structures of the filter media and their collected nanoparticles were characterized by SEM. Typical structures for all studied filter media are shown in Fig. 5. All used filters shown in Fig. 5 were tested at the 2.3 m/min filtration velocity; the collection duration for each filter was $\sim 14 \text{ min}$, which was the total time of four measurements following the protocol. The aerosol concentration is shown in Fig. 3. The quartz filter consists of a single type of thin fibers organized in a three-dimensional network as the representative structure of sampling filter (image A1 in Fig. 5); ENPs were seen to be captured on the fibers (A2). The membrane coating layer consists of thin fiber structure attached to the top of fabric fibers. The Teflon membrane applied on the WP fiber (WP-TMC) showed a condensed and uniform structure of thin Teflon fibers which were braided and connected with nodes

(B1), while the Teflon membrane applied on the PF fiber (PF-TMC) showed more randomly braided Teflon fibers (D1). Both WP-TMC and PF-TMC fabric filters were fully covered by the Teflon fibers and both Teflon layers collected many NPs. The thinner these fibers the more NPs were collected (B2, D2), which is consistent with filtration theory. The woven fabric filter (WP) shows bundles of woven fibers (C1) while the nonwoven (felted) filter (PF) shows fibers in a three-dimensional network structure (F1, F2). The Goretex membrane coating (E1) applied on the PF filter showed a much more open structure having many large nodes randomly mixed with Goretex fibers, and the felted fibers underneath the Goretex membrane layer were obvious in some areas. The used PF-G filter was able to collect many NPs on the Goretex fibers as well (E2).

Pressure drop and efficiency

Measured pressure drops and collection efficiency for the eight tested filters at the two filtration velocities are listed in Table 3. The results are in general agreement with filtration theory, which predicts that higher velocity results in higher pressure drop and lower collection efficiency. Comparing the two air sampling filters to the six fabric filters, the air sampling filters have considerably higher pressure drop, which is not surprising as air sampling filters are optimized for collection efficiency with little concern for the resulting pressure drop. Fabric filters, on the other hand, must be designed to have both high collection efficiency and low pressure drop. Looking at the data for the uncoated fabrics, the two woven fabrics (WP, FP) have much lower pressure drops than the felted fabric (PF). This is expected, as the woven fabrics consist of a single layer of threads and the felt consists of random fibers in a thicker layer. In addition, it is expected that the coated version of a fabric would have a higher pressure drop than its uncoated counterpart; this was found for both the PF and the woven polyester materials. Among the coated fabric filters, the PF with a Teflon membrane coating (PF-TMC) had the highest pressure drop, with values approaching those measured for the two air sampling filters.

Conclusions

All filters had higher collection efficiency at the lower filtration velocity. The highest efficiency (>99.5 %) was obtained using the quartz filter, followed by the glass fiber filter. The performance of coated fabric filters was found to have a high variation between 50 and 96 % efficiency; similar variation was seen for the uncoated fabric filters. A significant increase in collection efficiency was seen for coated fabric filters when compared to uncoated fabric filters. When tested at two velocities, both sampling filters maintained comparable performance according to the statistical analysis. In contrast, the performance of the fabric filters was significantly different under the different filtration velocities tested.

The sampling filters were designed to provide high collection efficiency under various conditions, and consistent results were seen in this study. On the other hand, environmental fabric filters gave much lower nanoparticle collection efficiency when operated under certain conditions. The 2.3 m/min filtration velocity is within the recommended range for both woven and nonwoven baghouse filters and was found to be an effective filtration velocity for all of the fabric filters tested in this study. According to the recommended velocity range for woven fabrics, the operating velocity would typically be below 2.3 m/min and theoretically the efficiency would be increased. The filter media in each category showed unique performance characteristics. Coating layers such as Teflon and Goretex membrane, as expected, were found to have a major influence on fabric performance. Membrane layers constructed with more condensed and uniform thin fibers as seen in the Teflon membrane of WP and PF filters were able to successfully capture many silica nanoparticles and provided about 95 % overall collection efficiency. In addition, the woven filters such as WP-TMC gave the best performance rating based on their low pressure drop

operation, making them suitable for long-term use and lower energy consumption in the industry, especially given their light weight and low thickness. In addition to fiber diameter, the structure of the membrane plays an important role. While the Goretex membrane was seen to collect many nanoparticles, however, the Goretex membrane was not evenly coated on to the felted fibers, allowing nanoparticles to pass more easily through areas where fewer membrane fibers were present. For the uncoated fabric filters, the performance in capturing nanoparticles was low, as expected. Felted filters (PF) gave higher collection efficiencies than woven filters, with the three-dimensional structure of the felted fabric increasing the likelihood of capturing nanoparticles by diffusion, consistent with other studies published in the past (Bergmann 1979; Culhane 1974).

The collection efficiency of nanometer and submicrometer particles can be influenced by many filtration factors including filtration velocity, filter thickness, membrane coating, fiber diameter, pore size, pore volume, and porosity. In addition, the particle physical properties such as shape, size, and charge distribution, agglomeration and surface area can influence the filter performance and require further research beyond this study. It is clearly seen from this study that an environmental fabric filter with a proper membrane coating such as the Teflon membranes described here can operate at very low pressure drop and give over 95 % of collection efficiency for nanometer and submicrometer particles. A multi-filtration system using coated fabric filters as the primary filtration mechanism to be supplemented by a high efficiency filter such as a HEPA filter or sampling filters could be a practical and economic strategy for workplaces where significant amounts of nanometer and submicrometer particles are emitted from production processes.

Acknowledgments

Authors would like to acknowledge the financial support from the Nanoscale Science and Engineering Centers for High-rate Nanomanufacturing (CHN) funded by the National Science Foundation (Award No. NSF-0425826), the NIEHS Grant (ES-0000002), the Center for Nanotechnology and Nanotoxicology at Harvard School of Public Health, the Program of Research Education for Undergraduate students associated with CHN, the Swiss National Science Foundation (Grant No. 200020-126694) and the European Research Council.

Appendix: environmental filtration control of engineered nanoparticles

See Fig. 6

References

- Balazy A, Podgorski A, Gradon L. Filtration of nanosized aerosol particles in fibrous filters. I—experimental results. *J Aerosol Sci.* 2004; 35(2):967–980.
- Bergmann L. Needled felts for fabric filters. *Environ Sci Technol.* 1979; 13(12):1472–1475.
- Brown, RC. Air filtration—an integrated approach to the theory and applications of fibrous filters. Pergamon Press; New York: 1993.
- Culhane FR. Fabric filters abate air emissions. *Environ Sci Technol.* 1974; 8(2):127–130.
- Danielson, JA. Air pollution control equipment for particulate matter, Air pollution engineering manual, AP-40. US Environmental Protection Agency; Research Triangle Park, NC: 1973. p. 91-168.
- Demokritou P, Büchel R, Molina RM, Deloid GM, Brain JD, Pratsinis SE. Development and characterization of a versatile engineered nanomaterial generation system (VENGES) suitable for toxicological studies. *Inhalation Toxicol.* 2010; 22:107–116.
- Gao P, Jaques PA, Hsiao TC, Shepherd A, Eimer BC, Yang M, Miller A, Gupta B, Shaffer R. Evaluation of nano- and submicro particle penetration through ten nonwoven fabrics using a wind-driven approach. *J Occup Environ Hyg.* 2011; 8(1):13–22. [PubMed: 21154104]

- Golanski, L.; Guillot, A.; Tardif, F. Efficiency of fibrous filters and personal protective equipments against nano-aerosols. Nanosafe Dissemination Report, DR-325/326-200801-1, Project ID-NMP2-CT-2005-515843. 2008. Nanosafe2 project website: <http://www.nanosafe.org>
- Golanski L, Guiot A, Rouillon F, Pocachard J, Tardif F. Experimental evaluation of personal protective devices against graphite nanoaerosols: fibrous filter media, masks, protective clothing, and gloves. *Hum Exp Toxicol*. 2009 doi: 10.1177/0960327109105157.
- Golanski L, Guiot A, Tardif F. Experimental evaluation of individual protection devices against different types of nanoaerosols: graphite, TiO₂, and Pt. *J Nanopart Res*. 2010 doi: 10.1007/s11051-009-9804-x.
- Heim M, Mullins BJ, Wild M, Meyer J, Kasper G. Filtration efficiency of aerosol particles below 20 nanometers. *Aerosol Sci Technol*. 2005; 39:782–789.
- Hinds, WC. Wiley-Inter-science; New York: 1999. Aerosol technology—properties, behavior, and measurement of airborne particles.
- Japuntich DA, Franklin LM, Pui DY, Kuehn TH, Kim SC, Viner AS. A comparison of two nano-sized particle air filtration tests in the diameter range of 10 to 400 nanometers. *J Nanopart Res*. 2007; 9:93–107.
- Kim SC, Harrington MS, Pui DYH. Experimental study of nanoparticles penetration through commercial filter media. *J Nanopart Res*. 2007; 9:117–125.
- Madler L, Kammler HK, Mueller R, Pratsinis SE. Controlled synthesis of nanostructured particles by flame spray pyrolysis. *J Aerosol Sci*. 2002; 33:369–389.
- Ma-Hock L, Treumann S, Strauss V, Brill S, Luizi F, Mertler M, Wiench K, Gamer AO, van Ravenzwaay B, Landsiedel R. Inhalation toxicity of multiwall carbon nanotubes exposed in rats for 3 months. *Toxicol Sci*. 2009 doi:10.1093/toxsci/kfp146.
- Neundorfer Particulate Knowledge Baghouse/Fabric Filters KnowledgeBase. [Accessed Sep 2011] 2011. http://www.neundorfer.com/knowledge_base/baghouse_fabric_filters.aspx
- Pall Corporation Glass Fiber filters, Pall product brochure. [Accessed Sep 2011] 2011. http://labfilters.pall.com/catalog/laboratory_20027.asp
- Poland CA, Duffin R, Kinloch I, Maynard A, Wallace WAH, Seaton A, Stone V, Brown S, MacNee W, Donaldson K. Carbon nanotubes introduced into the abdominal cavity of mice show asbestos-like pathogenicity in a pilot study. *Nat Nanotechnol*. 2008 doi:10.1038/nnano.2008.111.
- Pratsinis SE. Flame aerosol synthesis of ceramic powders. *Prog Energy Combust Sci*. 1998; 24:197–219.
- Pratsinis SE. Aerosol-based technologies in nano-scale manufacturing: from functional materials to devices through core chemical engineering. *AIChE J*. 2010; 56:3028–3035.
- Rengasamy S, King WP, Eimer BC, Shaffer RE. Filtration performance of NIOSH-approved N95 and P100 filtering facepiece respirators against 4 to 30 nanometer-size nanoparticles. *J Occup Environ Hyg*. 2008; 5:556–564. [PubMed: 18607812]
- Rengasamy S, Eimer BC, Shaffer RE. Comparison of nanoparticle filtration performance of NIOSH-approved and CE-marked particulate filtering facepiece respirators. *Ann Occup Hyg*. 2009; 53:117–128. [PubMed: 19261695]
- Rengasamy S, Eimer B, Shaffer RE. Simple respiratory protection—evaluation of the filtration performance of cloth masks and common fabric materials against 20–1000 nm size particles. *Ann Occup Hyg*. 2010; 54:789–798. [PubMed: 20584862]
- Rengasamy S, Miller A, Eimer BC. Evaluation of the filtration performance of NIOSH-approved N95 filtering facepiece respirators by photometric and number-based test methods. *J Occup Environ Hyg*. 2011; 8:23–30. [PubMed: 21154105]
- Ryman-Rasmussen JP, Cesta MF, Brody AR, Shipley-Phillips JK, Everitt JJ, Tewksbury EW, Moss OR, Wong BA, Dodd DE, Andersen ME, Bonner JC. Inhaled carbon nanotubes reach the subpleural tissue in mice. *Nat Nano-technol*. 2009; 4:747–751.
- Shaffer RE, Rengasamy S. Respiratory protection against airborne nanoparticles: a review. *J Nanopart Res*. 2009; 11:1661–1672.
- Shvedova AA, Kisin ER, Mercer R, Murray AR, Johnson VJ, Potapovich AI, Tyurina YY, Gorelik O, Arepalli S, Schwegler-Berry D, Hubbs AF, Antonini J, Evans DE, Ku BK, Ramsey D, Maynard A, Kagan VE, Castranova V, Baron P. Unusual inflammatory and fibrogenic pulmonary responses to

- single-walled carbon nanotubes in mice. *Am J Physiol Lung Cell Mol Physiol*. 2005 doi: 10.1152/ajplung.00084.2005.
- Shvedova AA, Kisin ER, Murray AR, Johnson VJ, Gorelik O, Arepalli S, Hubbs AF, Mercer R, Keohavong P, Sussman N, Jin J, Yin J, Stone S, Chen BT, Deye G, Maynard A, Castranova V, Baron PA, Kagan VE. Inhalation vs. aspiration of single-walled carbon nanotubes in C57BL/6 mice: inflammation, fibrosis, oxidative stress, and mutagenesis. *Am J Physiol Lung Cell Mol Physiol*. 2008 doi:10.1152/ajplung.90287.2008.
- Sotiriou GA, Diaz E, Long MS, Godleski J, Brain J, Pratsinis SE, Demokritou P. A novel platform for pulmonary and cardiovascular toxicological characterization of inhaled engineered nanomaterials. *Nanotoxicology*. 2011 doi: 10.3109/17435390.2011.604439.
- Strauss, W. Industrial gas cleaning. Pergamon Press; New York: 1975.
- Takagi A, Hirose A, Nishimura T, Fukumori N, Ogata A, Ohashi N, Kitajima S, Kanno J. Induction of mesothelioma in p53 $\pm$ mouse by intraperitoneal application of multi-wall carbon nanotube. *J Toxicol Sci*. 2008; 33:105–116. [PubMed: 18303189]
- VanOsdell DW, Liu BYH, Rubow KL, Pui DYH. Experimental study of submicrometer and ultrafine particle penetration and pressure drop for high efficiency filters. *Aerosol Sci Technol*. 1990 doi: 10.1080/02786829008959403.
- Whatman GE Healthcare Whatman Filter, Air Sampling Filters and Quartz Filters. [Accessed Sep 2011] 2011. <http://www.whatman.com/AirSamplingandQuartzFilters.aspx>

Fig. 1.

The Harvard VENES. Nanostructured materials are generated by FSP of organometallic precursors. The as-prepared nanoparticles can be collected on a glass fiber filter for ex situ characterization and in situ providing a stable aerosol for toxicological or other characterization

Fig. 2.
Filtration test system

Fig. 3. Particle size distribution and concentration generated by VENGEs. Primary Y-axis: upstream concentration at 2.3 m/min filtration face velocity; secondary Y-axis: upstream concentration at 3.5 m/min filtration face velocity

(a) Six filters tested at 2.3 m/min filtration velocity.

(b) Six filters tested at 3.5 m/min filtration velocity

Fig. 4.

Particle number collection efficiency versus particle diameter. **a** Six filters tested at 2.3 m/min filtration velocity, **b** six filters tested at 3.5 m/min filtration velocity. *Note Hollow symbol* air sampling filters, *solid symbol* coated air cleaning filter, *times symbol* is non-coated air cleaning filter

Quartz new, x1,000

Quartz used, x20,000

WP-TMC used, x200

WP-TMC used, x20,000

WP used, x150

WP used, x10,000

Fig. 5.

SEM images of various filter media and captured nanoparticles. **A1** Quartz-new filter, **A2** quartz-used filter with NPs on fibers, **B1** WP-TMC—used filter showing Teflon membrane layer above the woven fibers at the cut edge, **B2** WP-TMC—used filter with NPs on Teflon fibers, **C1** WP—used filter showing woven fibers, **C2** WP used woven fibers with NPs on thin fiber, **D1** PF-TMC new filter showing Teflon membrane layer, **D2** PF-TMC—used filter with NPs on Teflon fibers, **E1** PF-G—new filter showing Goretex membrane layer above the nonwoven fibers, **E2** PF-G—used filter with NPs on Goretex fibers, **F1** PF-TMC

—new filter showing the PF nonwoven fiber layer, **F2** PF–TMC—used filter showing 3D structure of felt fibers

Fig. 6. STEM images. *Note* Aerosol silica nanoparticles, TEM image of nanoparticles in the airstream post PF filter shown (a); STEM image of silica nanoparticle shown (b)

Table 1

Filter media collection efficiency (E)

Collection efficiency (number %) Analysis by channel, 29–191 nm			Collection efficiency (%) Analysis of total count, 5–560 nm		
E_{mean} %	γ and t test result, association with 3.5 m/min data	STD	Volume	Surface area	Number
(a) E % at 2.3 m/min face velocity					
Quartz	98.3 ^a	0.123, $p > 0.05$	3.3	99.9	99.7
A/E	92.0 ^a	0.165, $p > 0.05$	13.8	99.7	99.7
WP-TMC	96.2 ^t	0.284, $p < 0.01$	1.3	97.0	96.9
PF-TMC	95.8 ^{b,t}	0.842 ^{**} , $p < 0.01$	2.4	93.7	94.4
PF-G	86.6 ^{b,t}	−0.590, $p < 0.01$	6.5	81.1	82.6
PF	64.4 ^c	0.912 ^{**} , $p < 0.01$	14.2	52.4	53.2
WP	49.8 ^c	0.989 ^{**} , $p < 0.01$	4.5	46.1	46.5
FP	36.2	−0.798 ^{**} , $p < 0.01$	5.3	31.3	32.6
(b) E % at 3.5 m/min face velocity					
Quartz	95.2 ^a	0.123, $p > 0.05$	4.9	94.7	94.3
A/E	94.4 ^a	0.165, $p > 0.05$	4.2	94.1	93.4
WP-TMC	74.1 ^t	0.284, $p < 0.01$	14.9	85.0	79.5
PF-TMC	51.0 ^t	0.842 ^{**} , $p < 0.01$	5.5	47.8	49.0
PF-G	65.1 ^t	−0.590, $p < 0.01$	1.3	65.7	65.8
PF	42.1	0.912 ^{**} , $p < 0.01$	10.1	34.2	35.7
WP	27.8	0.989 ^{**} , $p < 0.01$	2.9	25.7	26.0
FP	25.4	−0.798 ^{**} , $p < 0.01$	3.6	27.7	27.4

E_{mean} % is the mean of number collection efficiency from channels of 29–191 nm. $N = 14$

Superscript alphabet a, b, c are correlation results of “within group” comparison: Number collection efficiencies were statistically analyzed for the Pearson correlations among 8 filters within the same velocity groups (2.3 m/min and 3.5 m/min). The efficiency numbers which share the same alphabet have high positive correlation ($\gamma > 0.9$) to each other with significance at the 0.01 level

Superscript t means that the paired t-test for “within group” comparison was tested, results showed that (a) at 2.3 m/min velocity, WP-TMC and PF-TMC were not significantly different ($p = 0.64$), and PF-TMC and PF-G are significantly different ($p < 0.01$) and (b) at 3.5 m/min velocity, WP-TMC to PF-TMC and PF-TMC to PF-G are significantly different ($p < 0.01$), WP-TMC to PF-G are significantly different ($p < 0.05$)

γ & t test: Result of “between groups” comparison, Pearson correlation coefficient (γ) gives the correlation of collection efficiency and p value of t test gives the significant difference for each filter type between two groups of 2.3 m/min and 3.5 m/min face velocity using number collection efficiency. $N = 14$

*** Correlation is significant at the 0.01 level (2-tailed)

Table 2

Filter media characterization results

Filter group	Material name	Structure	Thickness ^a (μm)	Weight ^b (mg)	SSA ^c (m^2/g)	Pore volume ^d (cm^3/g)	Volume median pore size ^d (μm)	ΔP^e (cm H ₂ O)	
								2.3 m/min	3.5 m/min
Sampling filter	Quartz	Fine fiber	616 $\pm$ 18	148	4.96, 4.82 (down 3 %)	6	55	6.1	10.2
	A/E	Fine fiber	470 $\pm$ 19	129	–	–	–	4.1	7.1
Coated fabric	WP-TMC	Woven fabric + Teflon fiber layer	679 $\pm$ 26	566	0.34, 0.59 (up 74 %)	1.2	30	1.5	3.6
	PF-TMC	Nonwoven fabric + Teflon fiber layer	2,690 $\pm$ 42	817	–	–	–	4.1	9.6
Plain fabric	PF-G	Nonwoven fabric + Goretex fiber layer	2,030 $\pm$ 23	883	–	–	–	3.8	6.1
	PF	Nonwoven fiber	1,990 $\pm$ 23	775	–	–	–	2.3	5.6
	WP	Woven fiber	883 $\pm$ 26	677	0.27, 0.32 (up 19 %)	1.8	75	0.8	1.5
	FP	Woven fiber	352 $\pm$ 21	381	–	–	–	1.3	2.5

^a Average of eight thickness measurements by micrometer $\pm$ one standard deviation^b Weight was measured of filter samples with an area of 17.4 cm²^c SSA data are measurements taken on cleaned and used filter samples, respectively, in an area of 1 cm²; percent changes are in parentheses^d Pore volume and volume median pore size data are for both clean and used filters taken in an area of 1 cm²^e Pressure drop (ΔP) were corrected for ΔP across the empty filter housing

Table 3

Data of pressure drop and collection efficiency at face velocities of 2.3 and 3.5 m/min for eight tested filters

	Pressure drop (cm-H ₂ O)		Collection efficiency (%)	
	V = 2.3 m/min	V = 3.5 m/min	V = 2.3 m/min	V = 3.5 m/min
Quartz	6.1	10.2	98	95
A/E	4.1	7.1	92	94
WP-TMC	1.5	3.6	96	74
PF-TMC	4.1	9.7	96	51
PF-G	3.8	6.1	87	65
PF	2.3	5.6	64	42
WP	0.8	1.5	50	28
FP	1.3	2.5	36	25