United States
Environmental Protection
Agency

EPA/600/R-08/053 | December 2008 | www.epa.gov/ord

Critical Assessment of Building Air Cleaner Technologies

FINAL REPORT

Office of Research and Development
National Homeland Security Research Center

EPA/600/R-08/053 | December 2008 | www.epa.gov/ord

FINAL REPORT ON

Critical Assessment of Building Air Cleaner Technologies

Contract No. GS-10F-0275K
Task Order 1105

to

Joseph Wood and Les Sparks
Project Officers

U.S. ENVIRONMENTAL PROTECTION AGENCY
Research Triangle Park, NC

Prepared by

Kent C. Hofacre	(614) 424-5639
Rick T. Hecker	(614) 424-7955
Anbo Wang	(614) 424-7144
Mary C. Shell	(614) 424-7219
Sara J. Lawhon	(614) 424-7376

"WARNING – This document may contain technical data whose export is restricted by U.S. law. Violators of export control laws may be subject to severe legal penalties. Do not disseminate this document outside the United States or disclose its contents to non-U.S. persons except in accordance with applicable laws and regulations and after obtaining any required authorizations."

BATTELLE COLUMBUS OPERATIONS
505 King Avenue
Columbus, Ohio 43201-2693

Office of Research and Development
National Homeland Security Research Center, Decontamination and Consequence Management Division

Table of Contents

Table of Contents

List of Tables

List of Figures

List of Acronyms

ABO	aerosols of biological origin
ADSP	Atmospheric Dust Spot Discoloration Method
AFS	American Filtration and Separations
ANSI	American National Standards Institute
APS	aerodynamic particle sizer
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
BCG	Bacillus Calmette-Guerin
Bg	*Bacillus globigii*
BLCC	Building Life-Cycle Cost Program
BTU	British thermal unit
BW	biological warfare
CADR	Clean Air Delivery Rate
CBIAC	Chemical and Biological Defense Information Analysis Center
CDC	Centers for Disease Control and Prevention
CD-ROM	Compact Disc read-only memory
cfm	cubic feet per minute
cm	centimeter
CPI	Consumer Price Index
CSEPP	Chemical Stockpile Emergency Preparedness Program
d_p	particle diameter
DHHS	U.S. Department of Health and Human Services
DOE	U.S. Department of Energy
DOL	U.S. Department of Labor
DOP	di-*n*-octyl phthalate
DTIC	Defense Technical Information Center
EAC	electronic air cleaner
ECBC	Edgewood Chemical Biological Center
EE	electrostatically enhanced
EEF	electrostatically enhanced filtration
EIA	Energy Information Administration
EMF	electret media filtration
EPA	U.S. Environmental Protection Agency
ERDEC	Edgewood Research, Development and Engineering Center
ESP	electrostatic precipitator
ETV	Environmental Technology Verification
fpm	foot (feet) per minute
h	hour

HAC	heating and air conditioning
HEPA	high efficiency particulate air
HP	horsepower
HPAC	heating, piping and air conditioning
HVAC	heating, ventilation and air conditioning
IAQ	indoor air quality
IEEE	Institute of Electrical and Electronics Engineers
IEST	Institute of Environmental Sciences and Technology
in.	inch
INTC	International Nonwovens Technical Conference
JAPCA	Journal of the Air Pollution Control Association
kV	kilovolt
KWH	kilowatt-hour
L	liter
m	meter
MECH	fibrous mechanical filter
MERV	minimum efficiency reporting value
min	minute
MLGW	Memphis Light Gas and Water
mm	millimeter
MPPS	most penetrating particle size
NBC	nuclear, biological and chemical
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Science and Technology
nm	nanometer
NSF	National Science Foundation
O&M	operations and maintenance
OSHA	Occupational Safety and Health Administration
Pa	pascal
PM1	particulate matter with a diameter less than 1 micrometers
PM5	particulate matter with a diameter less than 5 micrometers
PM10	particulate matter with a diameter less than 10 micrometers
PSL	polystyrene latex
RDECOM	Research Development and Engineering Command
RH	relative humidity
RPM	revolutions per minute
RS	Research Summary(ies)
SBCCOM	Soldier Biological and Chemical Command
sec, s	second
SIP	Structural Insulated Panel
SMPS	scanning mobility particle sizer

TB	tuberculosis
TFP	turbulent flow precipitator
TR	Technical Report
TWA	time-weighted average
ULPA	Ultra Low Penetrating Air
µm	micrometer, micron
UV	ultraviolet
UVGI	ultraviolet germicidal irradiation
V	volt
VAV	variable air volume
w.g.	water gauge
w/o	without
η	efficiency

Executive Summary

Recent events have shown that buildings and other infrastructure are vulnerable to terrorist attacks with biological agents. This report provides a review of the literature on technologies that could be used in heating, ventilation, and air conditioning (HVAC) systems to reduce contamination of a building following such an attack. There are, however, no identified "safe" levels of exposure to biological threat agents, thus it is not known the extent reduction of these particles required to provide protection to building occupants from illness or death resulting from exposure to these threat agents. This report was designed therefore to provide an evaluation of the removal efficiencies of the technology, and also to address space, power requirements, and cost factors.

The five technologies selected for critical review were deemed the most appropriate to reduce or inactivate biologically active particulate matter. Each review provides a description of the technology, a summary of the available literature, and a critical assessment that addresses technology performance, trends that affect performance, the impact of the technology on an HVAC system, and a cost analysis. The five technologies selected for review are as follows: (1) mechanical filtration, (2) electrostatically enhanced filtration, (3) electret filters, (4) electrostatic precipitation, and (5) ultraviolet germicidal irradiation (UVGI).

In general, the performance of particle removal technologies depends on the particle size. Thus, to aid the discussion of the technology reviews and critical assessments, background information regarding typical particle sizes for various types of aerosols, and particle removal concepts, are presented. In general, particles of biological origin range in diameter from less than 0.1 micron up to about 50 microns. *Bacillus anthracis* spores are between 1 and 2 microns in diameter.

This report also provides background information on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard test method 52.2 and the minimum efficiency reporting value (MERV) ratings. Air filtration technologies used in HVAC applications are tested with this method. ASHRAE 52.2 allows filters to be tested in a consistent fashion and performance ratings to be assigned. The MERV performance ratings for the various types of filters assessed are provided.

In general, the typical HVAC filtration system in a building is a relatively low efficiency mechanical filter that is intended to remove particles to keep the remainder of the HVAC system clean and to remove nuisance dust for the occupants. However, mature technologies exist to enhance particle removal without requiring extensive retrofits or significant duct modifications. Operating costs may increase because the technology is more expensive to maintain or operate.

Mechanical filters are by far the most widely used type of air cleaner for residential and commercial building HVAC systems. In general, the advantages of mechanical filters are their low cost and wide availability in a variety of sizes, types, and performance ranges. The key disadvantage of mechanical filters is that their pressure drop increases with use, thus requiring an increase in the power needed to maintain airflow and requiring replacement with a frequency that is proportional to their efficiency. Fibrous media are commonly used in mechanical filters because they can provide good filtration efficiency at a low pressure drop. The fibers are either woven into the filter frame or randomly oriented and thermally or chemically bonded to each other and to the filter frame. Particle capture using mechanical filters occurs through four primary mechanisms: (1) inertial impaction, (2) interception, (3) diffusion, and (4) electrostatic attraction.

Electrostatically enhanced filtration technology improves the performance over standard fibrous filters that rely solely on mechanical means for aerosol collection. The principle of operation is to ionize the incoming airstream and particles so that a surface charge is achieved on the incoming particles upstream of the filter. Fibrous filter media are located between a negatively charged electrode upstream and a positively charged electrode downstream. When power is applied to the electrodes, an electrical field is generated and the fibrous filter media are polarized, i.e., the fibers of the media form areas of negative and positive charge. In this manner, electrostatically enhanced filtration is similar to electret filtration (discussed next), except the fibers are not permanently charged as with electret filters.

The performance of electrostatically enhanced filtration technologies depends on several factors. Because mechanical filters are used, the performance depends on the fiber diameter and the number of fiber layers. The addition of the electrical field over the filter creates a dependence on the voltage, and performance also depends on the particle size and the face velocity through the filter.

Electrostatically enhanced filtration offers benefits over electret filters because the electrical field in the filter is less apt to degrade. Filtration efficiencies for electret and electrostatically enhanced filters are similar, although electret filters are more frequently used because they do not require electrical power. However, electrostatically enhanced filtration devices are relatively new to the market and relatively little research regarding their performance is available compared to established air cleaning technologies such as fibrous filters or electrostatic precipitators. The impact of using electrostatically enhanced technologies on an HVAC system is minimal. The pressure drops are not significantly different from what they are with other fibrous filters.

Electret filters use electrically charged media to attract particles. In contrast to the electrostatically enhanced filter, electret media are permanently charged in the course of manufacturing. Therefore, electret media do not need an electrode system to charge filter media or an ionizer to charge incoming particles during operation. Another advantage of electret media is their relatively high collection efficiency at very low pressure drops.

Electret filters collect particles using a combination of mechanical and electrostatic mechanisms. The efficiency of electret media depends on parameters such as charges on particles, charge density of fibers, and chemical compositions of particles and fibers. Efficiency also depends on mechanical factors, such as fiber diameter and packing density of the fibrous materials.

In the HVAC filtration market, electret filters are becoming increasingly popular. The electret filters used for commercial HVAC filtration generally have MERV ratings ranging from 8 to 16. The main concern with using electret filters is the effect of aerosol loading on collection efficiency. However, in spite of the collection efficiency degradation over time (primarily due to dust loading), the efficiency of an electret filter always exceeds that of an uncharged filter with the identical mechanical structure.

Electret filters have a lower pressure drop than conventional uncharged fiber filters; therefore, they can be installed into an existing HVAC filtration system without extensive modification such as the addition of an extra fan. These types of filters might require a new access door to be added to the existing unit and installation of new pressure gauges. Initial and installation costs would be inexpensive since there is no need for electric service.

Typical operating and maintenance costs are low for electrets. Maintenance includes yearly changing of not only the electret filters, but of the prefilters as well, thus increasing the maintenance costs of the typical office building somewhat. In general, however, electret filters are usually less expensive than glass fiber (mechanical) filters with the same MERV rating.

Electrostatic precipitators (ESPs) utilize particle collection technology that has been used for decades in industrial and combustion applications. Commercial and residential devices employing this technology are now widely available. With this technology, an electrical charge is imparted to incoming dust particles as they pass through an electrical field in the ionizing section. The charged particles are collected on plates of an opposite charge in the collection section. ESPs offer several advantages over traditional fibrous filters, such as high collection efficiencies at relatively low pressure drops, and with infrequent replacement.

In general, although the type of particle to be collected does not impact the collection efficiency of an ESP, particle size is a strong determinant. Also, the higher the voltage used to ionize and collect particles, the greater the collection efficiency will be. But as with traditional high-efficiency filtration, the performance of ESP devices can degrade over time. Performance degradation with ESP devices can be due to several effects, such as dust loading. However, as long as the ESP is cleaned regularly, performance can be maintained at a relatively high level.

While ESPs remain an effective technology for air cleaning, there are some negative effects, such as the additional electrical power requirement, and the potential for these devices to produce ozone. ESPs, because of their design, typically will not fit into an existing air handler or existing ductwork without major modifications. These filters would also require new electric service. For these reasons, the installation and initial purchase costs of these filters are very high. However, ESPs have relatively low operating and maintenance costs.

Ultraviolet germicidal irradiation (UVGI) can be used as an in-duct air disinfection system, as a recirculation system used to treat the air in a room, and as an “upper air” disinfection system. Unlike the other filter technologies discussed in the report, UVGI is used to inactivate the biocontaminant, rather than remove it from the air stream. While it is possible that these systems could be used in commercial and residential buildings, their application is not very common.

UVGI in wavelengths of 225 to 302 nm is frequently used for microbial disinfection, and DNA absorption of UV radiation is maximal at 254 nm. Lethality of the UVGI system depends on the dose of radiation that the microorganism receives. Environmental and design variables also affect the performance of UVGI systems and include relative humidity, temperature, air velocity and air mixing, lamp selection, the use of reflectors, and the combination of UVGI with filtration. Unfortunately, few experimental data are available for HVAC applications of UVGI.

The combination of UVGI and mechanical filtration appears to be the most likely use of UVGI due mainly to the fact that UVGI systems would probably be added to an existing HVAC system that already employs some type of mechanical filtration. This approach is advantageous since UVGI is most effective against biocontaminants in the particle size range where mechanical filtration is less efficient (1µm and smaller). Retrofit UVGI systems would have to be installed downstream of the original mechanical filtration system to aid in maintaining the fully developed light field. Periodic cleaning of the lamps will also be important in establishing the light field, which is critical in maintaining the effectiveness of the UVGI system.

A UVGI system can be installed in-duct in existing ventilation systems, although modifications are required. Moreover, because of the more complex design of these systems, their initial purchase cost is extremely high—much higher than for any of the other filters analyzed in this report. Maintenance and operating costs for these systems are also high as they include cleaning and changing the bulbs periodically, and because they use a large amount of electricity.

1.0
Introduction

Recent events have shown that buildings and other infrastructure are vulnerable to terrorist attacks with biological agents. The most serious effects of such an attack are on the health of the occupants of the buildings. Building occupants may suffer health effects ranging from irritation, to severe sickness, to death. The attack may also have long-term economic and other impacts due to contamination of the building. Although guidelines exist on how to prevent and/or mitigate a terrorist attack on a building, a thorough examination of all of the available scientific data has not yet been made to determine the optimum course of action. This report provides a review of the literature on technologies that could be used in heating, ventilation, and air conditioning (HVAC) systems to reduce the amount of biological threat agent in the indoor environment. There are, however, no identified "safe" levels of exposure to biological threat agents, thus it is not known the extent reduction of these particles required to provide protection to building occupants from illness or death resulting from exposure to these threat agents.

2.0
Objective

The objective of this report is to provide a critical assessment of technologies that could be used to reduce contamination of a building following an attack with a biological agent. The assessment was designed to provide not only an evaluation of the scientific merit of the technology, but also consider space, power requirements, and cost factors. In addition, although the focus of this report is primarily on technologies for protecting buildings from biological agents, the majority of this report deals with air filtration technologies, which would be applicable to any threat agent in aerosol form.

3.0
Approach

The critical assessment of air cleaner technologies began with a search for relevant technical literature, conference proceedings, and manufacturers' literature, with an emphasis on literature written within the past five years. Technologies were categorized under aerosol filtration or gas-phase filtration. A cursory evaluation of each technology was performed, and it was decided to focus the critical assessment primarily on aerosol filtration technologies (the exception is that UV germicidal technology is assessed) and include more mature technologies. Five technologies were selected for critical review as those most appropriate to protect a building against a biological terrorist attack. The five reviews are detailed in separate sections of this report. Each review provides a description of the technology, a summary of the available literature, and a critical assessment that addresses technology performance, trends that affect performance, the impact of the technology on an HVAC system, and a cost analysis.

Note that the purpose of this report is not to specify which technology is best, more effective, or beneficial. These questions cannot be answered through an assessment of air cleaner technologies alone; factors specific to each building under investigation must be considered. General trends regarding the importance of filtration and its effectiveness have been addressed in a related report (Wang and Hofacre, 2007). Another related report addresses which parameters are most important in mitigating a hazardous release and how accurately these parameters need to be measured and controlled (Hawkins and Hofacre, 2007).

3.1 Search and Selection of Literature

Information regarding air cleaner technologies was obtained by searching military technical databases, commercial technical databases, peer-reviewed journals, and relevant Web sites. A full list of those searches is provided in Appendix A. A summary of the search strategy and results from the primary search are also given in Appendix A. Searches were performed using the following keywords:

- air
- aerosol
- building
- electrostatic or electronic
- HEPA
- clean, cleaner, or cleaning
- particle, or particulate
- HVAC
- germicidal irradiation
- filter, filtering, or filtration
- indoor
- electret
- UVGI

Subsequent to the initial primary search, additional articles were obtained through an EPA database that was searched using similar keywords. Although some overlap with the previous searches existed, this database provided useful papers for the major technologies investigated. Reference sections of relevant articles were also used to identify further citations of use and interest. Although the searches focused on literature published in the past five years, important and representative studies from earlier years were included when appropriate.

3.2 Technology Selection

The literature search generated hundreds of citations. Titles and abstracts were reviewed for relevance. Prior to initiating the primary search, air cleaning technology surveys and searches previously conducted by Battelle were reviewed. As a result, the following categories of gas-phase and aerosol technologies were established:

- Mechanical filtration
- Electrostatically enhanced filtration
- Electret media
- Electrostatic precipitation
- Ultraviolet germicidal irradiation (UVGI)
- Reactive fibers/ membranes
- Inertial separation
- Aerosol membranes
- Scrubbers
- Cold plasma

A cursory evaluation of each technology category was performed based on previous experience in the field to focus the critical assessment primarily on aerosol filtration and more mature technologies. Five technologies were selected for critical review as those that could be used to reduce contaminant levels in buildings: (1) mechanical filtration, (2) electrostatically enhanced filtration, (3) electret filters, (4) electrostatic precipitation, and (5) ultraviolet germicidal irradiation (UVGI).

The above five technology categories were selected because they represented distinguishable particle removal technologies (or in the case of UVGI, a technology for inactivation of biological threat agents) that were considered practical for consideration in a building HVAC (or collective protection) application. Technologies such as wet scrubbers, which can be used to remove aerosolized particles from airstreams, were not considered reasonable to consider in the assessment. Articles, conference proceedings, and manufacturers' data relevant to the performance of each technology, variables that affect the performance of each technology, the impact of the technology on an HVAC system, and cost parameters were sought.

3.3 Technology Reviews

Each review provides a description of the technology, a summary of the available literature, and a critical assessment that addresses technology performance, trends that affect performance, the impact of the technology once installed in an HVAC system, and cost analysis. Section 10 of this report details areas in which data were lacking that would have been helpful in further assessing the building air cleaning technologies.

3.4 HVAC Particle Removal System Background

To aid the discussion of the technology reviews and critical assessments, background regarding particle removal is presented below. First, a discussion of particle size of interest and consideration is given. This is followed by a discussion of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard test method 52.2 and the minimum efficiency reporting value (MERV) ratings. The performance of all air cleaning technologies that remove particles from an air stream, regardless of application (i.e., regardless of whether to improve air quality or to remove a hazardous aerosol from a terrorist incident), depends on the particle size (diameter). Thus, the particle size of interest is important when comparing and assessing air cleaning technologies. Air filtration technologies used in HVAC applications are tested against American National Standards Institute (ANSI)/ASHRAE 52.2. ASHRAE 52.2 allows filters to be tested in a consistent fashion and performance ratings to be assigned. Summaries of that method and the performance ratings are provided.

3.4.1 Particle Size Considerations

The typical size ranges of commonly occurring aerosols are shown in Figure 1. In general, particles of biological origin range in diameter from less than 0.1 micron up to about 50 µm. *Bacillus anthracis* spores are between 1 and 2 microns in diameter (Carrera, 2006).

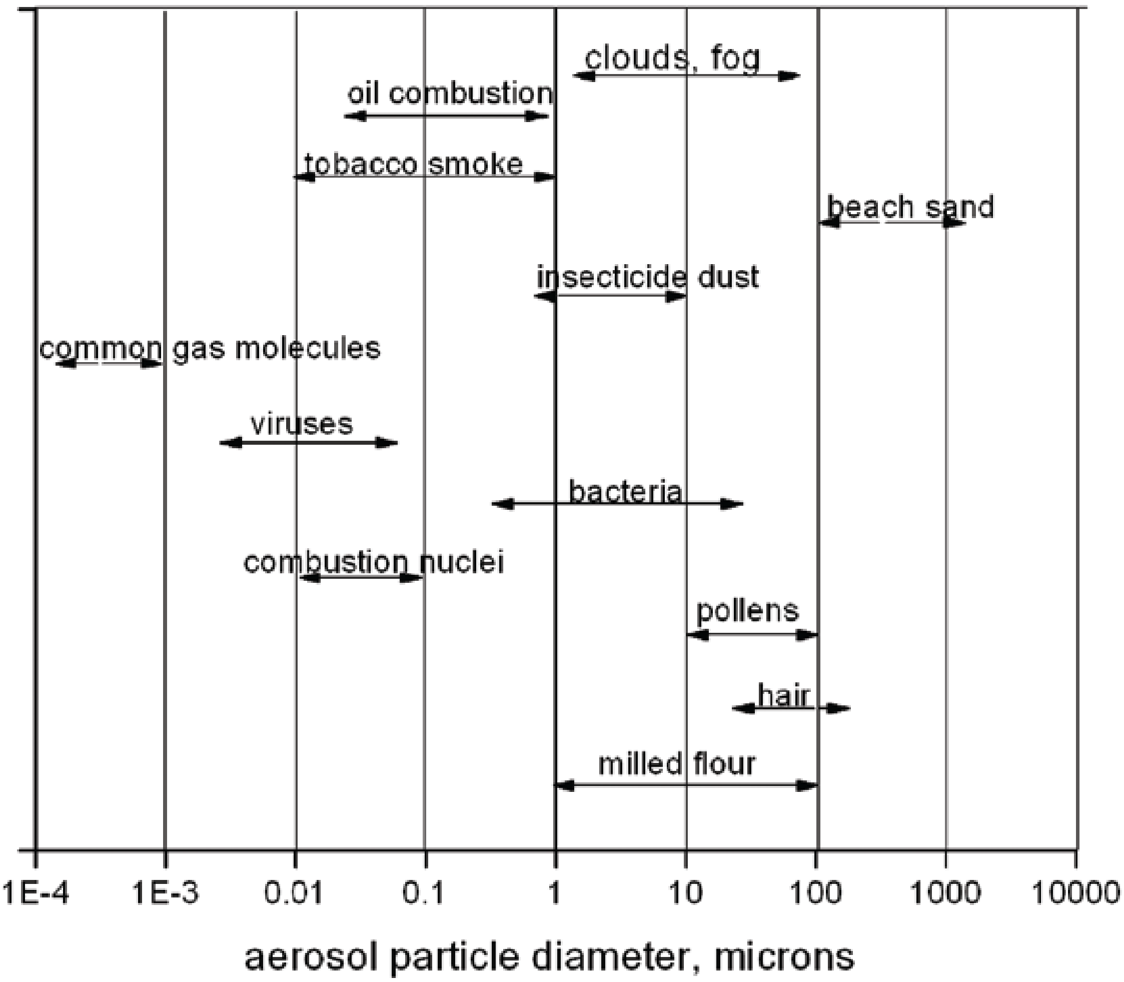


Figure 1. Typical Size Ranges of Commonly Occurring Aerosols (Owen et al., 1992)

Different air cleaning devices rely on different mechanisms to capture particles of varying size, as discussed in more detail under mechanical filtration in Section 5.4.1. To summarize, relatively large particles, larger than approximately 0.5 µm in diameter, are collected mostly by inertial effects and sedimentation, complemented by interception at the boundaries of the collection elements, while collection of smaller particles (<0.1 µm) is mostly due to diffusion. In the range from approximately 0.1 µm to 0.5 µm, none of these mechanisms dominates, which often results in a point of minimum collection efficiency (η) in the air cleaner performance curve. Air cleaning mechanisms that rely, at least in part, on the electrostatic force acting on charged particles in an electric field can affect the most penetrating particle size associated with filters that rely solely on mechanical filtration mechanisms. A larger charge-to-mass ratio is usually achieved for smaller particles, which, therefore, increases the collection efficiency of these smaller particles.

3.4.2 ASHRAE 52.2 and MERV Ratings

In the United States, ANSI/ASHRAE Standard 52.2-1999 (ASHRAE, 1999) is the standard method that is used to evaluate and rate HVAC filters. Although the ASHRAE 52.2 standard was designed for assessing mechanical filtration, the basic concept can be used to assess all types of air filtration devices. This standard describes the test procedures used to evaluate filters with capacities between 472 and 3,000 cfm (13 and 85 m^3/min). Potassium chloride particles in water are generated for the challenge aerosol. The concentrations upstream and downstream of the filter are measured to determine collection efficiency. These penetration measurements are taken with the new filter at four regular intervals as the filter is loaded with a specific test dust until its pressure drop has doubled. The measured collection efficiencies are then averaged over three particle size ranges (0.3 to 1.0 µm, 1.0 to 3.0 µm, and 3.0 to 10.0 µm) to classify the filter into one of 16 classifications referred to as minimum efficiency reporting values (MERVs). Table 1 lists the definitions of the various MERV ratings. Four MERV categories (17–20) are included in this list to demonstrate where High Efficiency Particulate Air (HEPA)/Ultra Low Penetrating Air (ULPA) filter performance rates, however, ASHRAE 52.2-1999 is not intended to be used to evaluate HEPA filter performance. Therefore, as indicated in Table 1, a different standard (IEST RP-CC001.3, 1993) is required to properly classify HEPA filters. Also, as noted in Table 1, filters with a MERV rating of less than 5 must be tested per ANSI/ASHRAE 52.1-1992 in order to determine their MERV rating. For filters with MERV ratings of less than 5, the average arrestance of the filter must be measured. As described in ANSI/ASHRAE 52.1-1992 (ASHRAE, 1992), the average arrestance of the filter is measured by exposing the filter to a relatively coarse dust (composed of 72% standardized air cleaner fine test dust, 23% powdered carbon, and 5% number 7 cotton linters) that has an average particle diameter and concentration significantly higher than for typical atmospheric dusts. The total mass fed and the downstream mass that penetrates the filter are measured at four regular intervals as the filter is loaded with the test dust. The arrestance is determined from the ratio between the total dust collected downstream of the filter and the total dust fed. The average arrestance is then determined by weighting the individual arrestances by the amount of dust fed to the filter between successive measurements. The average arrestance is then used to determine the MERV rating of the filter, as shown in Table 1. Due to the relatively new acceptance of ASHRAE 52.2-1999, the performance of some HVAC filters is still reported by some manufacturers using ASHRAE 52.1-1992. A recent study (Burroughs, 2004) has shown that filters with MERV ratings of less than 7 do not provide sufficient particle reduction to avoid particle accumulation in the duct system. Examples of typical applications for filters of various ranges of MERV ratings are listed below (Spengler et al., 2000).

MERV 1–4	Residential: pollen, dust mites
MERV 5–8	Industrial: dust, molds, spores
MERV 9–12	Industrial: *Legionella*, dust
MERV 13–16	Hospitals: smoke removal, bacteria
MERV 17–20	Clean Rooms: surgery, chem-bio, viruses

Table 1. Minimum Efficiency Reporting Value (MERV) Parameters (ASHRAE, 1999)

Standard 52.2 Minimum Efficiency Reporting Value (MERV)	Composite Average Particle Size Efficiency (%) in Size Range (μm)			Comments
	0.3 – 1.0 (E_1)	1.0 – 3.0 (E_2)	3.0 – 10.0 (E_3)	
1	NA	NA	$E_3<20$	Use of ANSI/ASHRAE 52.1-1992 is required
2	NA	NA	$E_3<20$	Use of ANSI/ASHRAE 52.1-1992 is required
3	NA	NA	$E_3<20$	Use of ANSI/ASHRAE 52.1-1992 is required
4	NA	NA	$E_3<20$	Use of ANSI/ASHRAE 52.1-1992 is required
5	NA	NA	$20\leq E_3<35$	
6	NA	NA	$35\leq E_3<50$	
7	NA	NA	$50\leq E_3<70$	
8	NA	NA	$70\leq E_3$	
9	NA	$E_2<50$	$85\leq E_3$	
10	NA	$50\leq E_2<65$	$85\leq E_3$	
11	NA	$65\leq E_2<80$	$85\leq E_3$	
12	NA	$80\leq E_2$	$90<E_3$	
13	$E_1<75$	$90\leq E_2$	$90\leq E_3$	
14	$75\leq E_1<85$	$90\leq E_2$	$90\leq E_3$	
15	$85\leq E_1<95$	$90\leq E_2$	$90\leq E_3$	
16	$95\leq E_1$	$95\leq E_2$	$95\leq E_3$	
17	NA	NA	NA	≥99.97% for 0.3 μm particles, IEST Type A
18	NA	NA	NA	≥99.99% for 0.3 μm particles, IEST Type C
19	NA	NA	NA	≥99.999% for 0.3 μm particles, IEST Type D
20	NA	NA	NA	≥99.999% for 0.1 – 0.2 μm particles, IEST Type F

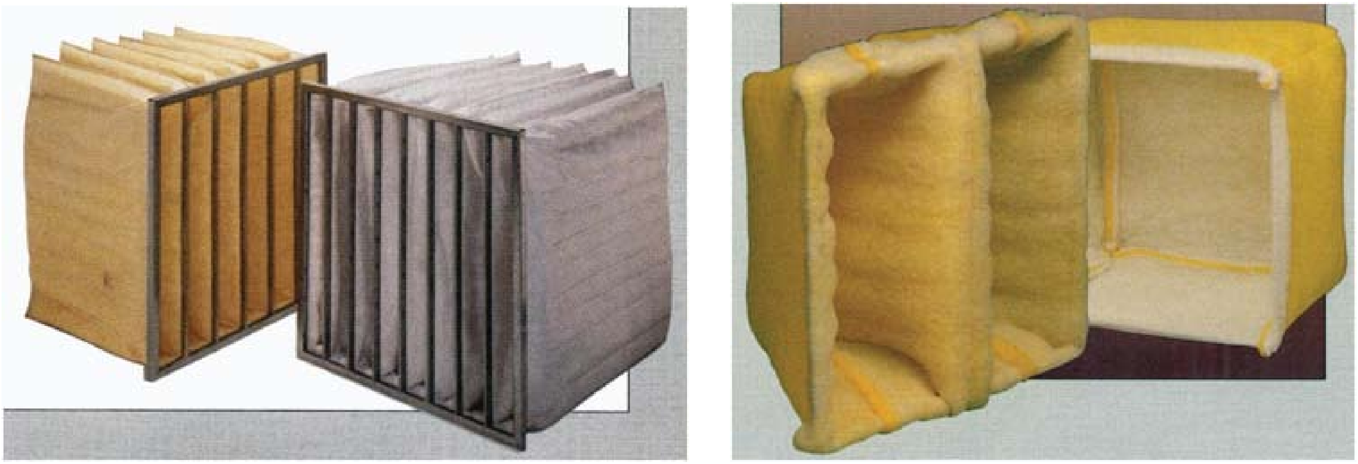
4.0
Critical Assessment of Mechanical Filtration

4.1 Technology Description

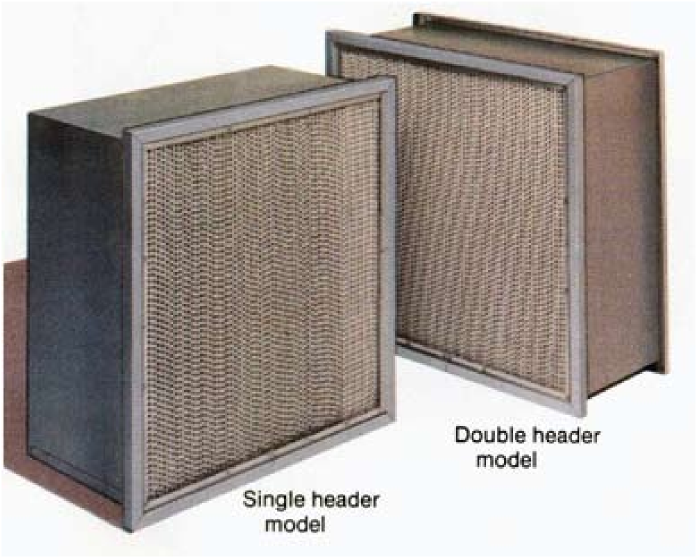
Mechanical filters are by far the most commonly used air cleaning devices in both residential and commercial HVAC systems. Mechanical filters come in a variety of shapes, sizes, compositions, and forms; however, panel filters are the most common. A rectangular frame containing a sheet of filter medium, as shown in Figure 2, comprises a panel filter. Panel filters come in an extremely wide variety of compositions, sizes, capacities, and efficiencies. The filter medium used in panel filters is usually constructed of woven or nonwoven fibers and is composed of a wide variety of materials, including glass, metal, synthetic (polymeric) materials (such as polypropylene), paper, or woven fabrics (such as cotton or nylon). The filters shown in Figure 2 have a 20 x 20 inch (51 x 51 cm) cross-section and a 2-inch (5.1-cm) depth.

As illustrated in Figure 3, there are several varieties of panel filters that have specific names and shapes. The filters depicted typically have a cross-section of approximately 61 x 61 cm and 30 cm depth. Cube filters have five filtration surfaces and can be force fit into an airstream duct without requiring clips, latches, or any type of frame. Shown in Figure 3 is the “pocket” filter or “multi-bag” filter. These are specific types of panel filters that use filter pockets or bags instead of a flat filter surface. The air flows through the pocket walls while the particles are collected inside. These filters are generally claimed to have higher dust loading capacities than standard panel filters because of their depth-loading nature. Also shown in Figure 3 is the “extended surface” filter. These filters generally use pleated paper media with aluminum separators. They generally have high collection efficiencies (up to HEPA) and higher initial and final pressure drops than other panel filters.

Figure 2. Typical Panel Filters



"Pocket" Filters **"Cube" Filters**



Rigid or Extended Surface Area Filters

Figure 3. Unusual Panel Filter Shapes

The size of a panel filter depends on the airflow rate it is intended to handle; however, panel filters generally remain less than a square yard in cross-sectional area and handle flow capacities of less than 2,500 cfm (71 m^3/min). Banks of panel filters are used in high airflow filtration applications. Pressure drops of clean panel filters range between 0.05 and 1 in. w.g. (12 and 249 Pa), and (except for high efficiency filters) the filters are generally replaced when the pressure drop reaches between 3 and 10 times the original pressure drop. In applications where high efficiency filtration is required, a sequence of increasingly efficient panel filters is generally employed to lengthen the service life of the more expensive high efficiency filters.

Fibrous media are commonly used in air filtration because they can provide good filtration efficiency at a low pressure drop. The fibers are either woven into the filter frame (woven) or randomly oriented and thermally or chemically bonded to each other and to the filter frame (nonwoven). The collection efficiency of fibrous media is directly related to the average fiber diameter, the media density, and the media depth or thickness. The smaller the fiber diameter, the smaller the particles that can be collected. Increasing the density and thickness increases the collection efficiency but also increases the pressure drop. Fiber diameters in fibrous media generally range between submicron and hundreds of microns.

Nonwoven fibrous media can be produced by the wet-laid process, which is a modification of the normal paper-making process. In this process, a slurry of fibers and water is introduced to a porous base. The water drains, while the fibers are collected and dried. The fibers tend to lie in the same plane but are randomly oriented. These fibers, when dried, form a continuous sheet of filter media. Glass, cellulose, and other materials can be used to make filter media using this method.

Spunbond nonwoven filter media are formed from continuous filaments that are extruded, drawn, laid into a filter web, bonded together, and collected in a roll goods form on a single process line. They are made from a wide range of polymers, including polyethylene, polypropylene, polyester, nylon, or combinations thereof. They are bonded together by thermal bonding, chemical bonding, or needlepunch fiber entanglement bonding. Because spunbond media are composed of large diameter (20 to 250 µm) fibers, they do not collect small particles effectively and are generally used as support structures for more efficient media.

Carding is another method of nonwoven fibrous filter media production. Carding is a process in which fibers are repeatedly combed with metal hooks to disentangle fiber clumps. Carded fibers, which are roughly aligned, can be compressed into a filter medium. Wool, cotton, and synthetic fiber media can be produced in this way. Carded filter media generally have fiber diameters larger than 15 µm and are generally very weak in the fiber plane direction but very strong perpendicular to the fiber orientation. Carded filters are generally weak and are not used in sheet form. Carded filters can be "felted," a process in which the irregular surfaces of the fibers are used to hold the fibers together by the application of heat, humidity, and pressure. Synthetic carded filters cannot be felted but can be "needled" together with barbed needles. These processes improve the filter media strength but often lower collection efficiency.

Metallic media are generally produced by weaving or sintering. Because of the strength of these media and the lack of any chemical sealant or bonding materials, metallic filters are very corrosion resistant. In the meltblown production process, polymer pellets are fed into an extruder where they melt, pass through a metered pump, pass through an array of thin "capillary" tubes, and then into a high velocity hot air jet and are deposited on a collecting drum. The fibers thermally bond, generally have thicknesses between 1 and 15 µm, and form high porosity webs. They possess clean, unused (virgin) surfaces, which makes them ideally suited for filtration. The fiber diameter and web thickness can be controlled by altering the pump flow rate, the size of the capillary tubes, the velocity of the air jet, and the speed of the collection step.

In the United States, ANSI/ASHRAE Standard 52.2-1999 (ASHRAE, 1999) is the standard method used to evaluate and rate HVAC filters. This fairly recent standard describes the test procedures used to evaluate filters with capacities between 472 and 3,000 cfm (13 and 85 m^3/min). Table 2 lists the definitions of the various MERV ratings, along with the minimum final resistance of each rating. An additional discussion regarding ASHRAE 52.2 and MERV rating is provided in Section 3.4.2.

In the residential market, the most inexpensive filters dominate. These include fiberglass, disposable polyester/cotton blends, and pleated air filters. The lowest MERV-rated filter identified for residential use was 4, and the highest rated filter available in the residential market was 12 (manufactured by 3M). Electrostatic filters were found to be dominant for the medium to higher efficiency residential filters. In fact, it was quite difficult to identify a residential filter with a MERV rating of 11 or greater that did not possess electrostatic media.

A much larger range of filters was identified in the commercial market. The most popular design in commercial applications is the pleated air filter. In the commercial market, it was not difficult to identify filters with MERV ratings between 1 and 15. MERV 16 filters were more difficult to identify than the other classes of filters, but some were identified.

Table 2. Minimum Efficiency Reporting Value (MERV) Parameters With Minimum Final Resistance (ASHRAE, 1999)

Standard 52.2 Minimum Efficiency Reporting Value (MERV)[a]	Composite Average Particle Size Efficiency (%) in Diameter Range (µm)			Minimum Final Resistance[b]	
	0.30 – 1.0 (E_1)	1.0 – 3.0 (E_2)	3.0 – 10.0 (E_3)	Pa	in. of water
1	NA	NA	E3<20	75	0.3
2	NA	NA	E3<20	75	0.3
3	NA	NA	E3<20	75	0.3
4	NA	NA	E3<20	75	0.3
5	NA	NA	20≤E3<35	150	0.6
6	NA	NA	35≤E3<50	150	0.6
7	NA	NA	50≤E3<70	150	0.6
8	NA	NA	70≤E3	150	0.6
9	NA	E2<50	85≤E3	250	1.0
10	NA	50≤E2<65	85≤E3	250	1.0
11	NA	65≤E2<80	85≤E3	250	1.0
12	NA	80≤E2	90≤E3	250	1.0
13	E1<75	90≤E2	90≤E3	350	1.4
14	75≤E1<85	90≤E2	90≤E3	350	1.4
15	85≤E1<95	90≤E2	90≤E3	350	1.4
16	95≤E1	95≤E2	95≤E3	350	1.4

[a] Filters with MERV ratings of less than 5 must be tested per ANSI/ASHRAE 52.1-1992 in order to determine their performance.

[b] The minimum final airflow resistance shall be at least twice the initial resistance, or as specified above, whichever is greater. The minimum final resistance is for test purposes to determine minimum efficiency, not as a recommendation for actual use. For example, air cleaners used in residences may be changed or cleaned at a lower final resistance than that required by this standard (ASHRAE, 1999).

4.2 Theory of Mechanical Filtration

In order to assist the reader in understanding the operating parameters and conditions that are likely to affect mechanical filters, a basic description of the mechanisms by which filtration occurs is provided. There are four primary mechanisms of particle capture, as illustrated in Figure 4: (1) inertial impaction, (2) interception, (3) diffusion, and (4) electrostatic attraction.

- **Inertial impaction** occurs when a particle traveling in the air stream and passing around a fiber deviates from the streamline (due to particle inertia) and collides with a fiber.
- **Interception** occurs when a particle does not deviate from the streamline but is intercepted by the fiber (i.e., streamline passes within one particle radius of fiber).
- **Diffusion** occurs when the random (Brownian) motion of a particle causes that particle to contact a fiber. This mechanism is most significant when the particle diameter is less than 0.1 µm.
- **Electrostatic attraction** plays a minor role in mechanical filtration. However, as discussed in other sections of this report, electrostatically enhanced fibers can be used to attract and retain particles.

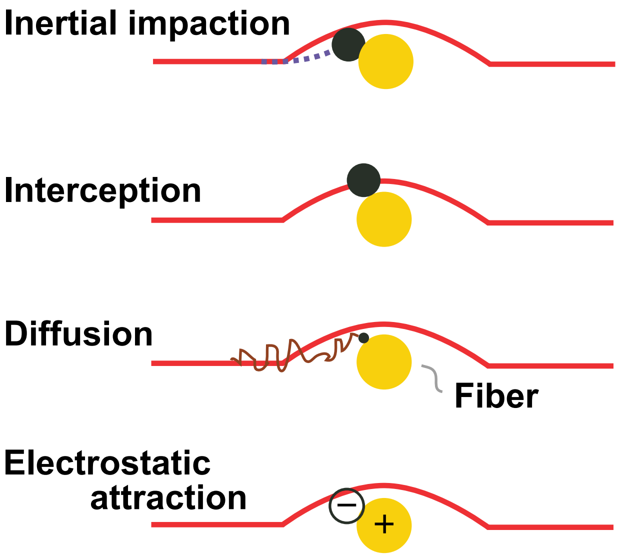


Figure 4. Four Mechanisms of Particle Capture (CDC, 2005)

Particle fractional penetration (P), expressed in terms of fractional efficiency (E) by P=1−E, is dependent on the diameter of the aerosol particles, filtration velocity (based on flow rate and available filter surface area), and filter parameters, including the thickness, fiber diameter, and solidity or fiber packing density (i.e., the ratio of solid fiber volume to gross filter volume). The general trends regarding the impact of these parameters on the filtration efficiency and airflow resistance are summarized in Table 3. As shown in Figure 5, the collection efficiency of filter media depends strongly on particle size. The most penetrating particle size (MPPS) for high efficiency filters is typically in the range of 0.1 to 0.3 µm.

The fiber diameter and packing fraction affect the filtration performance and the airflow resistance of the media. In general, the efficiency and resistance both increase as the fiber diameter decreases or packing fraction increases. High efficiency filters typically contain blends of fibers of varying diameter to satisfy the filtration requirements and to provide the physical strength. For example, High Efficiency Particulate Air (HEPA) filter media are typically less than 0.5 mm thick, have packing densities ranging from 0.03 to 0.05, and contain fibers of diameters ranging from 0.55 µm to approximately 6.5 µm but possess a nominal mean fiber diameter of approximately 0.65 to 0.70 µm.

The efficiency of a filter is typically inversely proportional to the filtration velocity (air velocity through the filtration media) for particles of all diameters. The only exception would be those particles that are collected predominantly by diffusional mechanism, typically those less than 0.1 µm. As the velocity increases, the diffusion mechanism becomes less effective and the interception and impaction mechanisms are enhanced. In any case, filters should always be used at the filtration velocity recommended by the manufacturer.

In general, particle penetration of a filter decreases (sometimes by as much as an order of magnitude) as particles are collected on the filter surface. The collected particles form an additional layer (termed a filter cake or dust cake) on the filter surface, which contributes significantly to the collection efficiency of the filter. The filter cake does not increase the filter's collection efficiency indefinitely, but collection efficiency increases quickly as particles are first collected and then levels off. Figure 6 illustrates the effect of particle loading on the collection efficiency of a MERV 9 filter. Of course, the airflow resistance across the filter also increases with the loading of particles on the filter as portions of the filter surface area become clogged.

Table 3. Influence of Filter Parameters on Filtration Efficiency and Airflow Resistance

Parameter	Penetration	Airflow Resistance
Fiber Diameter	Decreases with decreased fiber diameter	Increases with decreased fiber diameter
Thickness	Decreases with increased thickness	Increases with increased fiber thickness
Solidity	Decreases with increased solidity	Increases with increased solidity
Surface area	Decreases with increased surface area	Decreases with increased surface area

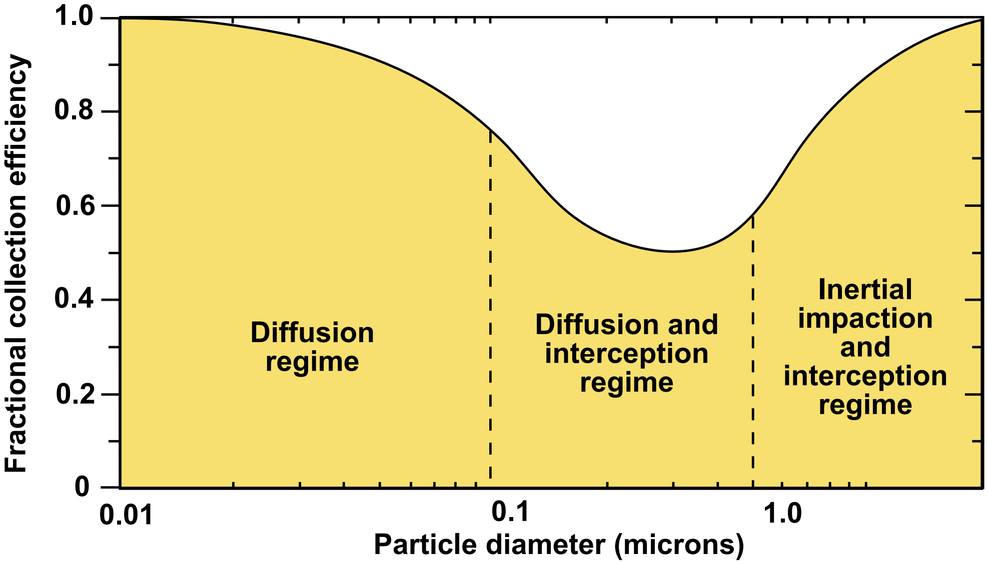


Figure 5. Primary Mechanisms of Capture for Various Particle Diameters (CDC, 2005)

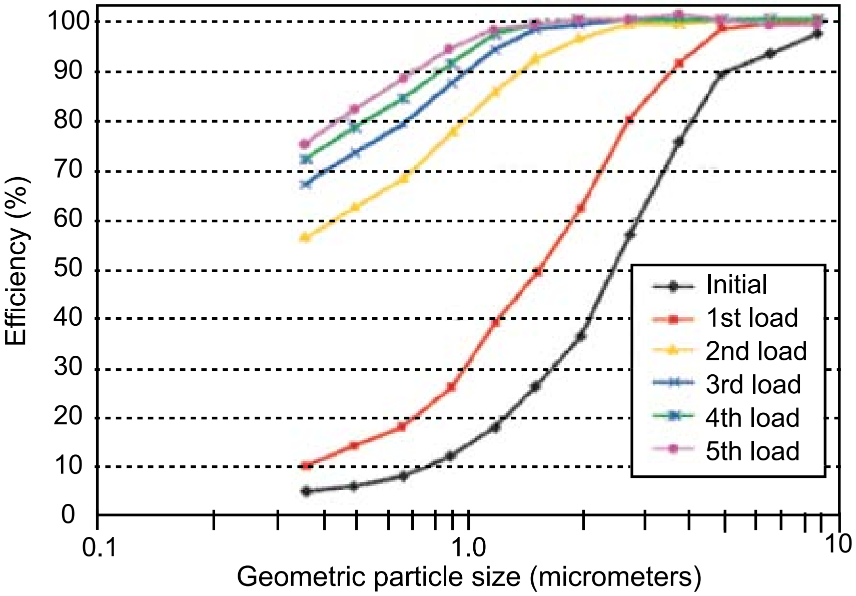


Figure 6. ASHRAE Standard 52.2 Test Data for a MERV 9 Filter Showing How Collection Efficiency Increases as the Filter Loads (CDC, 2005)

Excessive heat can affect the performance of filters by causing degradation of the materials that bond the filter fibers, the materials used to bond the media to the frame, or even the filter media itself. In general HVAC applications, excessive heat is unlikely to be a significant concern, but care should be taken to ensure that the filters are suitable for the likely operating temperatures.

Relative humidity also can affect the performance of mechanical filters. Under unusual conditions, excessively high relative humidity can affect the collection efficiency and airflow resistance of mechanical filters as water can condense onto the filter fibers and collected particles, causing a rapid increase in pressure drop that could damage the filter, or even cause the filter to burst. Therefore, care must be taken to ensure proper design of HVAC systems to prevent exposure of mechanical filters to saturated or supersaturated airstreams.

4.3 Summary of Relevant Studies

Recent studies in mechanical media are summarized in Table 4. Note that Table 4 focuses primarily on studies conducted since 1995. Only important and representative studies conducted before 1995 are included in Table 4.

The residential furnace filtration market has seen a large increase in the number and variety of available filters (Fugler et al., 2000). Consumers now have the option to purchase anything from a traditional mechanical filter made of recycled material to a HEPA filter for their HVAC system. Several studies were identified that provided background information on both filter performance and contaminants found in the air (Brown, 2001; Miller, 2002; Kowalski and Bahnfleth, 2002) to help homeowners select the correct balance of efficiency versus cost for their particular needs.

Filtration demands in commercial environments vary with the type of environment that uses the filtered air. For example, ASHRAE recommends a 90% average dust spot efficiency filter preceded by a 25% dust spot efficiency filter for general areas of hospitals, a 25% dust spot efficiency filter for the administrative areas, and a 25% dust spot efficiency filter, 90% dust spot efficiency filter, and HEPA filter in series for an operating room (Kowalski and Bahnfleth, 2002). The average commercial building will not meet these strict guidelines, and certain overviews (Miller, 2002; Kowalski and Bahnfleth, 2003) were identified to assist building owners in selecting an adequate filtration system.

The dust spot efficiency does not directly convert to a MERV rating due to the differences in the standard test methods. The dust spot efficiency represents an overall efficiency while the MERV is based on particle-size dependent efficiencies. For ASHRAE 52.2, potassium chloride particles ranging in size from 0.3µm to 10µm are used to test the filter, with penetration determined in 12 distinct size bins between 0.3µm and 10µm. For the previous standard, ASHRAE 52.1, collection efficiency was measured by two methods: arrestance and dust spot efficiency. Arrestance is measure by weighing the fraction of a synthetic test dust that passes through the filter. Dust spot efficiency is measured by comparing opacity meters upstream and downstream of the filter. Since collection efficiency is strongly related to particle size and the particle sizes of the materials used in the three tests are quite different, the tests are not directly comparable. However, Table 5 can be used as a general guideline. For example, a filter with a dust spot efficiency of 30% roughly corresponds to a MERV 8 filter.

Table 4. Summary of Mechanical Filter Studies

Basic Scope	Content/Conclusion	Reference
Overview of Filtration, Filters, or Contaminants	These papers provide an overview of mechanical filtration, including standards, capabilities of current filters, types of media, and potential contaminants.	Brown, 2001; Miller, 2002; Kowalski and Bahnfleth, 2002; Kowalski and Bahnfleth, 2003
Performance Data of Mechanical Filters	These studies provide experimental data on filtration performance for a wide variety of residential/commercial filters, tested in the laboratory according to ASHRAE standards.	Rivers and Murphy, 2000; Owen et al., 2003
Effect of Parameters on Performance	In these studies, different parameters of a filter setup were adjusted to test the effect on performance, including the orientation of different filters in series, variable housing geometry of a filter, and filter media.	Chambers et al., 2001; Peters et al., 2001; Letts et al., 2003
Innovations in Mechanical Filters	These studies and patents explore promising new developments, techniques, or equipment:	
	Filter immersed in a liquid	Agranovski et al., 2001
	New hygroscopic filter media	Kemp et al., 2001
	Indoor air purification system (patent)	Homeyer et al., 2001
	NBC-Building protection system and method (patent)	Fuchs et al., 2004
Impact in Actual Residential or Commercial Environments	These studies provide data on the impact of mechanical filters in actual home or commercial environments.	Howard-Reed et al., 2003; Wallace et al., 2004; Chimack and Sellers, 2000; Fugler et al., 2000
Designing an Air Filter System	These papers discuss the concept of Clean Air Delivery Rate (CADR) to help optimize air filter needs.	Rudnick, 2004; Ward et al., 2003
Inert versus Bioaerosol Filtration	These studies compare collection efficiency of bioaerosols compared to inert aerosols of comparable particle size.	Brosseau et al., 1994; Willeke et al., 1996; McCullough et al., 1997; Hofacre et al., 1996

Table 5. Comparison of ASHRAE Standards 52.1 and 52.2(a)

ASHRAE 52.2				ASHRAE 52.1		Particle size range, µm	Applications
	Particle size range			Test			
MERV	3 to 10 µm	1 to 3 µm	.3 to 1 µm	Arrestance	Dust spot		
1	<20%	-	-	<65%	<20%	>10	Residential light pollen dust mites
2	<20%	-	-	65–70%	<20%		
3	<20%	-	-	70–75%	<20%		
4	<20%	-	-	>75%	<20%		
5	20–35%	-	-	80–85%	<20%	3.0–10	Industrial dust molds spores
6	35–50%	-	-	>90%	<20%		
7	50–70%	-	-	>90%	20–25%		
8	>70%	-	-	>95%	25–30%		
9	>85%	<50%	-	>95%	40–45%	1.0–3.0	Industrial *Legionella* dust
10	>85%	50–65%	-	>95%	50–55%		
11	>85%	65–80%	-	>98%	60–65%		
12	>90%	>80%	-	>98%	70–75%		
13	>90%	>90%	<75%	>98%	80–90%	0.3–1.0	Hospitals smoke removal bacteria
14	>90%	>90%	75–85%	>98%	90–95%		
15	>90%	>90%	85–95%	>98%	~95%		
16	>95%	>95%	>95%	>98%	>95%		

(a) www.cdc.gov/niosh/docs/2003-136/2003-136c.html

4.3.1 Performance and Variables That Affect Performance

Filter performance information is currently provided by either an ASHRAE rating or a manufacturer's claim. Recent literature (Rivers and Murphy, 2000; Owen et al., 2003) has helped make public significant amounts of data on residential and commercial filter efficiency test results using ASHRAE 52.2-1999. Owen et al. (2003) tested 26 different filters, both residential and commercial, in the laboratory according to ASHRAE 52.2-1999. MERV ratings were determined from the test data, based on the assumption that an initial efficiency curve would represent the lowest efficiency values of each filter in an ASHRAE 52.2-1999 test (Owen et al., 2003). Particle diameters in the test ranged from 0.03 to 10 µm, as compared to the standard ASHRAE 52.2-1999 test range of 0.3 to 10 µm. The lowest efficiencies for all filters were located in the 0.1 to ~0.5 µm diameter range, with the higher-rated filters showing an increase in efficiency as the particle diameter increased in the particle size range (Owen et al., 2003). The filters with lower MERV ratings showed a definite increase in efficiency when the particle diameter increased but exhibited an inconsistent performance as the diameter decreased (Owen et al., 2003). The data were inconsistent in that both increases and decreases in collection efficiency have been reported with particle diameters of less than 1 µm.

Rivers and Murphy (2000) conducted a series of laboratory tests on 31 different air filters with a variety of ASHRAE dust spot efficiencies. The tests included the ASHRAE Standard 52.1 tests, filtration efficiency evaluations for different particle diameters, and reentrainment tests to determine whether the filter media contributed to the downstream concentration of particles. The filters were evaluated under both constant airflow and variable air volume (VAV) flow. The goal of the study was to be able to predict air filter resistance and efficiency in VAV systems. As a result, much of the paper is devoted to generating that model as opposed to presenting laboratory test results. Rivers and Murphy (2000) concluded that there was no significant drop in filter performance under VAV test conditions, with the exception of the lowest efficiency filters showing a greater loss of collected dust. These filters, however, showed high dust losses under both operating conditions and could not even withstand all of the tests (Rivers and Murphy, 2000).

The Environmental Technology Verification (ETV) Program, established by the U.S. Environmental Protection Agency, conducted laboratory tests on the performance of air filters in building HVAC systems. The results for fourteen of these evaluations, focusing primarily on pressure drop and filtration efficiency of bioaerosols and inerts, can be found on the EPA National Homeland Security Research Center Web site (US EPA, 2004). The filters were assigned MERV ratings based on the ASHRAE Standard 52.2 test from 0.3 to 10 µm diameter particles. The results showed an increase in filtration efficiency of bioaerosols with MERV rating, with higher efficiencies for dust-loaded filters. There was also a general increase in pressure drop with MERV rating. As with the previous references, the ETV data are laboratory data and do not represent actual HVAC impact data.

4.3.2 Assessment in an HVAC System

As noted in Table 4, a number of papers were identified that examined the impact of mechanical filters on the air quality in actual use environments (Howard-Reed et al., 2003; Wallace et al., 2004; Burroughs, 2004; Chimack and Sellers, 2000; Fugler et al., 2000). These papers are discussed in turn in the following sections.

Residential Environment. Filter efficiency in an actual residential environment was evaluated by Fugler et al. (2000) by comparing the performance of various furnace filters in six different test houses. Ten filters were used in an initial test house, and then five of these filters were chosen to be evaluated in the remaining five houses. Table 6 lists the efficiencies for these five filters, four of which were mechanical, after being tested in six houses.

The efficiencies in Table 6 were calculated for each particle diameter, based on upstream and downstream conditions. Experimental efficiencies were also found at PM5 (mass of particles below 5 µm) but were not provided because all diameters showed similar results to all tests (Fugler et al., 2000). The calculated efficiencies were meant to be comparable to ASHRAE dust spot efficiencies.

For the most part, the experimental data provided efficiencies that were similar to the filters' rated efficiencies. The 25-mm high quality media filter exhibited a range of 29 to 45%. As seen in Table 6, it was claimed to be 20 times better than an ordinary filter and 7 times better than an ordinary pleated filter. The results compare well to the ordinary furnace filter that showed a negative efficiency in the test house and a regular 25-mm pleated media filter that showed an efficiency of around 5% in the test house (Fugler et al., 2000). It is unclear how the electronic charged pad experimental efficiency data relate to the manufacturer's claimed performance. Both the 100-mm pleated and ESP filters performed at the level claimed by the manufacturer. The HEPA and TFP filters did not reach their expected efficiencies because they were used as bypass units, filtering only about 30% of the system air (Fugler et al., 2000). These filters did, however, operate at their expected efficiencies for the fraction of air that they handled (Fugler et al., 2000).

Fugler et al. (2000) also evaluated filter impact in a residential setting by measuring the reduction in concentration of respirable particles in the indoor environment. Table 7 lists the reduction of these particles based on percent improvement compared to a no-filter condition, with the experimental efficiency also provided for reference (Fugler et al., 2000).

Table 6. Filter Results vs. Manufacturers' Claims (Fugler et al., 2000)

Filter Description	Manufacturer Claimed Performance	Test Results, Upstream/Downstream Efficiency[a]	
		E% PM1[b]	E% PM10[b]
25-mm high quality pleated media	20 times better than ordinary filters, 7 times better than ordinary pleated filters	29%	45%
Electronic charged pad	Efficiency at 0.3–0.5 µm: 33–75%; 0.5–1.0 µm: 75–95%	17%	20%
100-mm pleated media	32% average dust spot efficiency	21%	36%
Electronic plate and wire type (ESP)	75% average dust spot efficiency	84%	90%
HEPA or TFP[c]	99.97% DOP (HEPA) 84% – 99%, based on particle diameter (TFP)	27%	30%

[a] The upstream/downstream efficiency technique is based on the mean particle concentrations at the upstream and downstream sampling points over the duration of the data period. It is meant to be comparable to dust spot efficiency, an ASHRAE evaluation method.

[b] PM1 and PM10 represent mass of particles below 1 and 10 µm diameter, respectively.

[c] HEPA or TFP (turbulent flow precipitator) filters were both used as high efficiency filters in the study but did not reach their expected efficiencies because they were used as bypass units, filtering only about 30% of the system air.

Table 7. Mean Reduction of Indoor PM10 Levels (a) Below "No-Filter" Case (Fugler et al., 2000)

Filter Description	Experimental Efficiency	Percent Improvement	
		Active	Nonactive
100-mm pleated media	36%	9%	13%
Electronic charged pad	20%	9%	29%
Bypass filter (HEPA or TFP)[b]	30%	23%	38%
25-mm pleated media high quality	45%	21%	57%
Electronic plate and wire type (ESP)	90%	31%	71%

[a] Although this table is for PM10 only, Fugler et al. (2000) reported similar results for all diameter ranges.

[b] The HEPA and TFP filters did not reach their expected efficiencies because they were used as bypass units, filtering only about 30% of the system air.

The percent improvement is a measure of how the concentration of PM10 particles in rooms of the house was lowered when a filter was used in the home HVAC system. Each filter's improvement is relative to a no-filter condition, in which the fan runs but no filter is in the duct. Active data refer only to periods of known activity in the house, causing the resuspension or generation of particles on real-time data charts. Nonactive data include periods when there is no activity in the house, such as when the occupants are sleeping or the house is unoccupied. As seen in Table 7, percent improvements during active periods were consistently much lower than the efficiencies. The exception is the bypass filter, but the 23% reduction was the result of handling only 30% of the system air. As would be expected, reductions in concentration were greater during periods of inactivity than activity (Fugler et al., 2000). Two of the filters showed a reduction lower than the filter efficiency, while the remaining three filters showed a reduction greater than the filter efficiency. The filters analyzed by Fugler et al. (2000) performed well when compared to their ASHRAE or manufacturer claimed efficiencies. Their impact in reducing the amount of indoor particles was much less significant than their single-pass efficiency during active periods. Inactive periods showed more comparable results, as some percent reductions were higher than single-pass efficiencies.

Howard-Reed et al. (2003) investigated the impact of central heating and air conditioning (HAC) forced-air fans and in-duct filters on the deposition rates and reduction of particle concentrations in a residential environment. Deposition rate includes removal of particles by deposition to room surfaces, removal by operation of the HAC fan (when the fan is on), and removal by a mechanical or electrical air cleaner (when a filter is used). The study took place in an occupied three-story townhouse over several years. Three different sources (cooking with a gas stove, burning a citronella candle, and pouring kitty litter) were used to introduce particles of varying shape and composition into the home. The deposition rates and particle reductions were calculated for four HAC configurations: (1) fan off, no filter; (2) fan on, no filter; (3) fan on, typical furnace filter; and (4) fan on, electrostatic precipitator (ESP) unit.

The results of the experiment showed the deposition rates for each particle diameter range were not influenced by the three different sources (Howard-Reed et al., 2003). The particle deposition rates did, however, vary with both particle diameter and HAC configurations, as seen in Figure 7 (Howard-Reed et al., 2003).

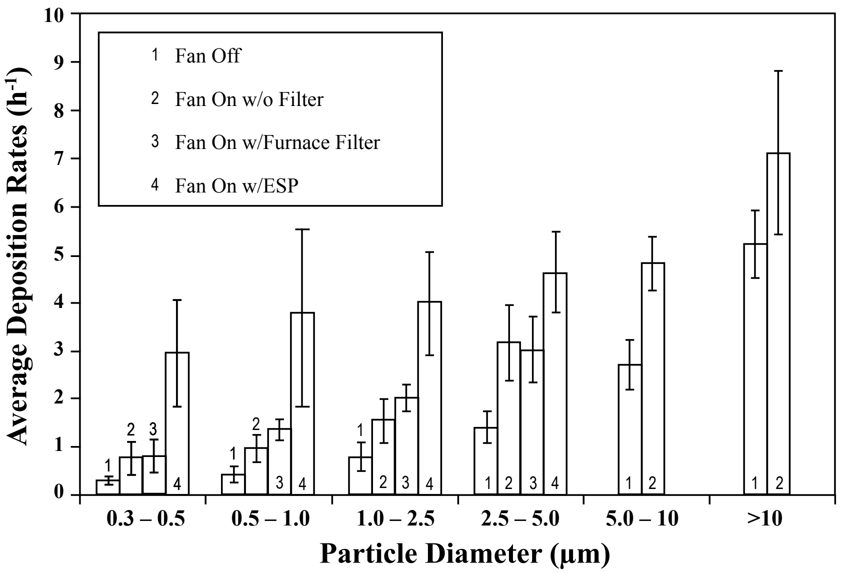


Figure 7. Comparison of Particle Deposition Rates for Different HVAC Configurations

Error bars are ± one standard deviation. The standard filters and ESP were used only in the cooking and candle burning source events, resulting in a lack of measurable decay rates for the larger diameter particles. (Howard-Reed et al., 2003)

Deposition rate clearly increased as particle diameter increased. The fan on, no filter configuration showed a marked increase over the fan off condition. The addition of a standard furnace filter demonstrated very little improvement over the fan on, no filter configuration. The addition of an ESP proved to have a very significant influence on particle deposition rates. The standard filters and ESP were used only in the cooking and candle burning source events, resulting in a lack of measurable decay rates for the larger diameter particles.

A similar experiment in a test house was conducted as part of the study to investigate the effects of room surface area and furnishings. An OFF!® citronella candle was burned in an unfurnished room with a similar floor surface area and slightly higher volumetric flow rate through the fan system. The results provided no significant deviations from the furnished townhouse (Howard-Reed et al., 2003).

The percent reduction of particles among the test conditions was estimated based on the mean deposition rates (Howard-Reed et al., 2003). Table 8 lists the percent reductions in particle levels for both a “tight” house (air change rate of 0.2 h^{-1}) and a “drafty” house (air change rate of 1.0 h^{-1}). Simply turning on the fan in the central heating and air conditioning unit had a significant effect in reducing indoor particles. The addition of an ESP filter had an even greater effect. The effect of the standard filter was too insignificant to be included in the table (Howard-Reed et al., 2003).

Table 8. Percent Reduction of Outdoor Particles Penetrating Indoors (Howard-Reed et al., 2003)

Ventilation/Filtration Setting[(a)]	Particle Diameter Range (µm)					
	0.3 – 0.5	0.5 – 1	1 – 2.5	2.5-5	5 - 10	> 10
Tight house						
Fan on	48%	47%	42%	53%	42%	26%
Fan on, ESP	84%	85%	77%	67%	-	-
Drafty house						
Fan on	27%	28%	29%	43%	36%	23%
Fan on, ESP	67%	70%	64%	57%	-	-

(a) The ESP filter was used only for cooking and candle burning (smaller particles) so there is a lack of measurable decay rate for larger diameter particles (Howard-Reed et al., 2003).

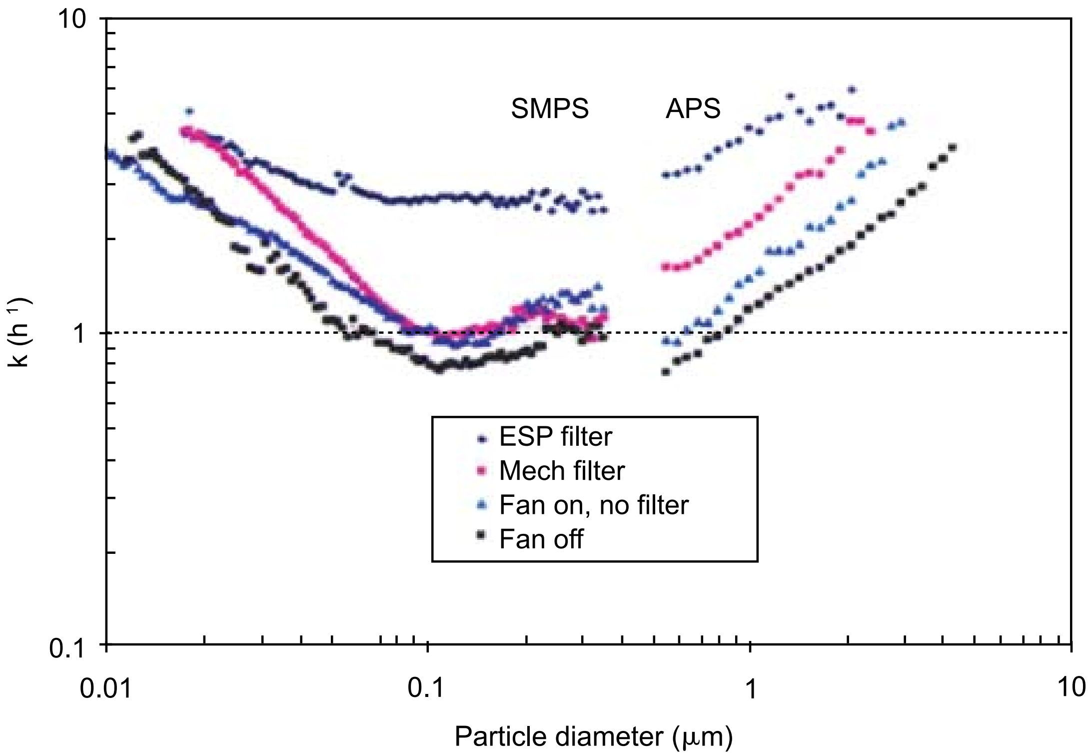


Figure 8. Deposition Rates by Particle Diameter for Each Test Configuration (Wallace et al., 2004)

Wallace et al. (2004) performed an extension of the Howard-Reed et al. (2003) study in the same townhouse to include particles of a much smaller diameter and also replaced the standard filter with a higher quality mechanical filter (Wallace et al., 2004). The fibrous mechanical filter, or MECH, had an extended surface area and an ASHRAE Standard 52.1 average arrestance of 93%. The same four HAC configurations were tested. Figure 8 illustrates how the deposition rates vary with particle diameter for the four test configurations.

Two particle sizing instruments, a Scanning Mobility Particle Sizer (SMPS) and an Aerodynamic Particle Sizer (APS), were required to gather the data over the proposed particle diameter ranges. Therefore, the graph is split into two halves, one for each instrument. As in the Howard-Reed et al. (2003) study, use of the central forced-air fan led to the reduction of indoor particles, and the addition of a filter reduced them further. The MECH filter did show an improvement over the no-filter condition, especially at the smallest particle diameters. The ESP filter exhibited the best performance but required cleaning (at intervals between 500 and 2000 hours) to maintain the high level of performance (Wallace et al., 2004). The graphs have minimum deposition values at a range of 0.11 – 0.13 µm, which agrees with theoretical predictions (Wallace et al., 2004).

As in the Howard-Reed et al. (2003) study, the percent reductions of particles among the test configurations were estimated. The values, presented in Table 9, are based on the mean deposition rates.

The air change rates for the tight, typical, and drafty houses were 0.2 h^{-1}, 0.64 h^{-1}, and 1.2 h^{-1}, respectively. The typical air change rate was determined by the average rate in the house over the course of a year. The table shows that simply running the fan with no filter has a significant reduction effect on indoor particles. The MECH filter produces an additional reduction effect, as does the ESP filter.

Commercial Environment. Few studies were found that included data from actual commercial environments. One such study by Chimack and Sellers (2000) compared the

Table 9. Percent Reductions in Particle Concentrations Due to a Central Fan, MECH Filter, and ESP (Wallace et al., 2004)

Ventilation/Filtration Setting	Percent Reduction
Tight house	
Fan on	18%
Fan on, MECH	28%
Fan on, ESP	59%
Typical house	
Fan on	14%
Fan on, MECH	23%
Fan on, ESP	51%
Drafty house	
Fan on	11%
Fan on, MECH	20%
Fan on, ESP	44%

use of an office building's current standard bag-type filters to a premium bag-type filter with extended surface area and a lower pressure drop. The results of the 40-week study show that the premium filter was able to maintain the lower pressure drop and would have a longer service life (Chimack and Sellers, 2000).

A more in-depth study by Burroughs (2004) evaluated several different filters, from MERV 5 to MERV 16, in a variety of commercial environments for a period of one year. The study included 55 different sites in 5 different cities, incorporating a variety of filtration needs. The sites were grouped into low (L), medium (M), and high (H) efficiency classes. Each class had its own MERV-rated filters, as shown in Table 10 (Burroughs, 2004).

Particulate loading in the air stream was identified and compared in upstream and downstream conditions, with data being acquired primarily at the filter bank. The impact of the filters was presented as percent reduction of particles for each diameter. The three filter efficiency results are listed in Table 11.

The data gathered in the study produced a very large range for all particle diameters and all efficiency classes, as there are high standard deviations for the numbers in the table (Burroughs, 2004). As shown in Table 11, higher MERV-rated filters generally remove more particles from the filtered space and produce higher quality air than lower MERV-rated filters, validating the MERV ratings as adequate predictors of field performance (Burroughs, 2004). Low-level filters showed very slight percent reductions at small diameters and moderate reductions at larger diameters. Other factors, including particle counts and on-site buildup, demonstrate that filters below MERV 7 do not adequately prevent particle accumulation in the system (Burroughs, 2004). Medium-level class filters provided a respectable improvement over the low class levels. High-level MERV filters proved superior in performance over the other two levels. They also, however, exhibited some variations within their class for certain particle diameters, as shown in Table 12 (Burroughs, 2004).

The detailed analysis of individual MERV ratings shows definite variations in the high class performance, in percent reduction by both particle diameter and MERV rating. Despite these variations, all high class MERV-rated filters maintained a superior performance overall (Burroughs, 2004).

The literature review indicates that the use of mechanical filters does, in fact, lead to the reduction of particles. In general, filters with higher MERV ratings (or higher expected efficiencies if not assigned a MERV rating) performed better than filters with lower MERV ratings when impacts in actual HVAC environments were evaluated. Note that there is not a significant amount of actual HVAC environment data available.

Table 10. Filter Types and Efficiency Classes (Burroughs, 2004)

Efficiency Class	Filter Type and Description	ASHRAE 52.1 ADSP %	ASHRAE 52.2 MERV
Low	Link-Panel – 1" using synthetic blanket media that may or may not be enhanced	<20%	MERV 5
	Conventional Pleated Filter – 2" or 4" pleat depth, low capacity pleating	<30%	MERV 6
	Pleated Filter – 2" or 4" pleat depth (An upgraded pleat using enhanced electret media)	30–35%	MERV 8
Medium	Pleated Filter – 2" or 4" pleat depth (An upgraded pleat using enhanced electret media)	50–65%	MERV 11
	Medium Efficiency Extended Media Bag Filter – with pockets made of synthetic media	40–55%	MERV 9
High	High Efficiency Cartridges – minipleat type with high capacity pleat	70–75%	MERV 12
	High Efficiency Cartridges – minipleat type with high capacity pleat	80–85%	MERV 13
	High Efficiency Cartridges – minipleat type with high capacity pleat	90–95%	MERV 14
	High Efficiency Cartridges – with pockets made of synthetic media	90–95%	MERV 14
	High Efficiency Cartridges – minipleat type with high capacity pleat	98%	MERV 16

ADSP – Atmospheric Dust Spot Discoloration Method (ASHRAE 52.1-1992)

Table 11. Summary of Percent Reductions of Particles (Burroughs, 2004)

Level	Particulate Diameter (μm)					
	0.3	0.5	1	3	5	10[a]
Low	2.3%	10.7%	26.4%	54%	65.7%	83.9%
Medium	13.8%	23.6%	41.2%	67.7%	77.6%	88.3%
High	41%	53.8%	67.7%	87.3%	92.3%	94.8%

[a] Actual counts of these particles were too low to derive any statistical conclusions from the data (Burroughs, 2004).

Table 12. Average Percent Reductions for MERV Ratings in High Class (Burroughs, 2004)

MERV value	Particulate Diameter (μm)					
	0.3	0.5	1	3	5	10[(a)]
MERV 12	23.3%	33.7%	51.3%	82.9%	89.5%	96.6%
MERV 13	50.5%	59.2%	76.7%	90.5%	92.9%	93.1%
MERV 14	32.3%	44.5%	62.3%	84.7%	91.8%	94.7%
MERV 16	84.5%	93.5%	96.1%	97.1%	97.3%	98.6%

[(a)]Actual counts of these particles were too low to derive any statistical conclusions from the data (Burroughs, 2004).

4.3.3 Additional Factors

Filtration of Inert vs. Bioaerosols. Several studies have compared measured penetrations of inert and biological aerosols through masks and respirator filters (Brosseau et al., 1994; Chen et al., 1994; Willeke et al., 1996; McCullough et al., 1997; Wake et al., 1997; Qian et al., 1998). Consistently, no significant difference in filter penetration was found between spherical inert and spherical bioaerosol particles of similar aerodynamic diameter, suggesting that inert particles of the same size may be used to predict bioaerosol efficiency. In some cases, the penetration of rod-shaped bacteria was lower than that of spherical organisms of the same aerodynamic diameter, indicating that in addition to particle size, particle shape also may affect penetration through respirator filters.

Relevant studies are highlighted below. Qian et al. (1998) found the filtration efficiencies of N95 respirators were equivalent when challenged with inert NaCl particles and polystyrene latex (PSL) spheres, and two bioaerosols, *Bacillus subtilis* (0.8 μm) and *B. megatherium* (1.2 μm), of the same mean aerodynamic diameter. These results were consistent with Brosseau et al. (1994), who found no significant difference in penetration though flatsheet fiberglass filter media when challenged with PSL spheres and *Mycobacterium chelonae* (0.78 μm) of the same aerodynamic size. Chen et al. (1994) report this same conclusion for experiments under equivalent test conditions, with a surgical mask and several disposable dust-mist-fume and HEPA respirators. Based on their results, Brosseau et al. suggest that an inert aerosol with aerodynamic particle size similar to a bioaerosol of interest is an appropriate test aerosol to predict bioaerosol filter collection.

In a recent report by RTI International, Hanley and Foarde (2003) assessed the filtration efficiency provided by the C2A1 canister against inert KCl particles and a bioaerosol of *B. globigii* (Bg) spores. In nearly all test cases, no Bg spores were detected downstream of the C2A1 canister. Results similarly demonstrated that inert aerosol penetration in the 0.7 to 1.0 μm range were consistent with those measured using the Bg spore challenge.

Research efforts on filter efficiency have largely focused on bacterial aerosols, thus limited information on viral aerosols is currently available. Hofacre et al. (1996) measured the penetration of PSL spheres (0.173 μm) and a viral aerosol of MS2 phage through a HEPA filter used for collective protection. Aerosol penetration measured using the light scattering technique was statistically equivalent for both the MS2 phage and PSL particles, while the penetration of MS2 phage measured using the bioassay method was consistently lower by a factor of approximately four. The study concluded that inert aerosols of similar size provided a conservative indication of HEPA filter performance against a bioaerosol.

Previous reports on filter performance against particles of various sizes, shapes, and aspect ratios (a measurement comparing the length and diameter of nonspherical particles) contain conflicting results. Willeke et al. (1996) compared penetrations through surgical masks and dust-mist respirators of several rod-shaped bacteria (*B. megatherium*, *Pseudomonas fluorescens*, *B. alcalophilus*) of varying aspect ratios with that of spherical *Streptococcus salivarius* and inert corn oil particles. Results indicate the penetration of spherical *S. salivarius* bacteria were approximately the same as spherical corn oil particles in the aerodynamic size range from 0.9 to 1.7 μm. The penetration of rod-shaped bacteria was lower than *S. salivarius* and decreased with increases in the aspect ratio, showing that filter penetration of bacteria is a strong function of their shape. Willeke et al. postulated that due to greater surface area of nonspherical particles compared to spherical ones, interception and electrostatic attraction cause greater removal (i.e., less penetration) for rod-shaped bacteria compared to spherical particles of the same aerodynamic size.

In comparison, McCullough et al. (1997) evaluated the penetration of inert PSL spheres (0.55 μm) and *M. abscessus* (0.69 μm), *B. subtilis* (0.88 μm), and *Staphylococcus epidermidis* (0.87 μm) bioaerosols through a variety of dust-mist-fume filters and surgical masks. In all cases, penetration of the inert aerosol was greater than any of the biological aerosols due to its smaller aerodynamic diameter. However, results showed that *B. subtilis* (a rod) was more penetrating than *S. epidermidis* (a sphere) at approximately the same aerodynamic diameter. Contrary to Willeke et al. (1996), the authors suggest that the aerodynamic diameter of the bacteria may not be an accurate predictor of aerosol penetration for nonspherical particles in these filters, particularly when electrostatic forces are dominant.

Reaerosolization. Limited information is available on the reaerosolization of particles from filter materials. The most relevant studies were conducted by Qian et al. (1997a, 1997b).

Qian et al. (1997a) evaluated the reaerosolization of inert and biological aerosols from three different models of N95 half-mask respirators at velocities of up to 300 cm/sec, intended to represent violent sneezing or coughing. The filters were loaded with aerosols of either sodium chloride (NaCl) in water, PSL spheres, or the bacterium *Bacillus subtilis* or *B. megatherium*. Reaerosolization was found to be insignificant for particles of less than 1.0 µm, with less than 0.025% becoming reentrained. For the condition of violent sneezing or coughing, only larger particles were reaerosolized in significant amounts: about 1% of 3 µm and 6% of 5 µm PSL particles. This is of importance as single bacteria may aggregate or attach to inert particles to form larger clusters, increasing their risk of reaerosolization. In addition, results indicate that bacteria become reentrained at high air velocities more easily than the NaCl particles of similar size, which the authors reason may signify a weaker bond to the filter fibers or more surface area exposed to the airflow. Finally, no reaerosolization of particles was observed when the relative humidity was increased to 35%, which the authors attribute to liquid bridging between particles and filter fibers that increases the adhesion force.

In a related study, Qian et al. (1997b) assessed the effects of particle size, inert particle type, filter type, and reentrainment velocity on reaerosolization of inert aerosols including NaCl in water, PSL spheres, corn oil, and dust. Test methods similar to the previous study were employed. Flat sheets of three types of fibrous filter media used in half-mask respirators were evaluated. Reaerosolization trends were in agreement with the previous study as reentrainment of 0.6 to 5.1 µm particles increased approximately with the square of particle size and the square of reentrainment velocity and decreased with relative humidity. Reaerosolization was also found to be a function of particle type as dust was found to have the highest reentrainment, while corn oil was not reentrained under any of the test conditions. This difference in reentrainment was attributed to differences in interaction with the filter fibers of oily particles compared to solid, irregularly shaped particles. Consistent with previous studies, electrostatic charges on the filter fibers significantly increased the collection of submicrometer particles; however, particle reaerosolization was only slightly impeded by the embedded charges. Finally, filter properties were found to significantly affect particle reaerosolization. The number of reaerosolized particles decreased slightly with filter thickness, an observation that supports the concept that most of the particles are reentrained from the front layer of the filter. Essentially no particle reentrainment was observed from charged felt, compared with up to 5 to 15% from glass fiber HEPA and polypropylene filters.

Reentrainment of bioaerosols from air ventilation filters has also recently been studied. Jankowska et al. (2000) compared the collection efficiency and reentrainment rate of the fungal spores *Penicillium brevicompactum* and *P. melinii* against that of inert potassium chloride (KCl) particles, using a medium prefilter and a higher efficiency fine filter. Reaerosolization increased with reentrainment velocity for all test particles. When the reentrainment velocity was the same as the loading velocity, the reaerosolization was less than 0.4%. When the reentrainment velocity was increased to 3.0 m/s, the reaerosolization of fungal spores was higher than that of KCl particles, ranging from 2 to 6% for *P. brevicompactum*, 5 to 12% for *P. melinii*, and 0.2 to 0.6% for KCl particles. The higher reentrainment of fungal spores was attributed to the presence of aggregated spores, where the reentrainment velocity may become sufficient to break up the aggregates and reentrain the spores. The differences between fungal spores were attributed to surface structure: *P. melinii* spores have a spiny surface, imparting weaker contact with the filter fibers.

In summary, particle size, shape and composition, air velocity, humidity, and filter properties were all factors found to affect particle reentrainment from filter materials. Large particles of approximately 5.0 µm diameter and greater were found to be most susceptible to reaerosolization. Biological particles were found to become reentrained more easily than inert particles of comparable size, possibly because of weaker contact with filter fibers due to irregular shapes and surface characteristics. In addition, aggregation of bacteria and fungal spores to form larger clusters was determined to also increase potential reaerosolization.

Pulsed Flow. A limited number of studies assessed the effect of pulsed or variable flow on filter performance. Two studies compared the aerosol penetration through respirator filters under constant and cyclic flow conditions (Stafford et al., 1973; Brosseau et al., 1990).

Stafford et al. (1973) measured the penetration of monodisperse PSL (0.176 to 2.02 µm) and dioctyl phthalate (DOP) (0.3 µm) aerosols through respirator filter cartridges at three cyclic flows with mean flow rates of 30, 35, and 53 L/min. These flows were selected to correspond to a range of work rates from moderate to heavy. Tests were also conducted at a constant flow rate of 16 L/min (equivalent to 32 L/min through a pair of cartridges). Under steady-flow conditions, the maximum penetration occurred at a particle size of 0.3 µm, which is consistent with theoretical single-fiber predictions. However, during cyclic flow the particle size that produced maximum penetration varied between filters, in one case less than 0.3 µm and in the other approximately 0.5 µm. Also, the maximum penetration was considerably higher than corresponding steady-flow values, suggesting that tests conducted under steady-flow conditions may overestimate filter performance.

Brosseau et al. (1990) compared the collection of silica and asbestos aerosols by dust/mist respirators under breathing and constant flows. The cyclic-flow was sinusoidal with a minute volume of 32 L/min, mean flow of 76 L/min, and a peak flow of 100 L/min. The constant flow rate was 32 L/min. In general, the silica penetration under cyclic flow conditions was about one and a half times as great as that measured under steady-flow conditions, which was consistent with the results of Stafford et al. (1973). The asbestos results were inconclusive as the results varied by filter.

Nanoparticle Filtration. Nanoparticles or ultrafine particles are generally defined as less than 0.1 µm (100 nm) in diameter. Based on the theory described in Section 4.2, the filtration efficiency is expected to improve as the particle size decreases below 100 nm due to the increased efficiency in capture due to Brownian diffusion. However, at some point, the particles will behave more like a vapor than a particle, and, thus, collection efficiency is expected to decline due to thermal rebound. Diffusion is the primary collection mechanism in the nanoparticle size range. The impact velocity is referred to as the thermal velocity. Thermal rebound occurs when the thermal velocity exceeds a critical value that results in particle bounce from a fiber surface following impaction. Wang and Kasper (1991) have modeled the filtration efficiency of nanometer-sized aerosol particles through fibrous filters and predicted that thermal rebound is unlikely to cause enough degradation in performance to be detected experimentally down to at least 2 to 5 nm. Several studies have recently assessed the performance of fibrous filtration media against nanometer-sized aerosols to determine the size at which thermal rebound becomes evident (Kim et al., 2006; Heim et al., 2005; Chen et al., 2006; Balazy et al., 2004; Balazy et al., 2005; Kim et al., 2007). Results to date have suggested that filtration theory remains valid down to particle sizes of at least 3 nm. Relevant studies are summarized below.

Kim et al. (2006) measured the filtration efficiency of two glass fiber filters against a sodium chloride aerosol over the range of 1 to 100 nm. The specific application for the filters was not provided. The effects of particle size, relative humidity, and particle charge were assessed. The measured efficiencies were independent of humidity over the range tested (dry to 92% at ambient temperature). The measured collection efficiencies were highest against the charged aerosol. The magnitude of the difference decreased as the particle size decreased. This observation was attributed to the fact that collection by diffusion becomes more efficient with decreasing particle size. The data suggest that thermal rebound may begin to occur at particle sizes below 2 nm. This conclusion is supported by the work of Heim et al. (2005) who characterized the performance of three low-efficiency filters/meshes over the range of 2.5 to 20 nm and concluded that thermal rebound was not detected in the size range down to 2.5 nm.

Chen et al. (2006) assessed the penetration of a salt aerosol over the range of 4.5 nm to 10 µm through two filtering facepiece respirators. No evidence of thermal rebound was observed down to a particle size of 4.5 nm. Tests were also performed after dipping the respirator filters in isopropanol to remove their electrostatic charge. Removal of the charge led to a shift in the most penetrating particle size from 50 nm to 200 nm. The collection efficiency of particles less than approximately 20 nm was unaffected, demonstrating that diffusion is the most important collection mechanism in this size range.

Japuntich et al. (2006) evaluated various test methods to measure nanoparticle penetration through a fibrous filter. The particle size range evaluated was 10 to 400 nm. The penetration appeared to decrease with decreasing particle size down to 10 nm as predicted based on the single fiber theory. Kim et al. (2007) characterized the performance of several fibrous filters against nanoparticles ranging from 3 to 20 nm. Penetration was observed to continuously decrease with decreasing particle size over the range tested. In a companion study, Wang et al. (2007) demonstrated that the measured collection efficiencies were in good agreement with classical filtration theory down to 3 nm.

Balazy et al. (2005) assessed the performance of two commercially available N95 filtering facepiece respirators against a nanoaerosol challenge over the range 10 to 600 nm. The effects of particle size, flow rate, and particle charge were assessed. The most penetrating particle size was between 40 and 70 nm for the respirator filters evaluated and penetrations exceeded 5% at the higher flow rate. The most significant increases in penetration were observed for particles of less than 100 nm when the flow rate increased from 30 to 85 L/min. Collection efficiencies of particles in the range of 10 to 20 nm were near 100%, indicating that thermal rebound was not an issue. As expected, charge neutralized particles were more penetrating than charged particles.

Fewer studies were identified in the literature specific to HVAC filters. Roth et al. (1999) assess the filtration efficiency of three fibrous filters used in HVAC systems. Two filters were reported as electrostatic filters, and one was reported as a HEPA filter. The challenge aerosol was ambient air and a differential mobility analyzer was used to measure efficiencies over the range of 10 to 200 nm. The airborne concentration of particles larger than 200 nm was not sufficient for measurement of efficiencies. The HEPA filter showed a minimum collection efficiency at about 60 nm. The two electrostatic filters behaved differently. One, a commercially available product, showed poor performance against particles ranging from 10 to 30 nm (with efficiency less than 20%) but a general trend of increased efficiency with increased particle size. The efficiency of the other electrostatic filter was fairly constant and over 90% for particles in the 10 to 100 nm size range.

Balazy et al. (2004) assessed the efficiency of two commercial fibrous filters, classified as F5 and G4 per EN 779, over the range of particle diameters from 10 to 500 nm. The challenge aerosol was oil and a wide-range spectrometer (WPS, Model 1000, MSP Corp.) was used to measure the challenge and downstream aerosol concentrations. A local maximum in collection efficiency was observed at about 20 nm, below which collection efficiency decreased with decreasing particle size. The authors suggested that this decrease was attributed to thermal rebound. Others have attributed this decrease to a low challenge concentration for particles less than 20 nm (< 100/cm^3) and errors in the downstream sampling approach (Harrington, 2005; Heim et al., 2005).

Owen et al. (2003) characterized the filtration efficiency of 26 residential and industrial filters for HVAC systems. The filters were selected to cover a range of MERV ratings (~5 to 16). The effect of particle size was assessed over the range of 30 nm to 10 µm. The challenge aerosol was potassium chloride. As expected, efficiency tended to increase with increased MERV rating. This trend was generally true for all particle sizes evaluated. The lowest efficiencies were generally measured in the 0.1 to 0.5 particle size range. The higher efficiency filters showed increased efficiency as the particle size increased or decreased away from the most penetrating. The lower efficiency filters performed very poorly against particles less than 100 nm. For example, collection efficiencies of two MERV 6 filters was less than 20% over the range from 30 to 100 nm.

In summary, high efficiency fibrous filters, especially those used in respirator applications, have been shown to perform as predicted based on single fiber filtration theory down to particle diameters of at least 2.5 nm. In general, collection efficiency has been observed to increase with decreased particle size due to the enhanced collection by diffusion. Studies completed with charge neutralized media have shown that diffusion is the dominating capture mechanism below 20 nm. Fewer studies were identified that assessed the performance of HVAC filters. However, assuming that fibrous filters were used, they would be expected to perform as predicted based on filtration theory. Owen et al. (2003) showed that collection efficiency of nanoaerosols tended to increase with increasing MERV rating. Several of the lower rated filters performed poorly against nanoparticles with penetrations nearly 100%.

4.4 Critical Assessment

4.4.1 Technology Assessment

Air cleaning methods that rely on mechanical filtration for particle removal are well established, reliable, understood, and described (predictable). [In general, HVAC applications such as residential or commercial buildings with no need for air cleaning other than to control nuisance dust and protection of mechanicals typically rely on relatively low (< 90%) efficiency mechanical filters.]

Filters that rely solely on mechanical particle capture mechanisms, especially HEPA filters, have been extensively studied and characterized. HEPA filters were originally developed to control emissions in the nuclear energy field and have since been the principal means of particle removal for individual and collective protection applications that require high efficiency.

In general, the literature review did not identify conflicting or controversial data. The literature is in good agreement regarding the controlling filter and particle characteristics that affect collection efficiency—hence, the well-established theory to predict aerosol penetration.

One area of interest within the past decade is the performance of mechanical filters with respect to aerosols of biological origin (ABO), or bioaerosols. Of specific interest is whether the capture efficiency of bioaerosols is comparable to that of inert aerosols of similar aerodynamic size, especially in applications for individual (respiratory) and collective protection systems, notably for military applications but also for healthcare workers. Battelle is currently supporting research for NIOSH to further study the penetration of inert and biological aerosols for respirator filters. In an assessment of literature on biological versus inert aerosol filtration, the general consensus is that mechanical filters are comparably effective at removing particles, independent of the particle type, as long as they are of comparable aerodynamic size.

Related to the bioaerosol versus inert aerosol collection efficiency is the concern regarding grow-through of organisms and reentrainment (particle shedding). There have been few studies of organism grow-through, which is the concern that collected organisms can grow on/in the filter, reaching the back side, and then shed to become an inhalation hazard. In summary, for sustained growth, moisture and a nutrient source are required. Although conditions can be achieved to support growth of organisms on filters, it does not yet appear to be an established hazard or problem. Proper filter maintenance can avoid these potential problems.

Shedding is a concern because post collection of a hazardous aerosol could result in reaerosolization. Very little has been published regarding reaerosolization, and the topic is currently being researched by Battelle for NIOSH. Although mechanical force can be used to dislodge heavily loaded dusts, whether lightly loaded filters with a bioaerosol challenge will dislodge is unknown. According to inert particle collection theory, once a particle has collected on a fiber, it is retained.

The main area of research regarding fibrous filters is apparently the development of nanofibers and surface treatments. Filtration media producers such as Donaldson and Freudenberg are developing “nanofibers” incorporated into filters. According to filtration theory, the smaller the fiber, the higher the collection efficiency. These media are in consideration for the advanced filter prototype to be developed under a different subtask of this contract. Treatment of fibers is also being explored for biocidal activity and for enhancing collection efficiency. For example, anionic surfactants have been applied to fibrous filters with marginal decreases (10 to 20% of ~0.3 µm particles) in penetration, without change in filter physical or mechanical properties. The concept is to enhance the electrostatic collection properties by establishing a surface change on the fibers.

4.4.2 Impact on HVAC System

Mechanical filters are by far the most widely used type of air cleaner. Mechanical filters are the standard against which other types of air cleaners and air cleaning technologies must be compared. Future developments, therefore, are not likely to include significant improvements in their performance. In general, the advantages of mechanical filters are their low cost, wide availability in a variety of sizes and performance ranges, and well-known performance. The collection efficiency of mechanical filters generally increases as they age, so their efficiency is generally lowest at installation. The key disadvantage of mechanical filters is that their pressure drop increases with use, requiring an increase in the power needed to maintain airflow, and requiring replacement with a frequency that is proportional to their efficiency (higher efficiency filters require more frequent replacement). In addition, high humidity air can cause rapid increases in pressure drop in some circumstances, as well as mold growth on the filter.

If filters selected for use in an HVAC system have higher pressure drops than in the original design, it will adversely impact the HVAC system. Additional booster fans may have to be used, or the speed of the existing blower may have to be modified to overcome the increase in pressure drop.

4.4.3 Cost Analysis

An in-depth cost analysis of mechanical filtration is provided in Section 9.2. If new mechanical filtration were added to an existing air handler in a typical office building, no major air handler modifications would be required because the filters would typically fit into an existing air handler and their pressure drop would be low. Mechanical filtration has the least expensive initial purchase and installation cost of all types of air cleaners analyzed in this report. Adding these types of filters might require installation of a new access door in the existing unit and new pressure gauges.

The operating and maintenance cost increase would be very small. Mechanical filters require only yearly changing (filters are easy to change), which may amount to a maintenance cost increase of 19% for a typical office building. The static pressure added to the air handler from the mechanical filtration would not be great; however, the fan speed would need to be adjusted, which would increase the operating cost of typical office building by 6%.

5.0

Critical Assessment of Electrostatically Enhanced Filtration

5.1 Technology Description

Electrostatically enhanced filtration technology improves the potential performance over standard fibrous filters that rely solely on mechanical means of aerosol collection. Aerosol filtration by fibrous filters has been described previously in the mechanical filtration technology description in Sections 4.1 and 4.2. Likewise, the enhancement that can be achieved by increasing the electrostatic capture forces will be discussed in the technology description for electret filtration media in Section 6.1. The electret media make use of polarization of the fibers to enhance particle collection by electrostatic forces, which supplement the forces of particle collection by mechanical mechanisms of interception, impaction, and diffusion. The electrostatically enhanced media are treated as a separate technology category because of the physical differences from standard fibrous media or electret media.

5.2 Theory of Electrostatically Enhanced Filtration

Technological advancements have been recently made and products such as StrionAir® GC Filter are now commercially available. The principle of operation is to ionize the incoming airstream and particles so that a surface charge is achieved on the incoming particles upstream of the filter. (See Figure 9 for an illustration of this concept.) Charging of these particles increases their electrical mobility and also the attractive force to oppositely charged surfaces. Fibrous filter media are located between a negatively charged electrode upstream and a positively charged electrode downstream. When power is applied to the electrodes, an electrical field is generated, and the fibrous filter media are polarized, i.e., the fibers of the media form areas of negative and positive charge. (See Figure 10 for an illustration of this concept). In this manner, electrostatically enhanced filtration is similar to electret media. In the case of the electrostatically enhanced filter, the fibers are not permanently charged like electrets, but rather are charged only in the presence of the electrical field. Particle collection thus occurs predominantly due to the electrostatic forces. Because particle collection is predominantly associated with electrostatic force, larger fiber diameters can be used for the fibrous filter (it is the small diameter fibers that are prevalent in particle capture in mechanical filters). All other parameters of a filter are constant: the larger the fiber diameter, the lower the airflow resistance. Rather than increase the collection efficiency of a fibrous filter by reducing the fiber diameter and thus increasing the pressure drop, the collection efficiency is enhanced by the charging of the particles and polarization of the fibers.

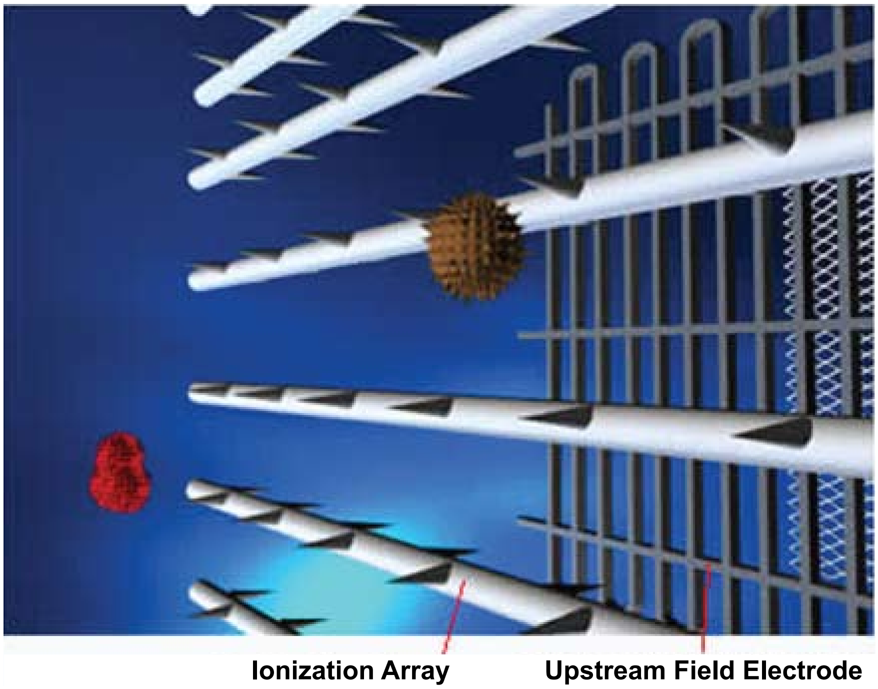


Figure 9. Illustration of Particle Charging Upstream of Fibrous Filter by Ionization Array (From StrionAir, Inc. Web site, www.strionair.com)

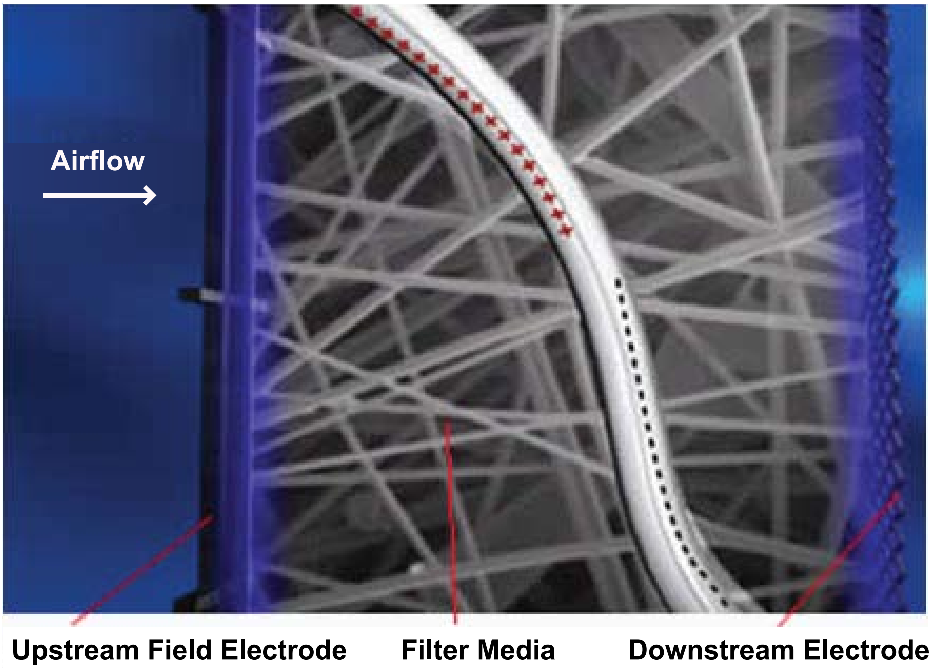


Figure 10. Illustration of Fiber Polarization by Oppositely Charged Electrodes (From StrionAir, Inc. Web site, www.strionair.com)

5.3 Summary of Relevant Studies

Many authors of the reviewed papers noted the improved performance of electrostatically enhanced media, regardless of how the electrical enhancement was achieved (Brown, 2001; Carlsson, 2001; Drouin, 2000; Emmerich and Nabinger, 2001; Fugler et al., 2000; Thorpe and Brown, 2003; Wang, 2001). However, several papers identified in this search actually used electret media, which are also described by some to be electrostatically enhanced (Brown, 2001; Carlsson, 2001; Drouin, 2000; Raynor and Chae, 2003). Electret media are discussed as a separate technology in Section 6.0 of this report.

Several recent studies of electrostatically enhanced devices are summarized in Table 13. One study performed a detailed examination of the variables affecting collection efficiency for an electrostatically enhanced filter, though incoming particles were not ionized before collection as described above (Thorpe and Brown, 2003). Other studies measured the in-duct efficiency in a house and the expected reduction in indoor particle concentrations with the use of filtration (Emmerich and Nabinger, 2001; Fugler et al., 2000). Both of these studies examined a range of devices and compared the performance of different technologies.

Table 13. Summary of Recent Studies on Electrically Enhanced Devices

Basic Scope	Content/Conclusion	Reference
Performance Data	Measured aerosol penetration for a range of fiber diameters, face velocities, applied voltages, and particle sizes; performance was as expected (increasing with decreased face velocity and fiber size and increased voltage and particle diameter; applied electrical fields offer improvements over mechanical filtration similar to electret media.	Thorpe and Brown, 2003: Agranovski et al., 2006.
Effectiveness Data	Measured in duct efficiency and indoor particle concentrations for a range of devices for comparison purposes; electrostatically enhanced filters performed better than mechanical filters, though not nearly as well as ESP filters.	Emmerich and Nabinger, 2001: Fugler et al., 2000.
Models of Electrostatic Collection Forces	Present equations describe electrostatic attraction forces for various scenarios involving charges on particles or particles in electrical fields; mathematical descriptions of performance are lacking for electrostatic filter forces, particularly for filters with significant loading.	Thorpe and Brown, 2003: Wang, 2001.

5.3.1 Performance and Variables That Affect Performance

The performance of electrostatically enhanced filtration technologies depends on several factors. Because the filters used are mechanical or fibrous filters, the performance depends on the fiber diameter and the number of fiber layers. The addition of the electrical field over the filter creates a dependence on the voltage used, as is the case with electrostatic precipitation technology. Also, the performance depends on the particle size and the face velocity through the filter, as is the case with both mechanical and electrostatic precipitation.

Three of the studies listed in Table 13 — Thorpe and Brown (2003), Emmerich and Nabinger (2001), and Fugler et al. (2000) — measured the collection efficiency of an electrostatically enhanced filter, with the latter two studies measuring the in-duct efficiency with the filter installed in a house.

All three studies examined the effect of particle size on collection efficiency. Emmerich and Nabinger (2001) measured in-duct efficiencies of about 7% for particle diameters of 0.3 to 0.5 µm, 10% for 0.5 to 1.0 µm, and 13% for 1.0 to 5.0 µm in an uninhabited test house. In Fugler et al. (2000), a collection efficiency of 20% for PM10 particles and 17% for PM1 particles was reported based on measurements taken in six different inhabited test houses. Both studies were short in duration and did not study performance over an extended period of time. Thorpe and Brown (2003) performed an experimental study of an electrostatically enhanced filter in a laboratory setting. Figure 11 shows the variation in aerosol penetration with particle diameter for several applied voltages, ranging from no field to 600 kV/m. Analogous to the results above, greater efficiency (or lower penetration) is seen at larger particle diameters. In fact, collection efficiencies are shown to increase by an order of magnitude for all particle sizes. Collection efficiency is also shown to increase with increased voltage, especially for the larger particles.

Of the above studies, Fugler et al. did not measure the in-duct velocity. Emmerich and Nabinger (2001) measured an average duct velocity of about 5 m/s with the filter in place and did not study other velocities. Figure 12 shows the results of Thorpe and Brown (2003) for filtration velocity for several voltages, again ranging from no field to 600 kV/m. As can be seen in the figure, the effect of face velocity is less significant with low electric field voltages. At higher electric field voltages (300 and 600 kV/m), aerosol penetration is greater at higher velocities. Emmerich and Nabinger reported a relatively high penetration (around 90% for all particles) at a much higher velocity, though it is unclear what electrical field voltage was tested.

As is clear from Figures 11 and 12, collection efficiency increases (and aerosol penetration decreases) with increasing electric field voltage (Thorpe and Brown, 2003). Emmerich and Nabinger (2001) and Fugler et al. (2000) did not report the operating voltages of the particular filters tested, so it is not possible to compare the performance measured in those studies with the study of Thorpe and Brown (2003).

Thorpe and Brown (2003) demonstrated little significance with regard to the polarity of the electrical field, as seen in Figure 13. This figure is another example of the improved performance at higher voltages, demonstrating decreasing penetration with increasing voltage.

Pressure drop was measured by both Thorpe and Brown (2003) and Emmerich and Nabinger (2001). However, pressure measurement results were not directly reported. Thorpe and Brown do report a 13% increase in pressure drop with a high loading test, as discussed in the next section.

Thorpe and Brown (2003) demonstrated only minor changes to aerosol penetration with time of operation when loading a filter with sodium chloride particles. To maintain performance for a reasonable test time, the charged electrode was exchanged with the grounded electrode in the downstream position, resulting in about 303 minutes of test time versus 10 minutes with the charged electrode upstream. Regardless of the position of the charged electrode, the filter failed by short circuiting due to the accumulation of sodium chloride particles in contact with the electrode generating the field. Without the electrical field, the performance of the filter was reduced, as shown above. The authors performed similar measurements with a permanently charged filter (probably electret) and noted significant increases in the aerosol penetration, presumably due to the shielding of the electric charge by the sodium chloride particles. The results can be seen in Figure 14. The other studies did not examine performance degradation with time.

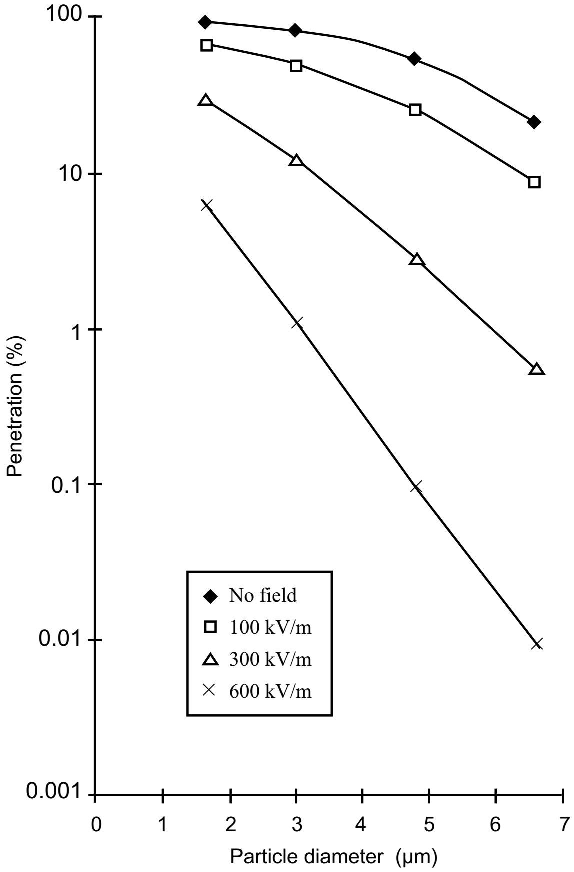


Figure 11. Penetration as a Function of Particle Diameter at Several Voltages Thorpe and Brown, 2003)

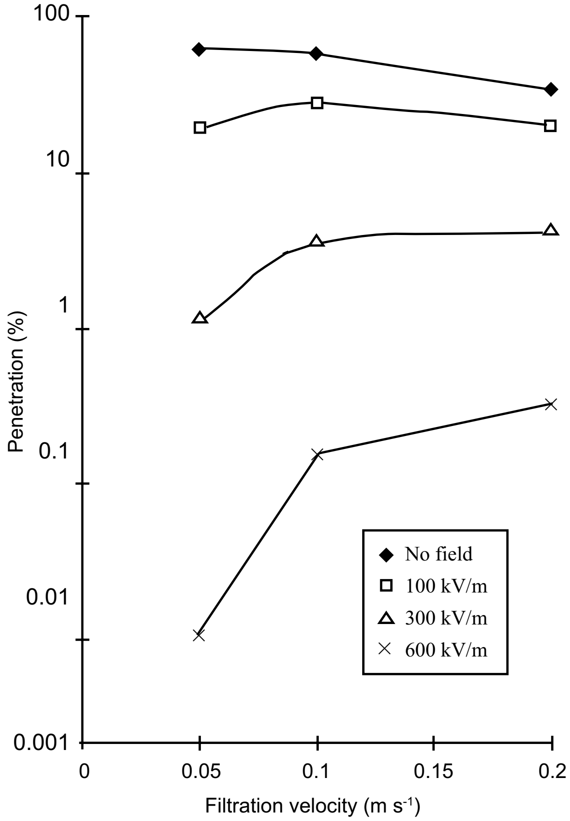


Figure 12. Penetration (with 37 μm diameter fibers) of Monodisperse Particles (of 4.8 μm diameter) as a Function of Face Velocity at Several Voltages (Thorpe and Brown, 2003)

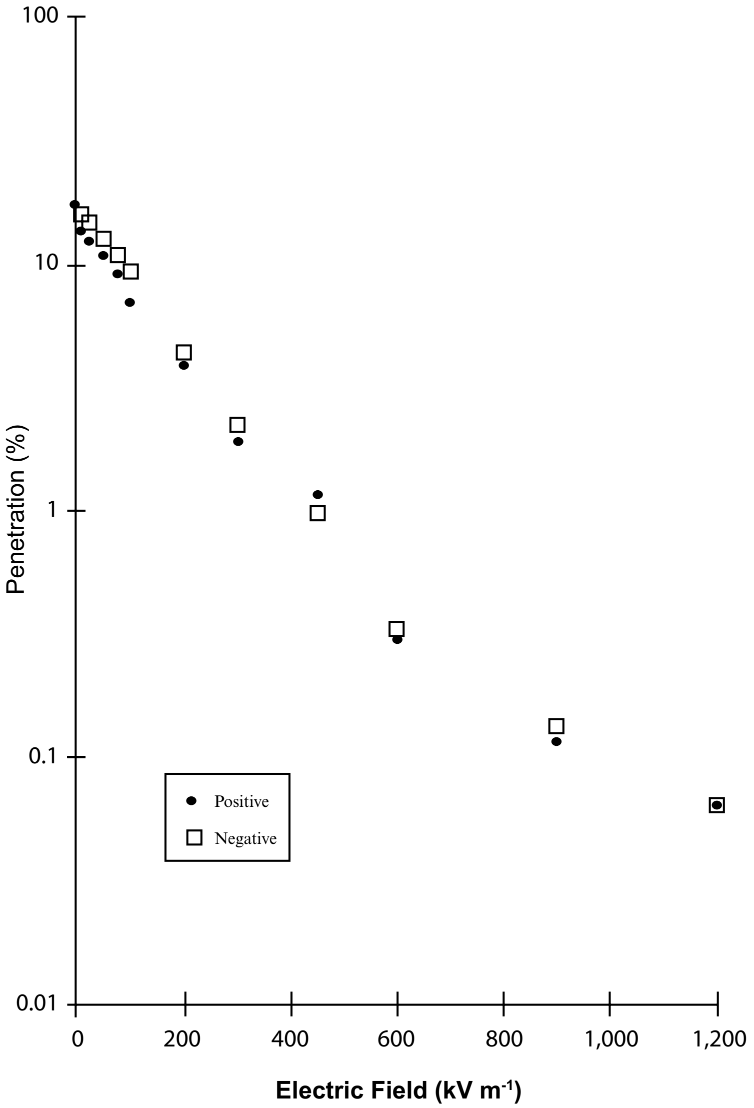


Figure 13. Penetration (with 37 µm diameter fibers) of Monodisperse Particles (of 3 µm diameter) as a Function of Voltage for Positive and Negative Electrical Fields (Thorpe and Brown, 2003)

Agranovski et al. (2006) assessed the impact of unipolar ionization on the collection efficiency of two low efficiency HVAC filters. The effects of particle size (0.5 to 1.5 µm) and distance between the emission source and filter surface were assessed. The face velocity was held constant at 1.1 m/sec resulting in pressure drops of 82 and 68 Pa across the two filters, respectively. Efficiencies of both filters were less than 20% for all particle sizes tested without the ionization source. The collection efficiency increased for all particle sizes with the use of the ion emitter. For example, for 1-µm particles, the collection efficiency jumped from 5 –15% to 40–90%. There was not a significant difference between the measured collection efficiencies with the ion emitter placed 5 and 10 cm upstream of the filter. The enhancement was less pronounced as the emitter was placed 25 cm from the filter. This concept was previously applied to respirator filters, and it was shown that particle penetrations were reduced by an order of magnitude (Lee et al., 2004b). In both studies, the authors attribute the improved performance to unipolar ions being deposited on the particles and filter media fibers resulting in a repelling force that shields a fraction of particles from the filter. The effect of loading was not assessed.

5.3.2 Assessment in an HVAC System

In studies by Emmerich and Nabinger (2001) and Fugler et al. (2000), collection efficiency was measured for a number of different devices installed in a house. In both studies, the electrostatically enhanced filter did not perform exceptionally well. In the study performed by Emmerich and Nabinger (2001), the electrostatically enhanced filter performed better than several other fibrous filters, but not as well as an electret filter, and much more poorly than an electrostatic precipitator device. The electrostatically enhanced filter performed poorly in Fugler et al. (2003), with a lower collection efficiency than several fibrous filters and an electrostatic precipitator (which again easily exceeded the performance of all the other devices tested).

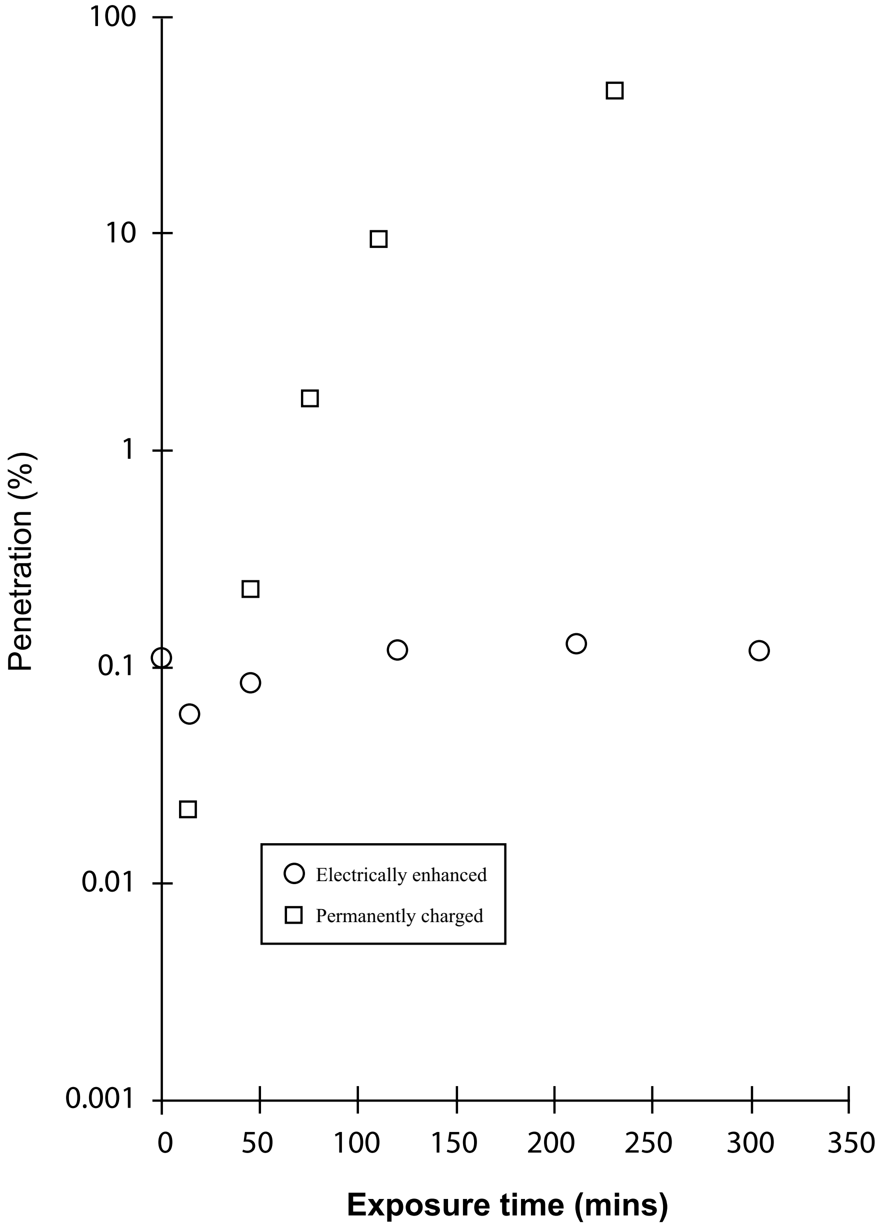


Figure 14. Aerosol Penetration of Monodispersed Particles (3 µm diameter) Through an Electrically Enhanced Filter and a Permanently Charged Filter as a Function of Operation Time (Thorpe and Brown, 2003)

5.3.3 Additional Factors

Reduction of Particles. Device effectiveness is often quantified by the reduction in particles. Both Emmerich and Nabinger (2001) and Fugler et al. (2000) measured indoor particle concentrations, but Emmerich and Nabinger (2001) do not directly report the reduction in indoor particles with the operation of the filter technology. Fugler et al. (2000) observed a 9% reduction in indoor PM10 levels during "active" periods (times when there is human activity) and a 29% reduction in indoor PM10 levels during "nonactive" periods (times when no one is home, everyone is sleeping, etc.). With these reductions, the authors note that the electrostatic precipitator, which showed an active reduction of 31% and nonactive reduction of 71% in particle concentration, did not significantly reduce occupants' exposure to indoor particulates. Figure 15 shows an example of the PM10 and PM1 concentrations measured within an occupied house for a 24-hour period while an electrostatic precipitation device was operating.

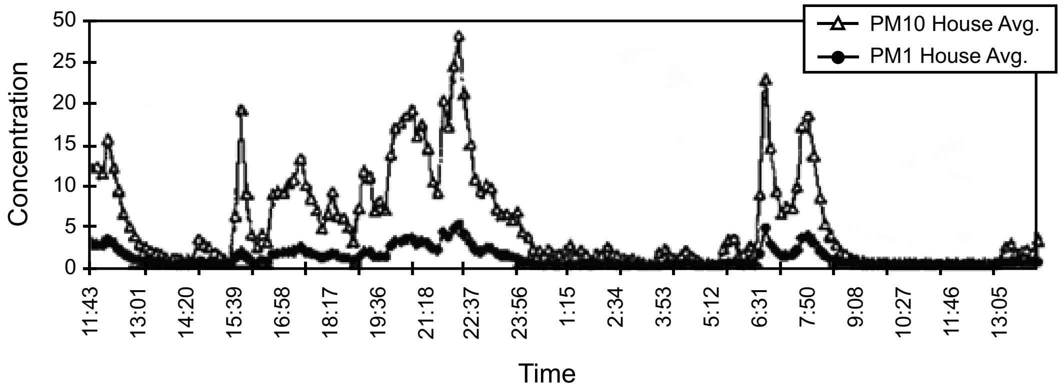


Figure 15. Example of Indoor Particle Measurements for a 24-hour Period With an Electrostatic Precipitation Device (Fugler et al., 2000)

Electrostatically enhanced filtration offers benefits over mechanical filtration since actively charging the filter region can significantly increase filtration efficiency, as is seen with passively charged electret filters. Electrostatically enhanced filters have the capability of using an adjustable electrical field strength, so increasing the electrical field voltage can improve filtration. Also, the electrical field in the filter is less apt to degrade due to the collection of charged particles or deterioration of the media, as can happen with electret filters. However, some electrical power is required to produce the electrical field, unlike electret. Filtration benefits are similar for electret and electrostatically enhanced filters, but electret filters are more frequently used because they do not have an additional electrical power requirement.

5.4 Critical Assessment

5.4.1 Technology Assessment

Electrostatically enhanced filtration devices are relatively new to the market and relatively little research regarding their performance is available compared to established air cleaning technologies such as fibrous filters or electrostatic precipitators. The principle of operation is not new, however. Electrostatically enhanced filtration is effectively the addition of electrostatic force to a variation of fibrous filtration in an effort to improve collection efficiency.

Consistent with electrostatic attraction theory (discussed in Section 4.2), collection efficiency increases with an increase in the applied voltage—an increase in the fiber charge. Depending on particle size, collection efficiency gains of one to three orders of magnitude were achieved, with the greatest increase experienced by the largest particles. The enhancement in collection efficiency is most significant as the filtration velocity decreases. Due to an increased residence time—longer time for the electrostatic forces to act on the particles—and reduction in inertial effects. Polarity of the field did not appear to matter.

Research conducted by Battelle (Kogan et al., 2007) regarding in-facility testing of units by measuring reduction in room aerosol concentration provides no useful information about the unit performance. There was only a 15% reduction in aerosol concentration found in a room equipped with a unit.

No comparison of performance of an electrostatically enhanced (EE) filter to an electret or fibrous filter was found. Excluding the cost of operation, the EE filters should be compared to other filters using the figure-of-merit metric given by:

$$\mathrm{FOM} = \frac{-\ell n\,(\mathrm{Pen})}{\Delta \mathrm{P}}$$

where Pen is the fractional penetration and ΔP is the pressure drop at a specified flow. In this manner, the increase in efficiency with reduction (or no increase) in pressure drop can be quantified for consistent comparisons.

5.4.2 Impact on HVAC System

The impact on an HVAC system of using electrostatically enhanced technologies is minimal. Because traditional fibrous filtration material is used, the pressure drops are not significantly different from what they are with other fibrous filters. Modifications to the HVAC system would not necessarily need to be made due to the pressure drop of an added electrostatically enhanced technology. As with any air cleaning device that employs an ionizing source, generation of ozone is a concern. There were no reported studies regarding ozone concentration measurements, but that does not mean that there was no ozone production. Ozone generation should be measured in future research.

5.4.3 Cost Analysis

Electrostatically enhanced filters can typically fit into an existing air handler without major modifications. Most filters that have been electrostatically enhanced do not increase the static pressure of the system. Units that charge particles upstream of fibrous filters to enhance filtration (e.g., using an ionization array) present an additional, finite, resistance on the system. The retrofit of an HVAC system with electrostatically enhanced filters or arrays might require a new access door to be added to the existing unit and new pressure gauges. Although these filters do not use a great deal of electricity during normal operation, installation would require new electric service. Due to the complexity of the filter itself, initial and installation costs for this type of filter are very high.

The operating and maintenance cost increase would be small. These filters require only annual changing (only the pads need to be changed), which may amount to a maintenance cost increase of 24% for a typical office building. The static pressure added to the air handler from the mechanical filtration would not be great. However, the fan speed would need to be adjusted, which would increase the operating cost for a typical office building by 6%.

An in-depth cost analysis on electrostatically enhanced filtration is provided in Section 9.3.

6.0

Critical Assessment of Electret Media

6.1 Technology Description

Many air filters in the market are currently manufactured using electrically charged media to attract particles. Filters that use this technology are commonly referred to as "electrostatic," "electrically charged," or "electret" media. In this report, the filters are referred to as electret media. The advantage of electret media is their relatively high collection efficiency at very low pressure drops.

Electret media are made of dielectric materials that have a significant microscopic bipolar charge on the fibers and a very low net macroscopic charge. Different from the electrostatically enhanced filter described in Section 5.0, electret media are permanently charged in the course of manufacturing. Therefore, electret media do not need an electrode system to charge filter media or an ionizer to charge incoming particles during operation.

There are many types of electret media, due to the variety of fiber-forming technologies (i.e., meltblown, split fiber, bi-component spunbond, needlefelt, etc.) and the variety of electrostatic treating technologies (i.e., corona charged, triboelectric charged, induction charged, etc.). A recent study demonstrated that electret filter media can also be generated by applying anionic surfactants on some polypropylene fibrous filters (Yang and Lee, 2005).

The composition of electret media varies from polycarbonate, polypropylene, and polyolefin, to a binary mixture of polypropylene and chlorinated acrylic fiber. The media manufactured by different technologies and different polymers could demonstrate a significant difference in filtration performance and degradation behavior (Barrett and Rousseau, 1998 and Romay et al., 1998b).

6.2 Theory of Electret Media

Electret filters collect particles using a combination of the conventional mechanical mechanisms (i.e., impaction, interception, and diffusion) and the electrostatic mechanisms (i.e., Coulombic attraction and dielectrophoretic capture). Charged particles are attracted to oppositely charged fibers by the Coulombic force. For singly charged particles, the attraction increases as particle size decreases. Neutral particles that are unaffected by Coulombic force are collected by dielectrophoretic force — the polarization force induced by local electrical fields within the filter media. Charged particles are also collected by dielectrophoretic capture. The efficiency of the dielectrophoretic capture increases with particle size.

The efficiency of electret media depends on parameters such as charges on particles, charge density of fibers, and chemical compositions of particles and fibers; efficiency also depends on factors that affect the efficiency of conventional uncharged filters, such as fiber diameter and packing density of the fibrous materials. Several theoretical models are available to predict the capture efficiency of electret filters (Pich, 1978; Pich et al., 1987; Brown, 1981; Lathrache and Fissan, 1987; and Otani et al., 1993). These models relate the electret collection efficiency to parameters, such as average charge density of fibers, number of charges on particles, fiber packing density, and fiber and aerosol diameters. The models provide a good qualitative description of the behavior of clean electret filters and show a generally good agreement with experimental results (Romay et al., 1998b; and Wang, 2001). For example, the empirical power law expressions for single-fiber efficiencies obtained by Romay et al. (1998b) when testing commercial electret filters were in good agreement with those predicted by Brown (1981).

Electret media capture particles by the same mechanisms as fibrous filters do, as described in Section 4.2. It is the enhancement of particle capture via the electrostatic mechanism that distinguishes electret media from fibrous media, and therefore a separate technology category is considered in this analysis. The local (particle-fiber regime) electrostatic force increases capture efficiency without the need for increasing thickness, increasing fiber packing density, or reducing fiber diameter. Thus, the overall particle collection efficiency is increased—all other parameters of the filter being equal—while the pressure drop (airflow resistance) is maintained or reduced.

6.3 Summary of Relevant Studies

Recent studies in electret media are summarized in Table 14. Note that Table 14 focuses primarily on studies conducted since 1995. Only important and representative studies conducted before 1995 are included.

6.3.1 Performance and Variables That Affect Performance

In the HVAC filtration market, electret filters are becoming increasingly popular (Myers and Arnold, 2003; Homonoff, 2004). Task 2 of the current overall project to select the representative filters to test found that most of the medium to higher efficiency filters were electrostatic filters. Nearly all high efficiency (MERV 11 or higher) residential filters were composed of electret material as well.

The electret filters available for residential HVAC filtration generally have MERV ratings ranging from 8 to 12. 3M is the leading company to produce high-end electret filters for residential application. 3M's Filtrete™ Ultra Allergen filter , Filtrete™ Micro Allergen filter, and Filtrete™ Dust & Pollen filter are rated as MERV 12, 11, and 8, respectively. The typical pressure drop for residential pleated electret filters ranges from 0.13 to

Table 14. Summary of Electret Studies

Basic Scope	Content/Conclusion	Reference
Review of Electret Media	An overview of current electret media types, charging techniques, and the fundamental impact of environmental factors on filter performance.	Myers and Arnold, 2003.
Collection Efficiency Model • Models • Models validation • Models review	Major models that are available for predicting the collection efficiency of electret; these theoretical models provide a good qualitative description of the behavior of clean electret filter and are in general agreement with experimental results.	Pich, 1978; Pich et al., 1987; Brown, 1981; Lathrache and Fissan, 1987; Otani et al., 1993; Romay et al., 1998a; Wang, 2001; Lee et al., 2002.
Methods for Making Electret	Recent studies and developments in making electret.	Rousseau, 1998; Nifuku, 2001; Drouin, 2002; and Tsai, 2002; Yang, 2005.
Degradation With Aerosol Loading	Electret media degradation studies: generally, the degradation depends on the type of aerosol, but filter properties can also affect the degradation; the degradation by oil aerosols such as DOP (dioctyl phthalate), diesel soot, and cigarette smoke is particularly severe in many electret filters.	Brown et al., 1988; Tennal et al., 1991; Lehtimäki and Heinonen, 1994; Lehtimäki, 1996; Walsh and Stenhouse, 1997; Walsh and Stenhouse,1998; Lifshutz, 1997; Liu and Romay, 1997; Barrett and Rousseau, 1998; Hofacre et al., 1999; Hanley et al., 1999; Hanley and Owen, 2003; Arnold and Myers, 2002; Janssen et al., 2003a; Janssen et al., 2003b; Ji et al., 2003; Raynor and Chae, 2002; Raynor and Chae, 2003; Romay et al., 1998a.
Performance Data for Electret Media	Experimental data on the performance of commercially available electret media; test data available include efficiency as a function of particle size, and pressure drop vs. face velocity curves at different filter basis weights.	Carpin et al., 1997; Liu and Romay, 1997; Romay et al., 1997; Romay et al., 1998b.

0.35 in. w.g. (32 to 87 Pa) at 300 fpm (1.52 m/s) of face velocity (3M Brochure, Improve Indoor Air).

The electret filters used for commercial HVAC filtration generally have MERV ratings ranging from 8 to 16. Freudenberg is the leading producer of high-end electret filters for commercial HVAC applications. Freudenberg's pleated electret filter Viledon® MV95 is rated as MERV 15 and has a pressure drop of only 0.35 in. w.g. (87 Pa) at 500 fpm (2.54 m/s) face velocity. Its pocket electret filter Viledon® MF95 is rated as MERV 16 with a pressure drop of 0.5 in. w.g. (125 Pa) at 500 fpm.

Fiber charge density affects the collection efficiency. Manufacturers and researchers have tried to increase the electrical charge density of electret fibers in order to improve collection performance (Nifuku et al., 2001; Lee et al., 2002). The effects of relative humidity (RH) (up to 100%) and temperature (up to 70°C), however, are almost negligible in most electret filter media available today (Liu and Romay, 1997; Arnold and Myers, 2002; and Myers and Arnold, 2003).

A major concern with using electret filters is the effect of aerosol loading on collection efficiency. A number of studies were conducted previously to determine the efficiency degradation of electret filters during aerosol loading (Brown et al., 1988; Tennal et al., 1991; Lehtimäki and Heinonen, 1994; Lehtimäki, 1996; Walsh and Stenhouse, 1997; Walsh and Stenhouse, 1998; Lifshutz, 1997; Barrett and Rousseau, 1998; Romay et al., 1998b; Arnold and Myers, 2002; Hanley et al., 1999; Hanley and Owen, 2003, Raynor and Chae, 2002 and 2003; Janssen et al., 2003a and 2003b; and Ji et al., 2003). Generally, degradation depends on the type of aerosol, but filter properties can also affect it (Barrett and Rousseau, 1998; Romay et al., 1998b).

Degradation by oil aerosols such as dioctyl phthalate (DOP), diesel fumes, diesel soot, and cigarette smoke is particularly severe in many electret filters (Lehtimäki, 1994; Lifshutz, 1997; and Ji et al., 2003). There appear to be two mechanisms for electret degradation by oil aerosols. The first involves wetting and coating of the fiber by the oil aerosol (Pierce and Lifshutz, 1997; Barrett and Rousseau, 1998). This wetting and coating process shields the electret charge on the surface. The second mechanism involves fine particles carrying a Boltzman distribution of electrostatic charges. As the oil aerosol wets and coats the fibers, these individual charges can migrate to and neutralize some fixed charges on the surface of the fibers. This process cannot occur with solid aerosols, since the charges on a solid particle are not mobile (Pierce and Lifshutz, 1997).

Due to the potential degradation of electret filters by oil aerosols, NIOSH's "Testing and Certification Standard for Particulate Respirators and Filters - 42 CFR 84" requires a loading test with DOP aerosol (Sigma-Aldrich, St. Louis, MO). Oil-resistant electret filters, which have much higher resistance to degradation by oily aerosols than the conventional electret filters, were developed and used in particle respirators (Barrett and Rousseau, 1998; Hofacre et al., 1999; Janssen et al., 2003a and 2003b; Romay et al., 1998a).

In a study conducted by Hofacre et al. (1999), the electret media fabricated by a leading media manufacturer were tested for aerosol penetration when being loaded with oil aerosol. The result demonstrated that improvement in electret media resistance to oil aerosol degradation can be achieved. An experimental electret media sample from the manufacturer exhibited no measurable increase in aerosol penetration when loaded with up to 6 mg/cm2 of fog oil aerosol, whereas an earlier version of electret was adversely affected.

Barrett and Rousseau (1998) reported that in their study, DOP loading tests were conducted with four different types of electret filters, including tribocharged polypropylene/acrylic, corona-charged polypropylene, fibrillated electret film, and new advanced electret media at a face velocity of 7.8 cm/s. The measured initial and final efficiencies at DOP loading of 0.82 mg/cm^2 are summarized in Table 15. As shown there, the initial efficiency and the efficiency degradation with DOP loading varied with the types of media. After being loaded with 0.82 mg/cm^2 of DOP, the efficiency decreased 0.1 to 8 % for the electret media tested. Among them, the P-type advanced electret filter demonstrated the best oil resistance, with efficiency decreased only 0.1% at DOP loading of 0.82 mg/cm$_2$. This P-type filter is an oil resistance medium developed by the manufacturer for the application of P-series respirators. The oil-resistant electret filters were not found in applications of HVAC filtration probably because oil aerosol is not the major component of ambient or indoor aerosols.

Figures 16, 17, and 18 are examples of degradation of electret by aerosol loading of diesel fumes, cigarette smoke, and Arizona road dust, which were measured by Lehtimäki and Heinonen (1994).

Table 15. Degradation of Electret Media Measured by Barrett and Rousseau (1998)

Electret Media		DOP Aerosol		
		Initial η%	Final η%	Change
Tribocharged Filter Media (media weight: 300 g/m^2)		98	90	-8 %
Fibrillated Electret Film (media weight: 200 g/m^2)		98	92	-6%
Corona-charged Polypropylene (media weight: 120 g/m^2)		97	91	-6%
Advanced Electret Filter (media weight: 120 g/m^2)	R-type	99.9	99.2	-0.7%
	P-type	97.0	96.9	-0.1%

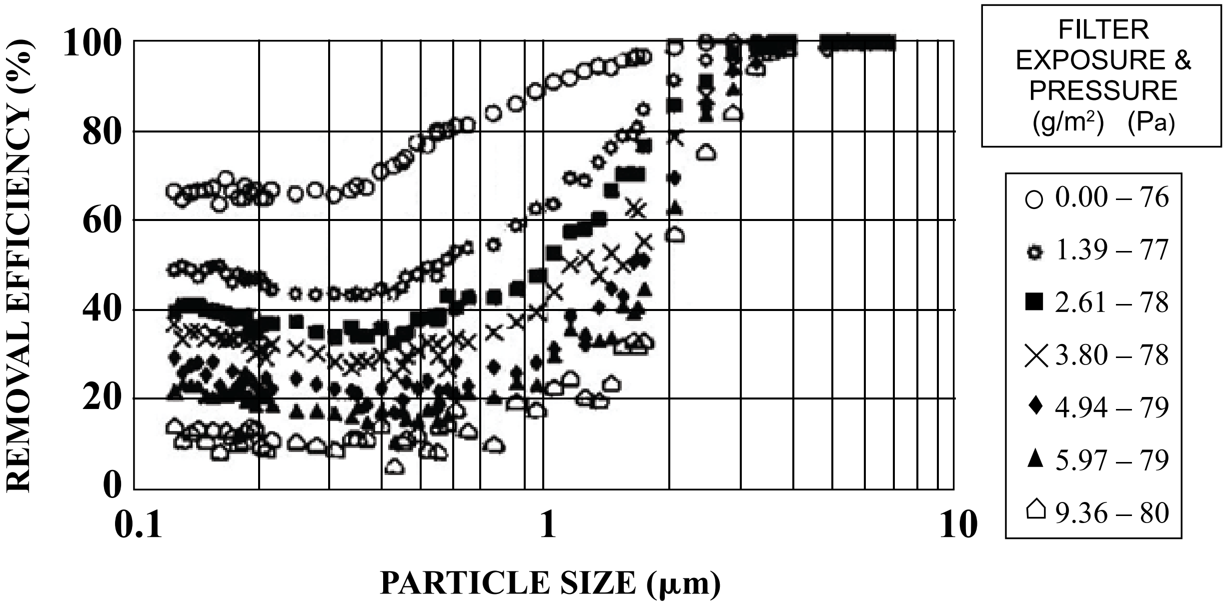


Figure 16. Effect of Diesel Fume Aerosol on the Removal Efficiency of an Electret Filter (Lehtimäki and Heinonen, 1994)

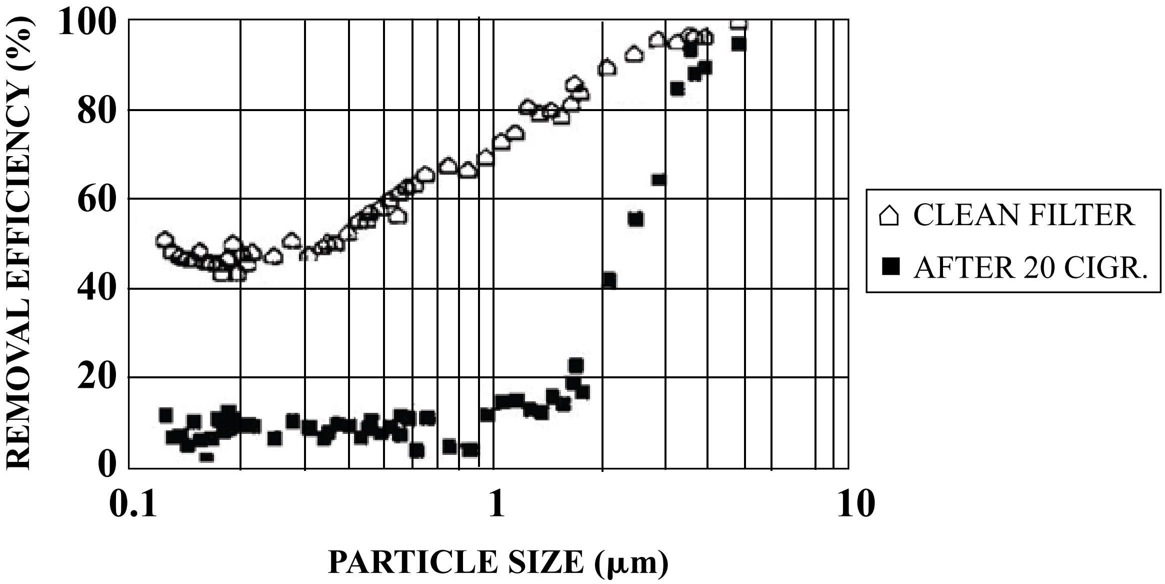


Figure 17. Effect of Cigarette Smoke on the Removal Efficiency of an Electret Filter (Lehtimäki and Heinonen, 1994)

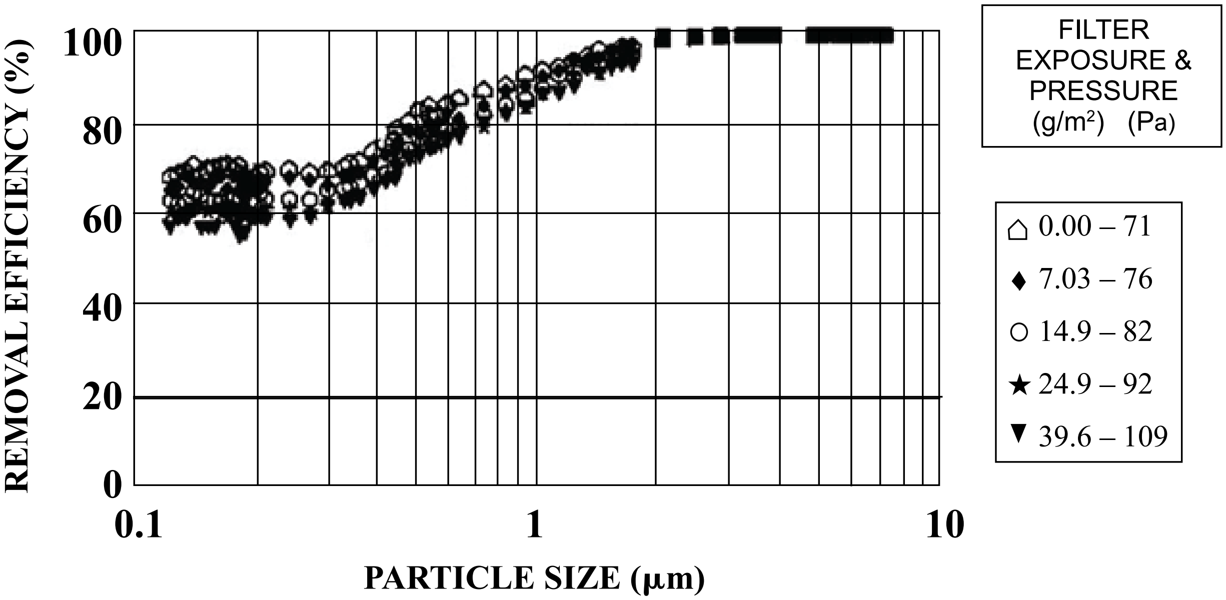


Figure 18. Effect of Arizona Road Dust on the Removal Efficiency of an Electret Filter (Lehtimäki and Heinonen, 1994)

As shown in Figures 16 and 18, the aerosol loading with Arizona road dust was significantly higher, compared to diesel fume loading. The removal efficiency, however, decreased only slightly with the dust loading, compared to the significant efficiency decrease when the filter was loaded with diesel fume aerosol.

Because solid aerosols are the major components of ambient and indoor aerosols, the study on the potential degradation of electret media used for HVAC filtration applications should focus on the effect of loading with solid particles. The collection efficiency of an electret filter for solid particles decreases with operation time in its early stage of collection as the fibers are coated and shielded. Then the collection efficiency becomes relatively constant but increases with time because of the mechanical collection mechanism for the filter media loaded with the solid particles.

Arizona road dust is the ASHRAE test dust that is currently used for the conditioning step in the ASHRAE Standard 52.2. Several studies (Lehtimäki 1996; Hanley et al., 1999; Raynor and Chae, 2002 and 2003) revealed, however, that the degradation of an electret filter when loaded with the ASHRAE dust is less significant than when the filter was exposed to a real ambient condition. Lehtimäki (1996) conducted tests to compare ASHRAE 52.2 test results for electret filters to field test results. Two commercially available EU7 electret filters were tested. The collection efficiency of both filters was reduced significantly in the field tests (after up to four-month exposure), with a reduction of the efficiency of up to 4 times for 0.3 µm particles and up to 2 times for 1 µm particles. When the filters were loaded with the ASHRAE dust, however, the collection efficiency was reduced only slightly (less than 10%) for one test filter and the efficiency even increased for the other test filter.

A series of tests conducted with the support of EPA's Environmental Technology Verification Program (ETV) compared the efficiency reduction for electret filters under real-life exposures and laboratory test conditions (Hanley et al., 1999; Hanley and Owen, 2003). The electret filters included a rigid-cell filter charged via an electrodynamic spinning process and a residential filter charged via a split-fiber process. Exposures consisted of outdoor ambient air, in-home air, ASHRAE dust, ASHRAE dust without carbon black, and a sub-micron KCl aerosol.

The results, as shown in Figures 19 and 20, indicated that the efficiency of the electret filters exposed to outdoor ambient air decreased significantly. The laboratory test used the ASHRAE dust, however, and did not reproduce these reductions. Similarly to the tests conducted by Lehtimäki (1996), the ASHRAE dust tests showed either significantly less reduction in efficiency with loading than the ambient exposure test (the residential electret filter) or even an increase in efficiency with loading (the rigid-cell electret filter).

In addition, as shown in Figures 19 and 20, there were no significant differences in the effects of the loading with the ASHRAE dust and the ASHRAE dust without carbon black. The sub-micron KCl aerosol demonstrated an effect closer to the ambient aerosol exposure than the ASHRAE dust, although the magnitude of the efficiency decrease was still underestimated.

The decreasing efficiency over the 3.0 to 10 µm range, as shown in Figure 20 for the "6 weeks ambient test" data, was attributed to particle bounce (Hanley et al., 1999) The authors do not further explain the reason or definition of particle bounce in this context.

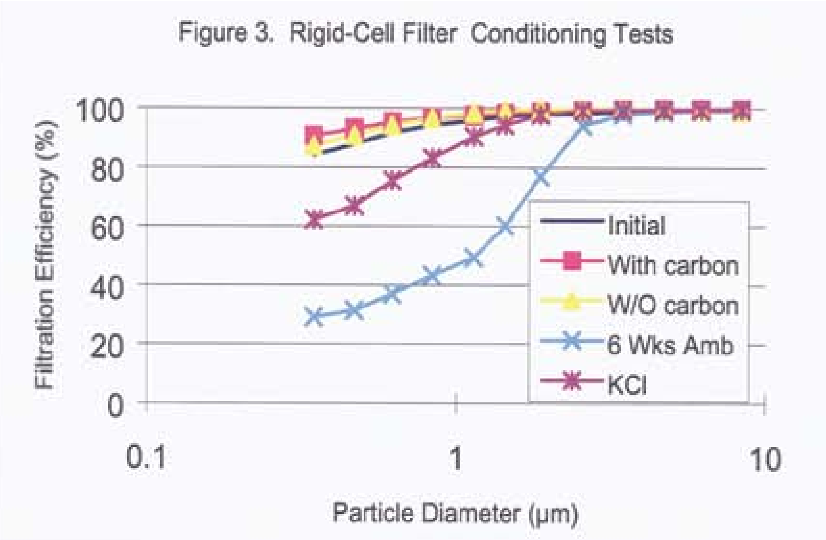


Figure 19. Efficiency Reduction of the Rigid-Cell Electret Filter With Aerosol Loading (Hanley et al., 1999)

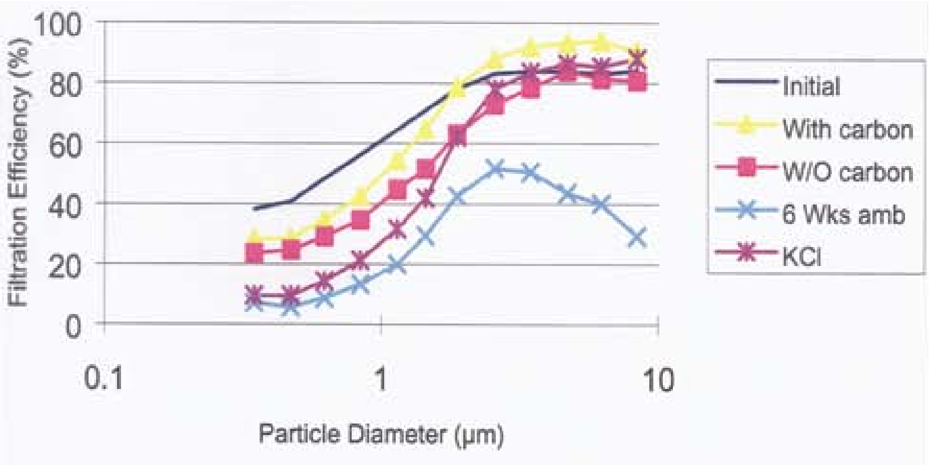


Figure 20. Efficiency Reduction of the Residential Pleated Panel Electret Filter With Aerosol Loading (Hanley et al., 1999)

6.3.2 Assessment in an HVAC System

In the two studies conducted by Raynor and Chae (2002 and 2003), a series of tests was conducted to investigate the degradation of electret filters in a real HVAC system. Electret filters made from polyolefin fibers were used continuously in the system for more than 19 weeks. Collection efficiencies of the electret filters were found to decline substantially during the test. The efficiencies for the 0.337, 0.626, and 1.1 µm particles were reduced to 2, 2.2, and 1.6 times, respectively. In these studies, the same types of electret filters were also tested according to ASHRAE Standard 52.2-1999. Unlike the results observed in the real HVAC tests, accelerated dust loading tests run according to the ASHRAE Standard 52.2 did not show any efficiency decrease.

The efficiency differences when the filters were loaded with the ASHRAE dust and the ambient dust may be caused by the difference in the particle sizes. In Raynor and Chae's study (2003), most of the mass of the particles collected by the filters in the real HVAC system was contributed by particles smaller than 1 µm, while most of the mass in the ASHRAE dust was contributed by particles with diameters larger than 1 µm. Most of the atmospheric particles are small in diameter and the prefilters in the real HVAC systems collected almost all particles larger than 3 µm in diameter. Several studies regarding aerosol loading and filter performance clearly showed that smaller particles cause a more rapid degradation in efficiency of electret filters than larger particles (Walsh and Stenhouse, 1997 and 1998; Ji et al., 2003) probably because the smaller particles may be more capable than larger particles of masking or screening the charges on electret filters.

The studies described above revealed that the ASHRAE 52.2 dust loading procedure does not adequately reproduce the reduction in filtration efficiency that electret filter undergoes in actual HVAC systems. The ASHRAE Standard 52.2, which was developed to determine the minimal efficiencies of a filter over its lifetime, may actually provide an artificially higher MERV rating for an electret filter.

Realizing that the ASHRAE Standard 52.2 tends to show an artificially higher MERV rating for electret filters, ASHRAE supported a research project conducted by Research Triangle Institute (RTI) to develop a loading dust for a new loading test method that will more nearly represent the minimum efficiency points of an electret filter in a real-world application (Hanley and Foarde, 2003). In this project, the new test method was developed to replace the first dust loading step (or the conditioning step) of ASHRAE 52.2, using nano-sized solid-phase KCl aerosol (with number mean diameter of 0.035 µm) as the conditioning aerosol. The new method provided a means of accelerating the drop-off in efficiency that electret filters undergo in real-life applications. A draft addendum (Addendum C) to ASHRAE Standard 52.2 was prepared in the project; a detailed protocol for conditioning electret filters using nano-sized KCl aerosols to mask (or screen) the charges on electret filters was included. Addendum C is currently undergoing public review.

6.3.3 Additional Factors

No additional factors were identified for electret media.

6.4 Critical Assessment

6.4.1 Technical Assessment

Electret media are found in a variety of filter products, primarily respirator filters and HVAC filters. Electret filters have gained significant market share and acceptance in HVAC filtration applications over the past few years (Arnold and Myers, 2002; Homonoff, 2004) despite the potential efficiency degradation of electret media with use. As discussed above, filters made of electret media offer the advantage of a lower airflow resistance for an equivalent efficiency, or a higher efficiency for an equivalent airflow resistance. Also, electret filters are usually less expensive than mechanical filters (glass fiber filters) with the same MERV rating. In addition, in spite of the collection efficiency degradation, the efficiency of an electret filter always exceeds that of an uncharged filter with the identical mechanical structure.

When selecting an electret filter for an HVAC application, it is important to evaluate filter performance data for the particular application conditions. If the real-life performance data are not available, a laboratory loading test, which is able to more nearly represent the minimum efficiency points of an electret filter in a real-world application, should be conducted to ensure that the selected electret filter can meet the design goals of a particular HVAC application.

Although the advantage of improved filtration efficiency compared to that of standard fibrous media is well documented, the single greatest concern regarding electret filters is degradation. Degradation is associated with aerosol loading, aging, and environmental effects. The studies discussed above clearly show the effect is real and a valid concern. The loading effects have been considered of such importance that both the respirator industry (through filter certification standards for NIOSH) and the HVAC industry (through specific filter conditioning specifications in ASHRAE 52.2) have attempted to address this issue by requiring filters to meet standards with filter loading requirements.

The use of ambient aerosol was found to be more degrading than the original loading dust (Arizona road dust) for ASHRAE 52.2 testing—hence, the exploration of a KCl nano-sized loading aerosol. Similarly, filters for respirator applications are loaded with DOP aerosol to demonstrate oil resistance and meet performance requirements, since the particle size more closely matches ambient conditions. In the respirator industry, there has been criticism that the DOP aerosol is not representative of the use conditions; the concentrations and loadings are much greater than those that would be experienced in use. Likewise, the selection of KCl as a conditioning aerosol for ASHRAE filter testing can be questioned. Previous research has demonstrated that different aerosols can cause different extents of degradation. The difference appears to be associated with the aerosol composition and not necessarily the particle size. Nonetheless, the selection of KCl as the conditioning aerosol for electret filters, as well as the loading concentration, merit further consideration.

Another concern with selection of a specific aerosol and loading concentration for ASHRAE 52.2 testing is that media manufacturers will produce media specifically to meet or pass performance requirements. For example, respirator manufacturers design media such that their filters will meet certification requirements for P100 filters. Passing a standard test will not necessarily ensure resistance to degradation. Filters of all media types should be tested in the same manner, including conditioning aerosols.

Other degradation concerns with electret media are operating temperature and redistribution of charge where local (on the fiber) charge separation no longer exists or has been reduced. Temperature may affect charge redistribution. Also, the polymeric fibers are not suitable for relatively high temperature (> 120°C) operation because of the melting point of the polymer. Within the context of HVAC applications, operating temperatures should not cause the polymer fiber to melt.

Due to the limitations listed above in tests such as the ASHRAE 52.2 conditioning step, standardized tests may not provide a completely reliable measure of electret performance degradation and thus not provide a reliable MERV rating. Because electret filters are used in high efficiency applications and because electret filters show significant reduction in efficiency for many applications, care should be used in selecting electret media. Where possible, electret filters should be tested to determine degradation under the conditions where they will be used.

Despite the concerns regarding electret media degradation, electret filters merit use as HVAC filters. Strategies to reduce the effects of degradation are possible and are being explored. One approach is to mix fibers (specifically nanofibers) to provide additional mechanical filtration capability. Also, as respirator filter manufacturers have demonstrated, improvements in resistance to degradation can be achieved.

6.4.2 Impact on HVAC System

Electret filters have a relatively lower pressure drop than conventional uncharged fiber filters; therefore, they can be installed into an existing HVAC filtration system without extensive modification such as the addition of an extra fan.

The performance degradation of electret filters with service (or loading) may cause the actual efficiency of an electret filter to be significantly lower than the design efficiency over the entire service life. This reduction in filter efficiency, however, should not have any impact on the performance of the HVAC system.

6.4.3 Cost Analysis

Electret media filters can typically fit into an existing air handler without major modifications, and the static pressure increase in the system would be small. These types of filters might require a new access door to be added to the existing unit and installation of new pressure gauges. Initial and installation costs are very inexpensive since there is no need for electric service.

Typical operating and maintenance costs are low. Maintenance includes yearly changing of not only the electret filters, but of the prefilters as well, increasing the maintenance costs of the typical office building by 14%. The operating cost increase would also be small. One could expect a 9% increase in the operating cost of a typical office building.

An in-depth cost analysis of electret media is provided in Section 9.4.

7.0

Critical Assessment of Electrostatic Precipitation

7.1 Technology Description

Electrostatic precipitation (ESP) is a technology that has been used for some time in industrial applications to reduce the amount of particulate matter resulting from combustion and other processes. Commercial and residential devices employing ESP, often called electronic air cleaners (EACs), are now widely available. Figure 21 shows a schematic of the ESP process. In general, an electrical charge is imparted to incoming dust particles as they pass through an electrical field in the ionizing section. The charged particles are collected on plates of an opposite charge in the collection section. Additional filters may be used to reduce the number of large particles before the ESP stages (i.e., a prefilter as shown in Figure 21), collect agglomerated particles dislodged from the collection plates (i.e., the after-filter), or to remove odors. ESPs and EACs offer several advantages over traditional fibrous filters. By employing electrical forces, ESPs may achieve high collection efficiencies at relatively low pressure drops. EACs also require less frequent replacement. EACs require regular cleaning, with lower operating costs. General ESP theory is well explained in several sources, including Oglesby and Nichols (1970), White (1963), and Rose and Wood (1956).

7.2 Theory of Electrostatic Precipitation

In the ionizing section, particles acquire a charge from ions generated within the electrical field. These ions are created by corona generation. Corona is the phenomenon of ionization of gas molecules in regions of high electrical field strength. A relatively high voltage is applied to the ionizing electrode, resulting in a high electrical field near the electrode. Electrons present in the field are accelerated and impact gas molecules, releasing more electrons and creating positive ions. Depending on the polarity of the electrical field, the electrons and positively charged ions move in different directions. A negative ionizing electrode creates a negative corona where the positive ions are attracted to the electrode, producing more free electrons when they collide with the electrode. The electrons are attracted to the positively charged collection plate(s), impacting gas molecules to create negative ions as the strength of the ionizing electrical field diminishes. A positive ionizing electrode (positive corona) produces an opposite effect. Both positive and negative coronas are used in ESP, though negative coronas are used less often for cleaning air in occupied spaces because greater amounts of ozone are generated (Huang and Chen, 2001). Negative coronas do offer advantageous electrical performance, resulting in greater efficiency for the same operating conditions. The corona is affected by electrode geometry and gas composition and conditions.

The ions created by corona generation impact particles in two ways. Larger particles tend to travel along electrical field lines and directly impact particles in a process called field-dependent charging. As a particle becomes saturated with charge, it diverts the electrical field lines so that other ions do not impact the particle. The saturation charge of the particle is related to the magnitude of the electrical field responsible for charging the particle, the size of the particle, and the dielectric constant of the particle.

Smaller particles (0.2 µm and less) receive less charge through field-dependent charging and more charge from direct collisions between the ions and particles due to thermal motion, or diffusion charging. As with field-dependent charging, as charge is accumulated on the particle, the probability of impact with additional ions is decreased. However, since there is no upper limit to diffusive motion, there is no saturation limit for diffusion-charged particles. In either case, the higher the charge on the particle, the greater the electrical force between the particle and the collection electrode. Greater residence times within the electrical field will result in higher charges when the saturation charge has not been reached.

The collection of the charged particles is controlled by the forces on the particle, which include electrical, gravitational, inertial, and aerodynamic forces. Electrical and aerodynamic

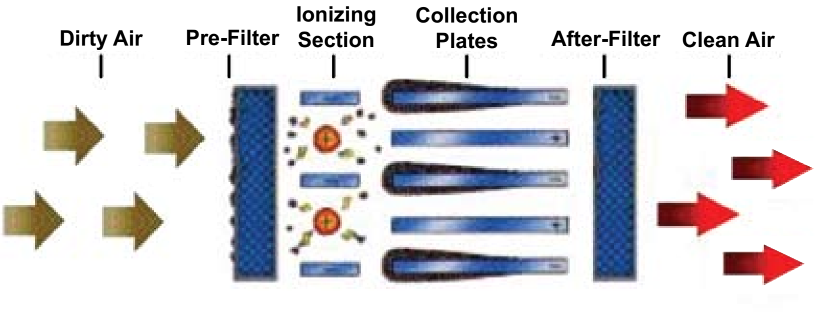


Figure 21. Schematic of ESP Process

forces are the most significant in this case. The electrical force will be acting on the particle to move it toward the collection electrode while the aerodynamic drag force will oppose the forward motion of the particle. When these two forces are balanced, the particle will have reached a sort of terminal velocity called the migration velocity. The migration velocity will be dependent on the charge of the particle, the size of the particle, the strength of the electrical field, and the viscosity of the gas around the particles. The following is a general equation for the migration velocity:

$$w = \frac{q \cdot E_p}{6 \cdot \pi \cdot a \cdot \mu}$$

where w is the migration velocity, q is the charge on the particle, E_p is the precipitating electrical field strength, a is the particle radius, μ is the gas viscosity, and π is the irrational number pi.

The collection performance for ESP can be predicted by a range of models (Park et al., 2004). One of the simplest relationships to predict the collection efficiency is the Deutsch-Anderson equation:

$$\eta = 1 - e^{\frac{w \cdot A}{Q}}$$

where η is the collection efficiency, A is the total surface available for collection, w is the migration velocity, and Q is the flow rate of air through the EAC device. As migration velocity (w) or collection area (A) increases, the collection efficiency increases. As the flow rate (Q) increases, the collection efficiency decreases. This relationship makes a number of assumptions:

- Particles are charged instantaneously.
- Turbulent and diffusive transport causes particles to be uniformly distributed through the device.
- Gas velocity does not affect migration velocity.
- Viscous drag follows Stokes' law.
- Particles always move at migration velocity and are identically sized.
- Mutual repulsion between dust particles can be neglected because they are sufficiently separated.
- Collisions between ions and neutral gas molecules are neglected.
- Unusual effects such as uneven gas flow, backward corona, erosion or particle reentrainment are neglected.

7.3 Summary of Relevant Studies

Recent studies of ESP/EAC devices are summarized in Table 16. Note that Table 16 focuses on recent studies (conducted since 1995). In the reviewed literature, the purposes of the studies varied. Several studies focused on measuring the effectiveness of ESP devices in reducing indoor air particulate concentrations. Other studies measured the performance of ESP devices by quantifying the collection efficiency as a function of particle size. Some studies also examined other variables, including face velocity, ionization voltage, and even corona polarity.

The devices in the reviewed literature also varied significantly. Several papers reviewed stand-alone ESP/EAC devices that were not connected to a building's HVAC system but instead were self-contained devices that sample the air and filter it. Other papers reviewed devices that were designed to operate within an HVAC system. One study appears to discuss an ESP device used with a window-mounted room air conditioner (Park et al., 2002), and one other study examines an industrial ESP system (Zukeran et al., 1999). It is not clear exactly what types of devices are used in some studies.

A number of studies directly address the performance, or collection efficiency, of ESP/EAC devices. ESP performance is impacted by the size of the particle to be collected, the velocity of the air and particulates through the device, and the magnitude of the electrical charge applied to the particles. Some studies consider additional variables based on the particular device studied. Part of the device performance is the pressure drop associated with the device, though because ESP devices typically have lower pressure drops than traditional HVAC filters, pressure drop was not often measured in the reviewed studies. Several studies also addressed collection of biological particles specifically.

7.3.1 Performance and Variables That Affect Performance

In general, the type of particle to be collected does not impact the collection efficiency of an ESP device. Studies by Morawska et al. (2002), Howard-Reed et al. (2003), and Mainelis et al. (1999) comparing several types of particulates show that neither the type of particle nor the particle shape has a significant effect on particle collection. However, particle size is a strong determinant of collection efficiency. As with traditional types of high efficiency filters, most data sets demonstrate a particular particle size with a minimum collection efficiency, often referred to as the most penetrating particle size (MPPS). The value of the most penetrating size will depend on the operating conditions of the ESP device, but values of the MPPS with ESP are similar to values for traditional filters (particle diameters of around 0.3 µm, Huang and Chen, 2001). However, Huang and Chen (2002) note that collection efficiency of ESP devices has also been observed to decrease with decreasing particle size for particles smaller than tens of nanometers.

Particle collection efficiency increases with increasing particle size over the range of 0.3 to 10 µm, as demonstrated in Figure 22. Figure 22 also shows the effect of loading on the performance of the ESP as the collection efficiency is reduced with time. Figure 23 shows aerosol penetration as a function of particle size and applied voltage. As shown, the penetration decreases across all particle sizes as the applied voltage increases. The MPPS is also observed to shift toward smaller particles as the applied voltage is decreased. For comparison, the MPPS is 0.4 to 0.5 µm at 8 kV and 0.2 to 0.3 µm at 4.5 kV.

Table 16. Summary of Recent EAC/ESP Studies

Basic Scope	Content/Conclusion	Reference
Performance Data • Free-standing units • Duct-mounted units • Room AC filter	Recent studies of the effectiveness of ESP filtration; studies typically varied one or more variables, including flow rate or face velocity, ionization voltage, and corona polarization; performance generally increases with increasing voltage and particle size, and decreasing face velocity.	Huang and Chen (2001, 2002); Mainelis et al. (1999); Morawska et al. (2002); Park et al. (2002)
Effectiveness Data • Free-standing units • Duct-mounted units	Studies using ESP for reduction of airborne and/or surface dust; ESP devices can offer significant reduction (values reported from 20 to 85%) of indoor particulate concentrations as tested in both residential and commercial use.	Croxford et al. (2000); Richardson et al. (2001); Howard-Reed et al. (2003); Wallace et al. (2004); Emmerich and Nabinger (2001); Fugler et al. (2000)
Degradation With Duration of Use	Describes method for appropriately simulating filter degradation to quantify reduction in performance with time. Approach appears reasonable, though did not produce anticipated results for all devices tested.	Hanley et al. (2002)
Models of Performance or Effectiveness	Detailed experimental studies linked with a detailed indoor model, employing a network of well-mixed volumes with good agreement.	Howard-Reed et al. (2003); Wallace et al. (2004)

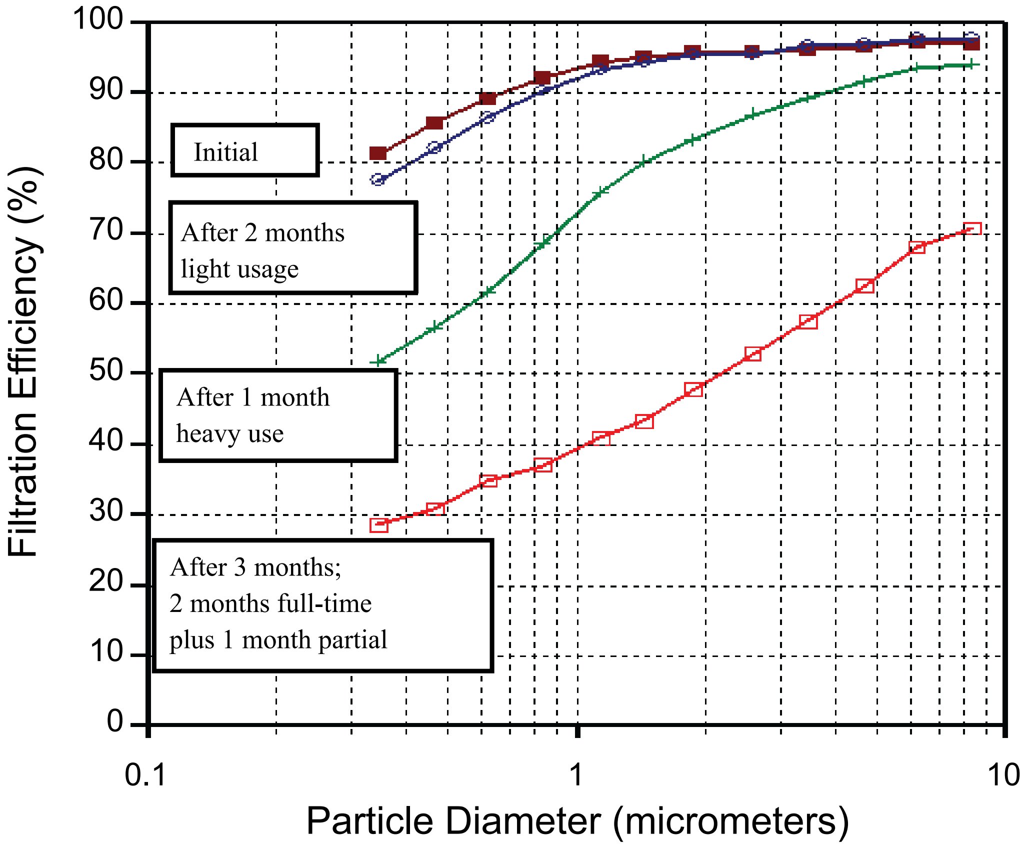


Figure 22. Collection Efficiency as a Function of Particle Diameter After HVAC Use (Hanley et al., 2002)

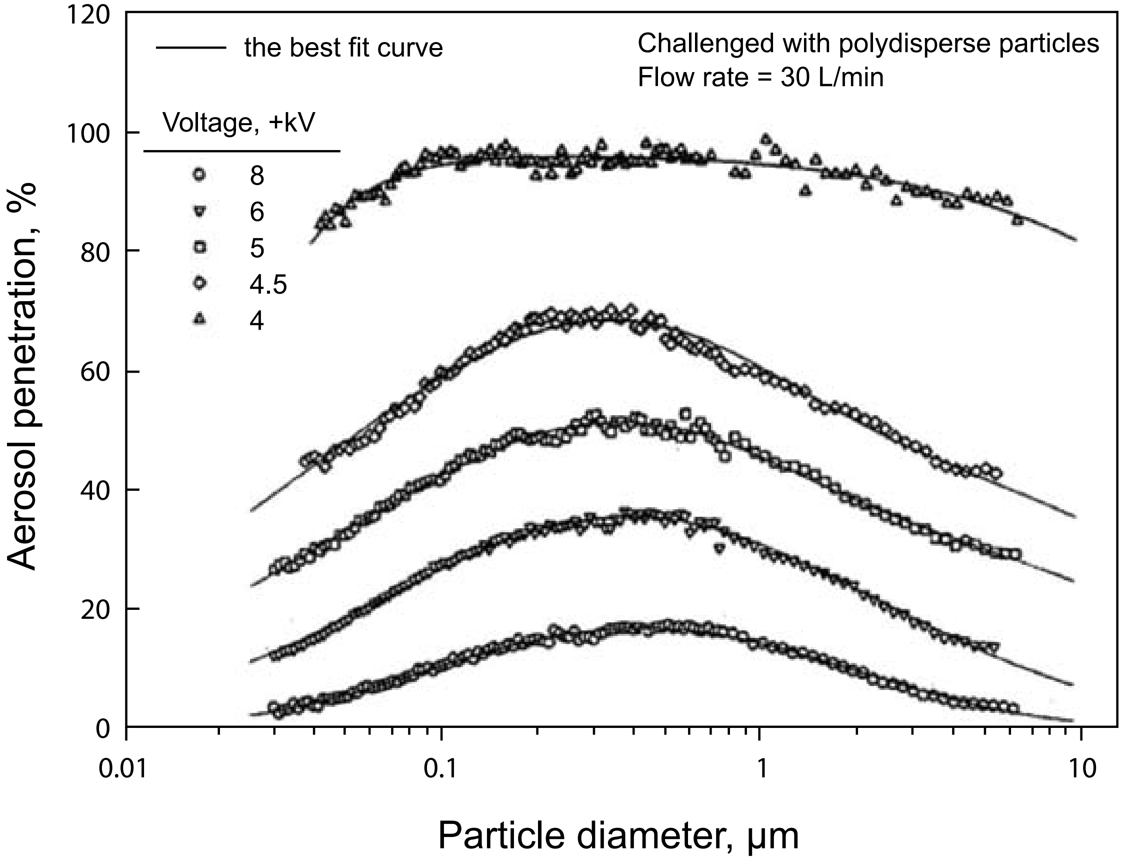


Figure 23. Aerosol Penetration as a Function of Particle Diameter at Various Applied Voltages (Huang and Chen, 2001)

Several studies have shown that collection efficiency may actually increase slightly for some small particles, as seen by U-shaped efficiency or penetration curves in Figures 23 to 28. Figure 23 shows the aerosol penetration (1 – collection efficiency) for particle diameters of 0.03 to about 7 µm. Aerosol penetration decreases (collection efficiency increases) as particle diameters decrease below about 0.3 µm. In Figure 24, several curves of collection efficiency for particles ranging from 0.5 to 10 µm in diameter show increasing efficiency below 1 µm. Figure 24 also shows a peak in collection efficiency around 5 µm particle diameter, with lower collection efficiencies above that threshold. The increased collection of very small particles is also demonstrated in Figure 26, with particle diameters ranging from 0.03 to about 10 µm.

There are significant differences in the experimental ESP systems used to generate the data in Figures 22 through 26. Park et al. (2002, Figure 24) studied a small filter for a window air conditioner. Hanley et al. (2002, Figure 22) and Morawska et al. (2002, Figure 25) both studied duct-mounted commercially available two-stage ESP devices. Huang and Chen (2001, Figures 23 and 26) studied a miniature ESP device (less than 11 cm long) from a commercial air cleaning device. Huang and Chen (2002, Figures 27 and 28) used a longer ESP device (30 cm long) in a later study. The measurement devices used in the various studies also varied significantly. The wide variety of testing environments increases the likelihood that the most penetrating particle diameter would be different for the various ESP devices. For any particular device, there will be an optimum combination of voltage, face velocity, and other variables.

Huang and Chen (2002) assessed the penetration of nanoparticles with nominal diameters ranging from 0.01 to 0.06 µm through an ESP. In previous studies by Huang and Chen, the smallest particle size evaluated was 0.03 µm. The results are shown in Figures 27 and 28. Consistent with the previous work, the penetration is observed to decrease with decreasing particle size over the range of 0.1 to 0.03 µm. However, a minimum is observed at about 0.015 µm, and penetration begins to increase as particle size decreases. The effect was minimized at the highest applied voltages as penetration of particles less than 0.03 µm was less than 1%. However, the authors attributed the poorer performance at the lower voltages to partial charging of the nanoparticles.

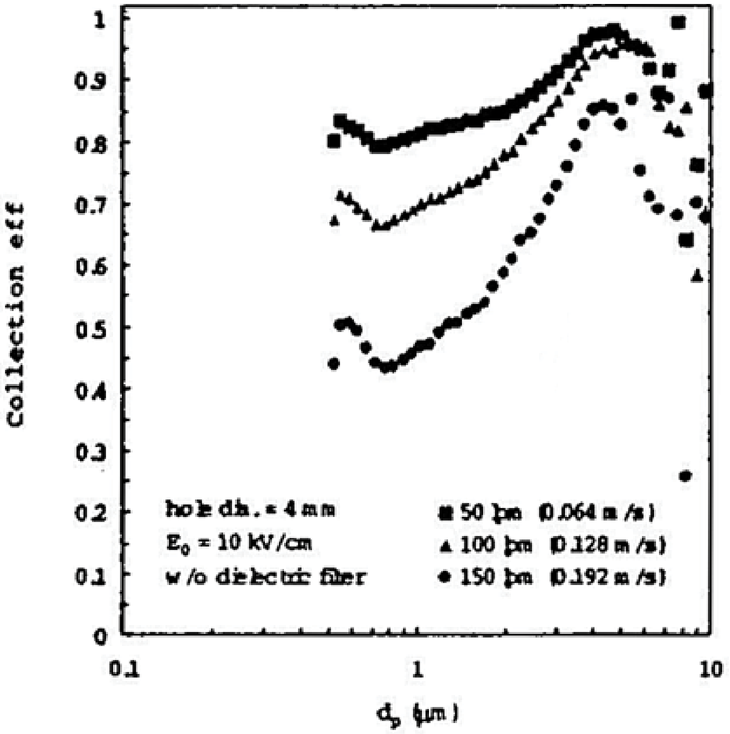


Figure 24. Collection Efficiency as a Function of Particle Diameter for Several Face Velocities (Park et al., 2002)

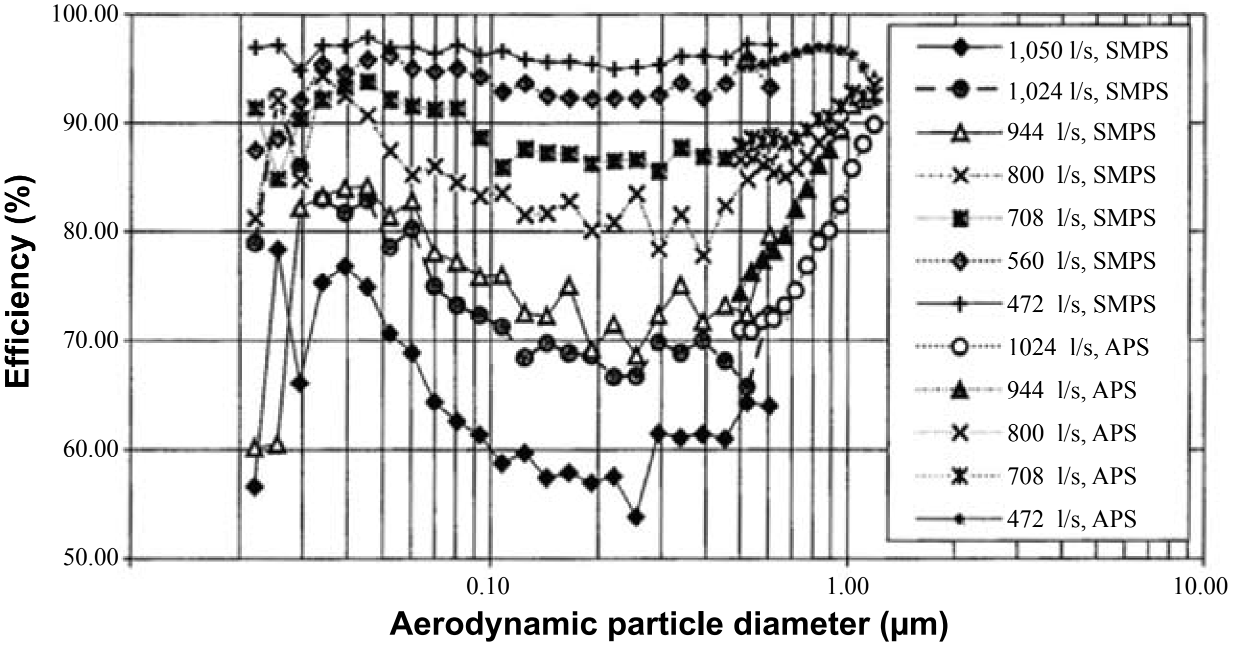


Figure 25. Collection Efficiency as a Function of Particle Diameter for Various Face Velocities (Morawska et al., 2002)

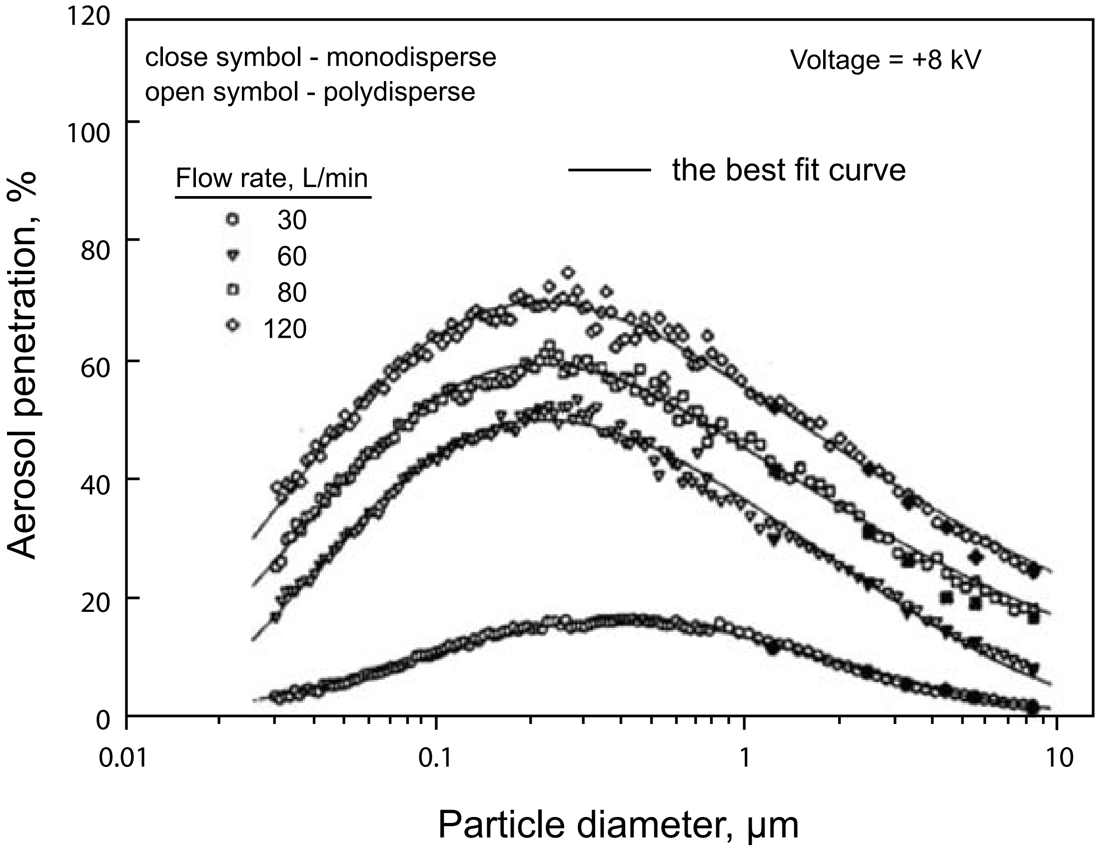


Figure 26. Aerosol Penetration as a Function of Particle Diameter for Several Face Velocities (Huang and Chen, 2001)

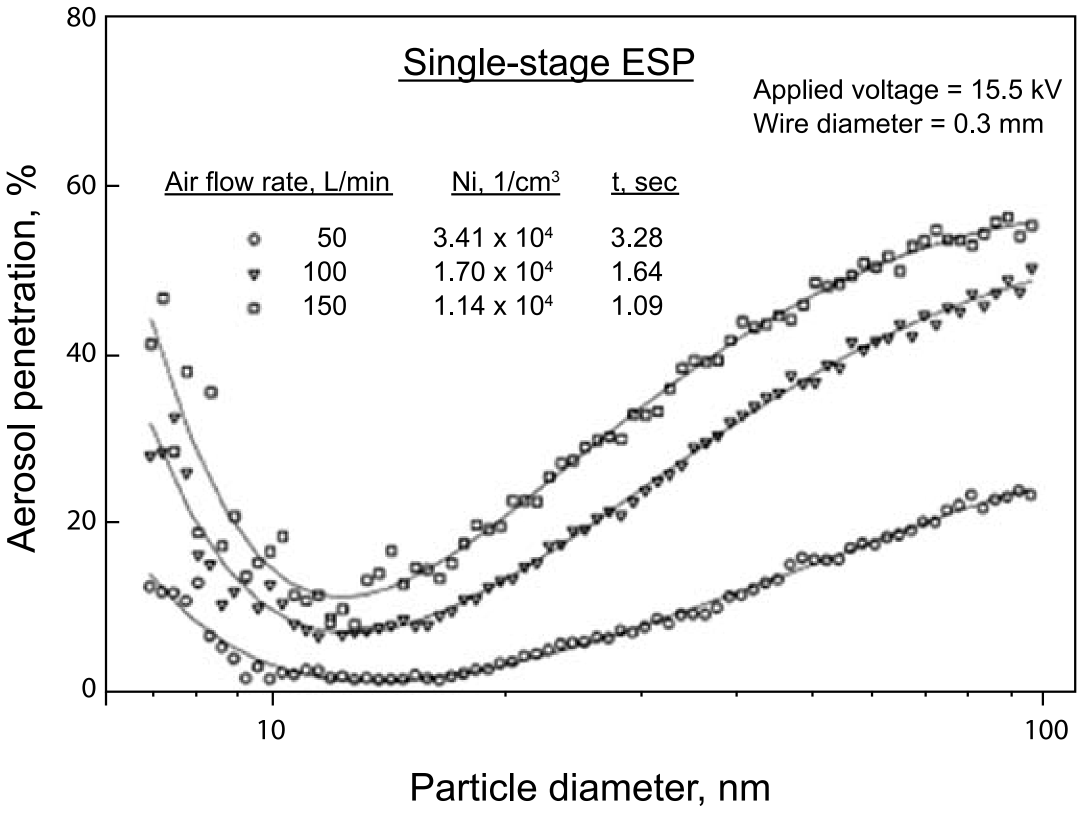


Figure 27. Aerosol Penetration as a Function of Particle Diameter for Several Face Velocities (Huang and Chen, 2002)

The face velocity or flow rate of air through an ESP device will significantly affect the collection efficiency. In general, collection efficiency is reduced as the face velocity increases. The higher particle velocities create a shorter residence time for the particles to be attracted to the collection plates. In Figures 24 and 25, collection efficiency clearly increases as the face velocity or flow rate decreases. Figures 26 and 27 demonstrate the same effect, though aerosol penetration is shown rather than collection efficiency. As flow rate through the device increases, aerosol penetration increases (collection efficiency decreases) due to a reduction in residence time.

Again, it is difficult to directly compare the results of the different studies because of the diversity of devices tested, as well as the differences in experimental conditions and measurement devices. However, all studies indicated that collection efficiency decreases as face velocity increases.

Increasing voltage will generally increase the collection efficiency. In Figures 23 and 28, aerosol penetration curves for several applied voltages are shown. As applied voltage is increased, the aerosol penetration decreases (meaning the collection efficiency increases). Figure 29 establishes a similar trend of increasing collection efficiency with increasing voltage.

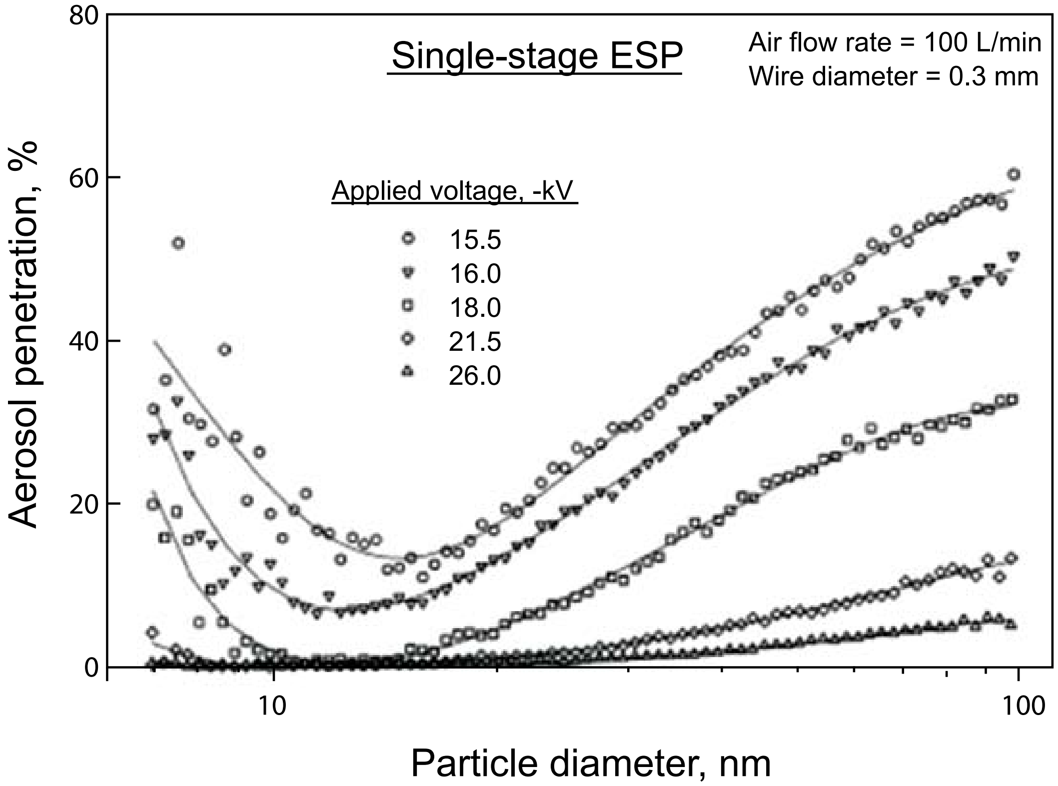


Figure 28. Aerosol Penetration as a Function of Particle Diameter at Various Applied Voltages (Huang and Chen, 2001)

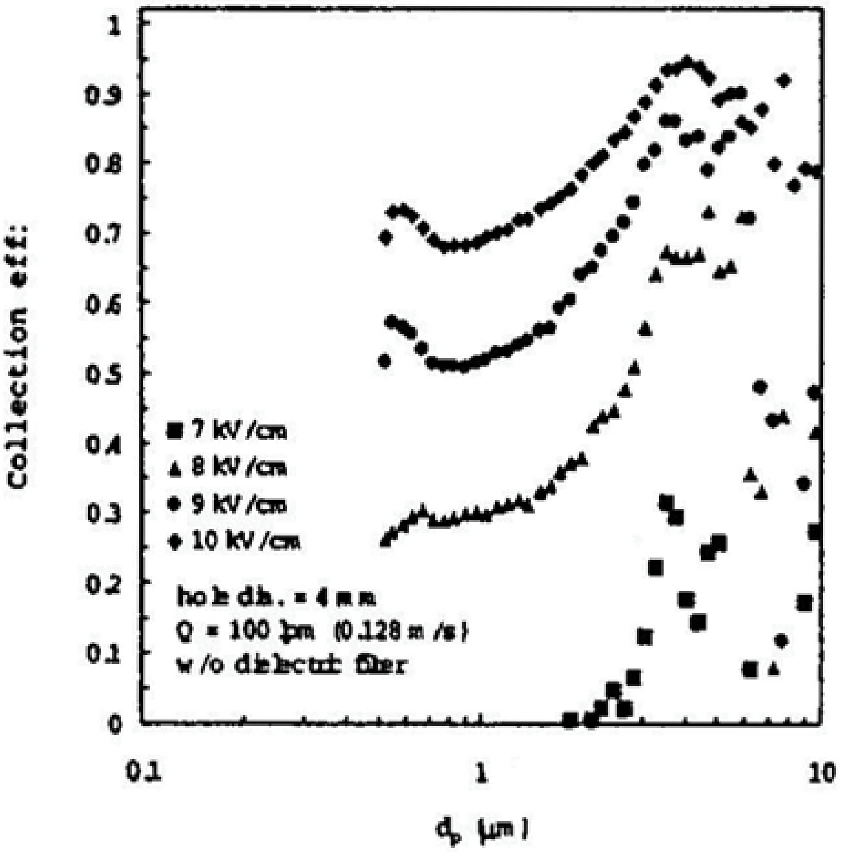


Figure 29. Collection Efficiency as a Function of Particle Diameter for Several Applied Voltages (Park et al., 2002)

The polarity of the corona used to ionize particles for collection affects the collection efficiency. As noted by earlier authors of ESP theory, particle collection can be higher with negative corona ionization under identical operating conditions because of the greater electrical currents generated at the same voltage (Oglesby and Nichols, 1970; White, 1963; Rose and Wood, 1956). An example of this effect from a recent study can be seen in Figure 30. In Figure 30, best fit lines for positive corona voltages are shown with data for negative corona voltages. Negative corona voltages of 4 kV and 6 kV perform as well as positive corona voltages of 5 kV and 8 kV, respectively.

In the literature reviewed, only Park et al. (2002) measured pressure drop of the ESP device studied. These authors had a specific interest because they were creating an ESP filtering device for a room air conditioner with specific pressure drop limitations. This device differs significantly from other ESP devices for room air cleaners and duct-mounted ESP devices. Measured pressure drops for this device can be seen in Figure 31. A number of mechanical configurations relating to the size and spacing of holes in the collection plate were tested over a range of face velocities. In general, fewer holes and, to a lesser extent, smaller holes resulted in lower pressure drops. Other authors simply state that the pressure drop is much lower than traditional or HEPA filtration.

As with traditional high-efficiency filtration, the performance of ESP devices can degrade over time. Performance degradation with ESP devices can be due to several effects. With residential ESP devices, dust loading (the amount of dust collected) may affect performance. Howard-Reed et al. (2003) and Wallace et al. (2004) both state that “frequent cleaning” was required to maintain high efficiency for the ESP device studied. No indication of the type of cleaning was given. Figure 32 shows the decrease in collection efficiency with time for fine (0.3 to 2.5 µm diameter) and coarse (2.5 to 10 µm diameter) particles. Arrows at the top indicate when the unit was cleaned.

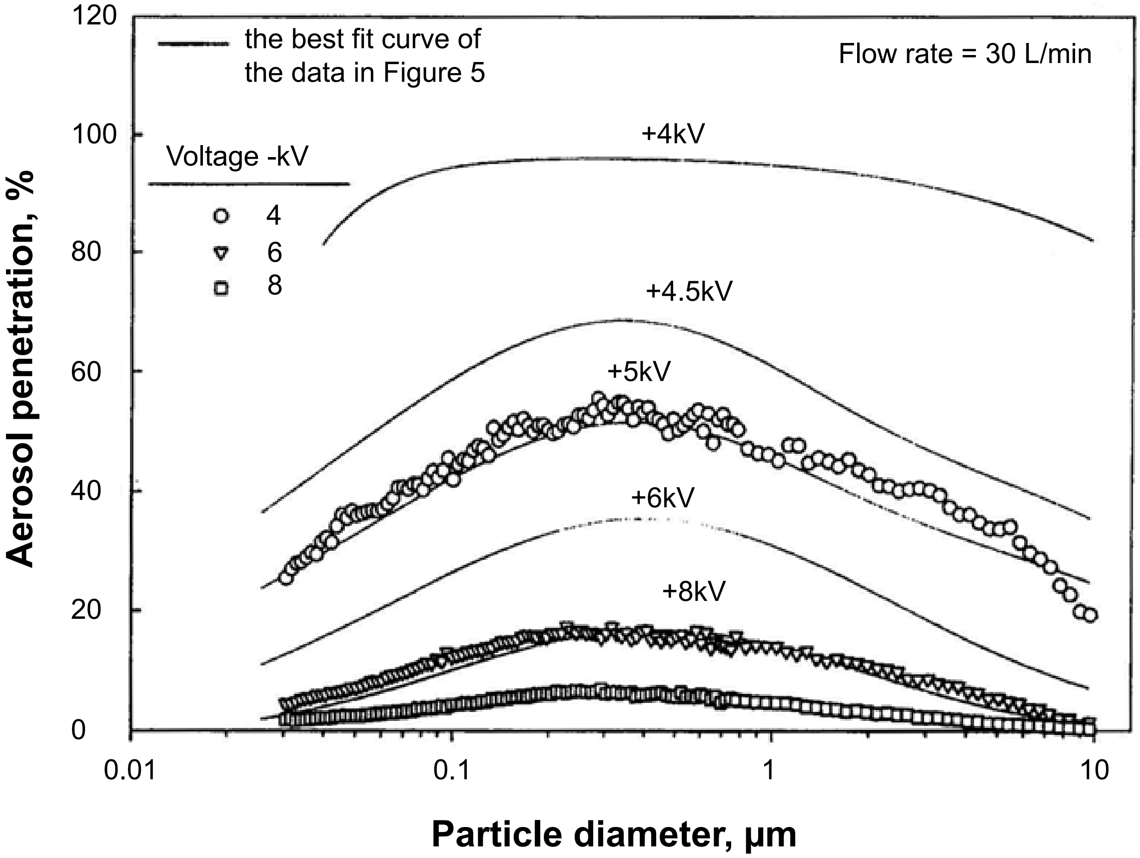


Figure 30. Aerosol Penetration as a Function of Particle Diameter for Several Positive and Negative Corona Voltages (Huang and Chen, 2001)

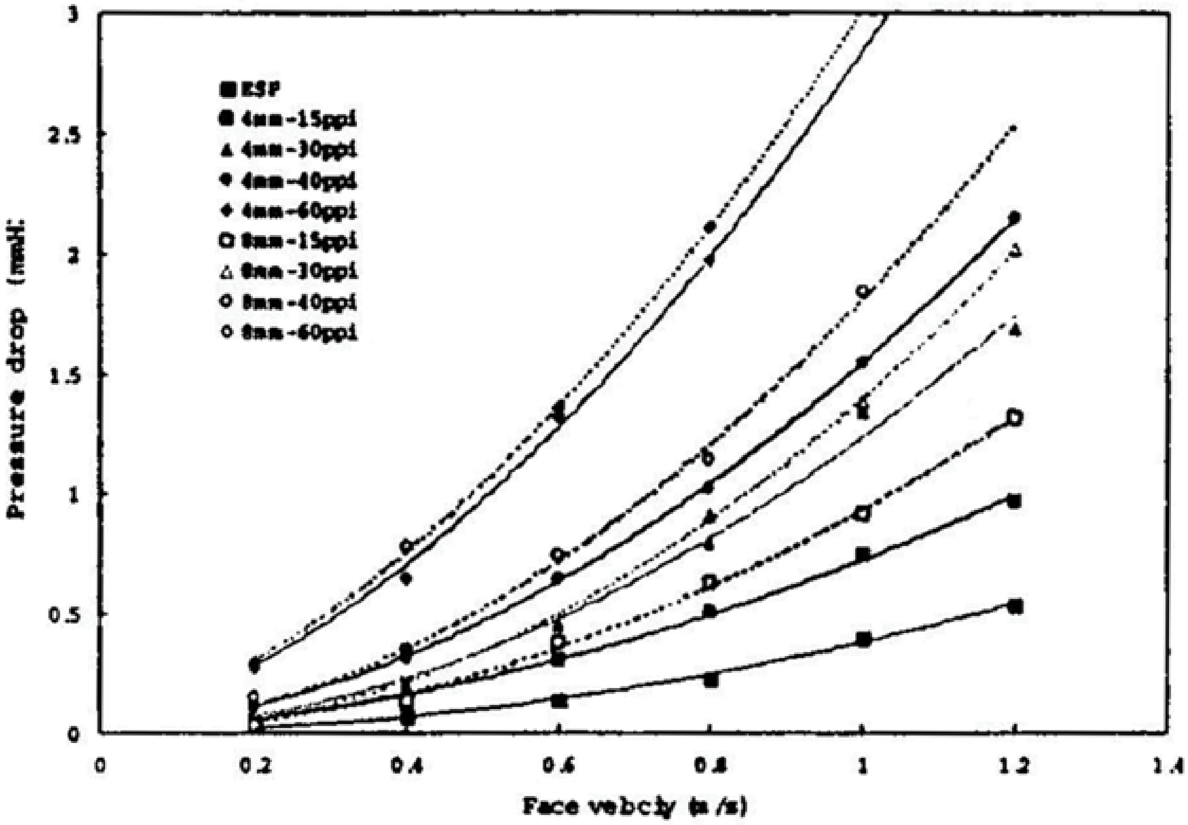


Figure 31. Pressure Drop as a Function of Face Velocity for Various Filter Configurations (Park et al., 2002)

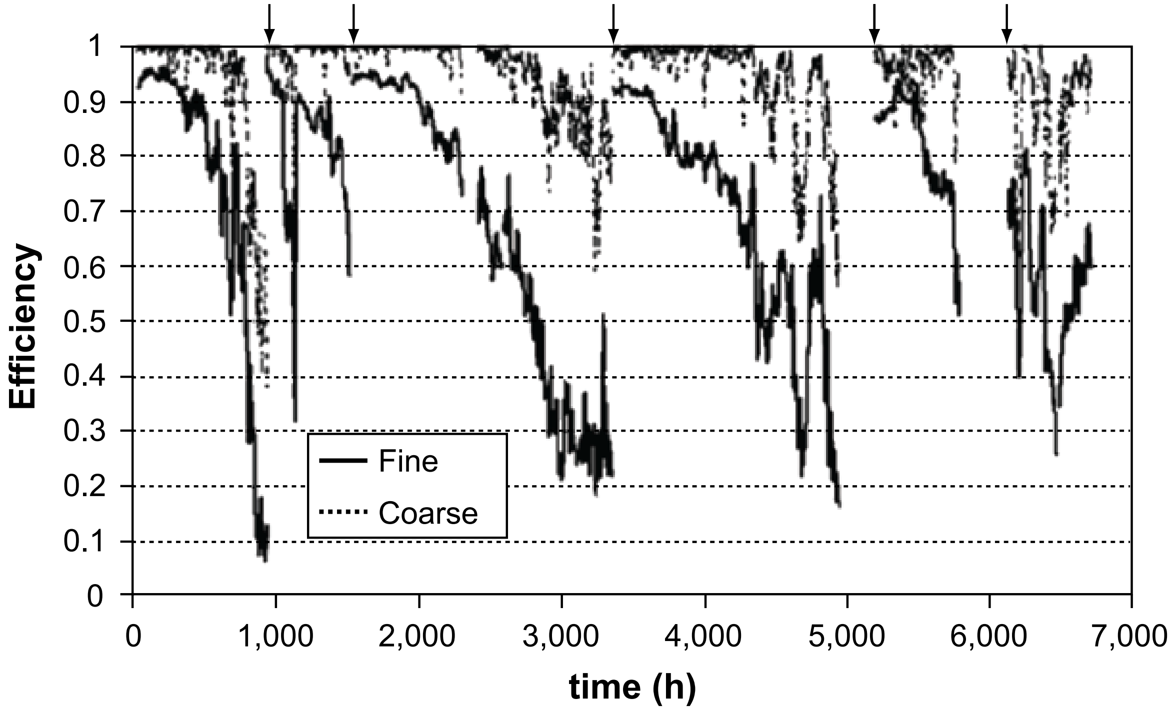


Figure 32. Overall Collection Efficiency as a Function of Time With Cleaning (Wallace et al., 2004)

Hanley et al. (2002) discovered that dust loading was a poor predictor of performance degradation of ESP devices with time. Performance of the ESP devices studied by Hanley et al. did decrease with time, as seen in Figure 33, but the observed degradation was due to decreased corona ionization attributed to silicon deposits on the ionization wires. A new testing protocol was suggested to replicate the degradation of the device with time in use. The ESP device was to be operated in a sealed test chamber with a source of liquid silicon to allow significant amounts of silicon to deposit on the ionization wires. Figure 33 demonstrates the degraded performance observed for two different ESP devices after exposure in the sealed silicon test chamber. Note that the performance of the second device (on the right) did not degrade as quickly as the first.

Though some authors have indicated a significant dependence of collection efficiency on dust loading, others have found none. Howard-Reed et al. (2003) and Wallace et al. (2004) indicated degraded performance with time, but it is not known what caused the degraded performance. Cleaning restored the efficient operation. Hanley et al. (2002) observed no significant reduction in ESP performance with increasing dust on the device collection plates but observed that deposition of impurities on the corona wires occurred over time and did degrade performance. It is possible that the effect seen by Howard-Reed et al. and Wallace et al. is the same as the effect identified by Hanley et al. (2002).

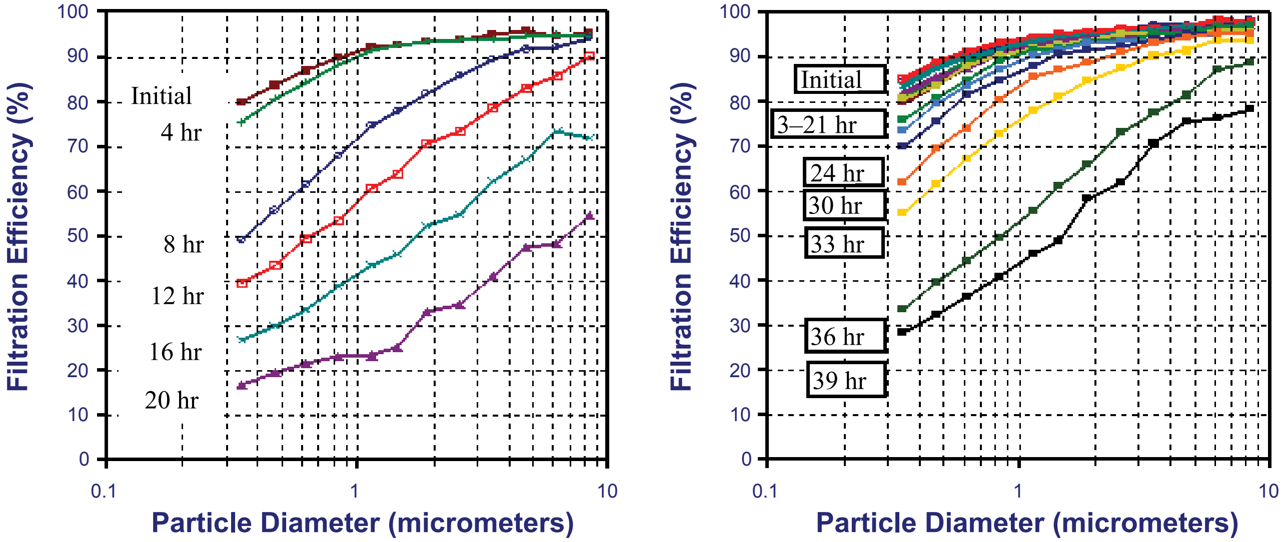


Figure 33. Degradation of Filtration Efficiency After Exposure in Silicon Vapor Chamber for Two ESP Devices (Hanley et al., 2002)

Several studies specifically address collection of biological particles. In Mainelis et al. (1999), collection of biological particles was determined to occur in the same ways as collection of nonbiological particles. An ESP device was modified to use three different sampling media (agar, water, and filter material). In this study, biological organisms were collected in order to identify them, meaning that the organisms must remain culturable (or alive). Three different organisms were tested, a spore-forming organism (*Bacillus subtilis* var *niger*, or BG, a relative of the organism causing anthrax), a bacterium with high resistance to drying, disinfecting, and other environmental processes (*Mycobacterium bovis*, a relative of the organism causing tuberculosis), and a more sensitive bacterium (*Pseudomonas fluorescens*). BG was collected with greater than 90% efficiency on the filter substrate, about 55% on agar, and about 20% in water. *M. bovis* was recovered with an efficiency ranging from 0 to 8% in all three media. Very little of the more sensitive *P. fluorescens* was recovered. The physical collection efficiency of the ESP device was about 90% for both biological and nonbiological (polysterene latex) particles.

In subsequent studies, Mainelis et al. (2001 and 2002b) examined the electrical charging on airborne microorganisms and the effects of electrical charging and fields on airborne microorganisms. Based on those studies, Mainelis et al. (2002a and 2002c) designed a new ESP device to maximize the bio-recovery of microorganisms by collection on agar. This device was able to achieve about 90% overall physical collection efficiency (2002c). In Mainelis et al. (2002a), BG, *P. fluorescens*, and *Penicillium brevicompactum* (a fungal spore causing respiratory infections and allergies) had biological collection efficiencies of about 70%, 20%, and 75%, respectively. These bioefficiencies compared well with results from another biological sampling device, the BioSampler (SKC, Inc., Eighty Four, Pennsylvania). The ESP device showed nearly equivalent collection for BG and *P. brevicompactum* and higher collection efficiency for *P. fluorescens*.

Yao and Mainelis (2006) investigated whether natural electrical charges on airborne organisms can be used for their collection without the need for active charging. The specific application was development of a low-volume novel air sampler (< 20 L/min). The resulting collection efficiency was independent of particle size over the range tested (0.3 to 3.0 µm) but decreased dramatically from about 80 to 30% as flow rate increased from 1.2 to 10 L/min. The study demonstrates the potential of the bioaerosol sampler, as the collection mechanism does not stress the organism as much as inertial or impaction methods. However, the authors also note considerable “day-to-day” variability due to differences in the charge levels of the organisms, potentially due to differences in weather conditions or organism source/generation method. Thus, actively charging an aerosol would be preferred for consistency in an HVAC application.

For both of the above devices, the biological collection efficiency is lower than the overall collection efficiency for several reasons. First, some of the collected microorganisms were shown to be collected on surfaces other than the agar. Only organisms collected on the agar were counted towards the bioefficiency. Second, some of the organisms collected can be injured during or after collection, further increasing the difference between the biological collection efficiency and the overall collection efficiency. Also, any losses due to the aerosolization process are not accounted for in this study, though *P. fluorescens* in particular may be subject to degradation during aerosolization.

7.3.2 Assessment in an HVAC System

Measurements of collection efficiency are useful in determining the performance of a device, but another measure of performance is the effectiveness of the device in real applications. Several authors have examined ESP/EAC devices from this perspective.

Emmerich and Nabinger (2001) and Fugler et al. (2000) measured the performance of several in-duct filtration devices, including ESP devices. Emmerich and Nabinger reported collection efficiencies ranging from about 96% for particle diameters of 1 µm and less to 91% for 1–5 µm diameters. Fugler et al. measured collection efficiencies of 84% for PM1 and 90% for PM10 particles. In both studies, the ESP device clearly outperformed the other devices tested, which included a range of mechanical, electret, and electrostatically enhanced filters.

Several studies examined the effectiveness of in-duct mounted ESP devices. Howard-Reed et al. (2003) and Wallace et al. (2004) both presented results of the reduction in indoor particulate concentrations within a three-story townhouse. The townhouse was occupied and both mechanical and ESP filtration were studied. Both authors calculated the deposition rates of several aerosols using a mathematical model. Howard-Reed et al. reported that the in-duct ESP reduced particle concentrations by 57–85% for 0.3 to 10 µm particles. Wallace et al. studied 0.01 to 0.1 µm and 0.54 to 2.5 µm particles in the same way (though different particle measurement devices were used). In this second study, a reduction of 44–59% was reported for the particle sizes studied. Both studies concluded that simply running the HVAC central fan would significantly reduce concentrations by 14–50%. Fugler et al. also presented data on the reduction in indoor dust levels for in-duct ESP with values of 31% when occupants were active and 71% when occupants were inactive.

The literature search also revealed several other studies in which the use of ESP was studied in office spaces. Croxford et al. (2000) and Richardson et al. (2001) both studied the use of several ESP devices located within the office spaces themselves, though it is not clear whether these devices were simply ionizers or also included collection plates. Croxford et al. found that using ESP devices within the “breathing zone” results in a 49% reduction in particles 2 µm and less, about a 46% reduction in particles 10 µm and less, and an overall reduction of 37% for all particle sizes. The authors concluded that the devices used were more effective at removing the smaller particles. Richardson et al. reported a 21% reduction in indoor particle concentrations for particles of 3 μm and less.

There is a wide difference in the reduction of particle concentrations reported in these two studies. The incomplete description of the devices used in Croxford et al. (2000) and Richardson et al. (2001) makes it difficult to determine the reason for the differences. The locations, buildings, and measurement devices were also different in these studies.

7.3.3 Additional Factors

While ESP remains an effective technology for air cleaning, there are some negative effects. Ozone concentration and generation of excessive ionization are possible problems. Power consumption in general has not been well examined, at least in the studies reviewed for this effort. It is not clear whether the electrical power required for ESPs to function is offset by the reduced pressure drop of these devices.

ESP devices form ozone, and to a lesser extent, other nitrogen by-products. In fact, though negative polarity corona results in more advantageous operation, much more ozone is produced than with positive corona, as much as 5 to 6 times as much (Huang and Chen, 2001). As a result, most indoor air cleaning applications use positive corona for this reason. Note that the time-weighted average (TWA) for ozone is 0.1 ppm (National Research Council, 1984).

Measurements of ozone concentration vary and will be device and experiment dependent. Huang and Chen (2001) measured ozone concentrations over 0.2 ppm with positive corona devices and over 1.6 ppm with negative corona in 30 L/min of air, as shown in Figure 34. When mixed into the air of a room (this device was from a room air cleaner), these levels would likely become lower than the NIOSH TWA of 0.1 ppm. Grabarczyk (2001) reported that ozone exceeded the smell threshold (about 0.005 ppm) after two hours of operation. Fugler et al. (2004) measured ozone levels in houses equipped with ESP devices and concluded that indoor levels of ozone were similar to those measured outdoors.

Another unintended consequence of using ESP technology for indoor air is the accumulation of ions in the air. As noted by Grabarczyk (2001) and Lee et al. (2004a), objects within a room can become charged and result in static electric shocks. Furthermore, the accumulation of charged dust particles will result in significantly increased deposition on indoor surfaces (Grabarczyk, 2001). These effects are more significant with whole-room ionization technologies that use devices that do not also collect the charged particulates. These effects also may occur with normal ESP devices that are collecting at very low efficiency (ASHRAE, 2004).

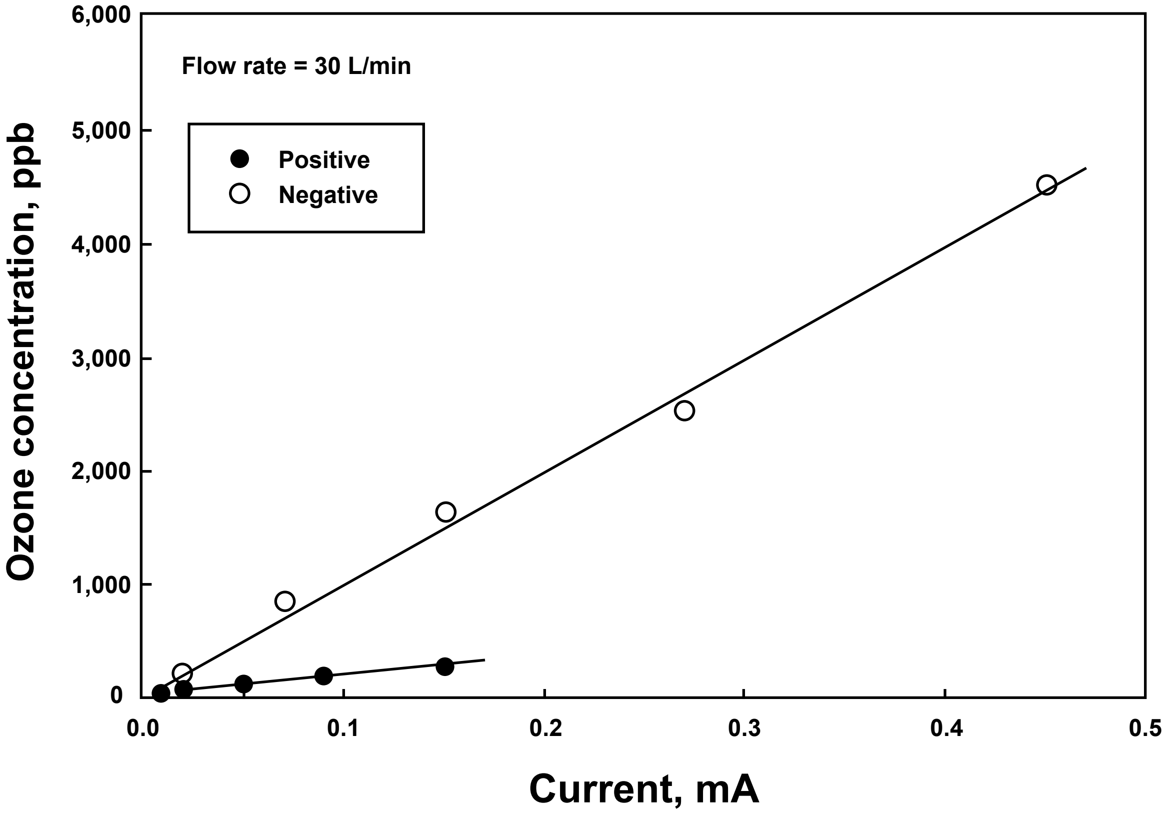


Figure 34. Ozone Production as a Function of Current for Positive and Negative Corona (Huang and Chen, 2001)

7.4 Critical Assessment

7.4.1 Technology Assessment

ESP devices generally offer high filtration efficiency at a low pressure drop. A lower pressure drop (than that of mechanical filtration) is associated with lower power consumption, but it is unclear whether this benefit is nullified by the power required to run the ESP. The several studies comparing residential ESPs with other types of residential filtration have demonstrated the superior performance of the ESPs (Emmerich and Nabinger, 2001; Fugler et al., 2000). Residential ESP units are limited, as most ESP units are for commercial applications.

In the review of the research regarding ESP collection efficiency, it was clear that test aerosol challenges and conditions (either environmental or equipment operation such as field strength) are not standardized. Thus, data are not easily compared between studies, and therefore not easily comparable between units or technologies. Recent work by EPA as part of the ETV program has made an effort to test ESPs for residential use in a consistent manner. The EPA data, as well as data from many other authors, suggest that the composition of the test aerosol used to measure collection efficiency is not critical. It does appear as though the particle composition and size used for any loading or preconditioning of the ESP prior to collection efficiency measurements is very important. As previously mentioned, the work of Hanley (2002) has led to the recommended use of nano-sized KCl particles for loading.

The purpose of conducting performance tests with ESPs that have been conditioned is to simulate the rapid and significant decrease in collection efficiency with use. Hanley et al. (2002) have attributed degradation to the formation of silicon deposits on the ionization wires. Hence, the practice of preconditioning an ESP by exposure to silicon vapor as a means to simulate in-use operation is recommended.

As long as the selected ESP is cleaned regularly, performance can be maintained at a relatively high level (Hanley et al., 2002; Howard-Reed et al., 2003; Wallace et al., 2004). Cleaning of the ESP collection surfaces has demonstrated the ability to “regenerate” the initial operating performance of ESPs. There is no definitive work regarding the number of cleaning cycles that may be used before the degradation is permanent. The literature did not suggest specific cleaning techniques to be used.

The recent work conducted by Battelle as part of this current project has shown an increase in aerosol penetration of a commercial ESP unit for particles less than about 0.05 µm. The increase in penetration for the nanoparticles is believed to be due to particle charging efficiency. The charge that can be maintained on the particles is relatively low, and thus the capture efficiency begins to drop.

Finally, ESPs can have a biocidal effect on collected microorganisms under some operating conditions. In general, the survival of organisms decreases as the operating voltage increases, especially for relatively delicate organisms such as viruses or vegetative cells. Robust organisms are relatively unaffected by typical operating voltages. Survival of the organisms also depends to some extent on the collection media. In a standard ESP with metal collection plates, only the most robust organisms will not be injured by the dry conditions. High collection voltages and harsh collection conditions can be used to disinfect collected particulates to some degree.

Because ESPs can also operate in a range that allows for the survival of many organisms, ESPs may be used as effective bio-sampling devices. Mainelis et al. (2002c) demonstrated that about 70% of robust organisms and 20% of vegetative organisms can be recovered unharmed using an ESP collection device. Compared to a typical biosampling device, the ESP bio-efficiencies were equal and, in fact, greater for the vegetative organism.

Because ESP devices can generate ozone, ozone levels should probably be monitored, particularly when used in the homes of people with particular sensitivity to ozone. For this reason, most devices intended for occupied spaces operate with positive polarity coronas rather than the more efficient negative polarity corona since the negative polarity corona generates more ozone.

7.4.2 Impact on HVAC System

As described above, ESP devices offer much lower pressure drops than traditional high-efficiency filters. Because of the lower pressure drops, the effect on HVAC systems is minimal. An indirect impact might be the electric power required to run a particular ESP device. The higher the voltage used to ionize and collect particles, the greater the collection efficiency will be. However, greater collection efficiencies will come with the addition of higher electrical power cost. Note that applied voltage is something typically determined by the manufacturer as part of product design and is probably not something that would be adjustable by the end user of an ESP device.

7.4.3 Cost Analysis

Electrostatic precipitators, because of their design, typically will not fit into an existing air handler without major modifications. For this reason they may be installed outside the air handler, in the ductwork. This arrangement would require modifications to the existing ductwork, which may demand additional services for redesign of the ductwork system. These filters would also require new electric service. For the above reasons, the installation and initial purchase costs of these filters are very high.

Despite their high initial costs, these filters have small operating and maintenance costs. In comparison to mechanical filtration, there is a small increase in static pressure and a small increase in the electricity used to power the ESP, but they do not require periodic changing. An increase of 12% in maintenance costs for a typical office building includes the labor required to clean the prefilters and electrostatic precipitators. The increase in operating cost of a typical office building would be 3%.

An in-depth cost analysis of electrostatic precipitation is provided is Section 9.5.

8.0

Critical Assessment of Ultraviolet Germicidal Irradiation

8.1 Technology Description

The uses of ultraviolet (UV) radiation can be classified into two general categories, air and surface disinfection. A variety of systems have been developed to accomplish these two applications. Air disinfection systems fall into three general categories: (1) in-duct air disinfection systems for reducing the circulation of infectious material (e.g., tuberculosis) in a facility, (2) recirculation systems used to treat the air in a room, and (3) "upper air" disinfection systems, which consist of UV lights mounted in a room so that the air above them is irradiated. To limit exposure of the occupants, upper air disinfection systems are installed at heights greater than 7 ft (~2 m) above the floor and/or some type of shielding panels are used. Surface disinfection systems can be classified into four general applications: (1) microbial growth control systems such as UV exposure of a filter surface, (2) laboratory disinfection such as the UV lights used in biosafety cabinets, (3) portable disinfection systems, and (4) mail room decontamination systems. Both air purifying and surface decontamination systems are used in hospitals, shelters, prisons, and clinics (Kowalski and Bahnfleth, 2000b). Unlike other previously discussed filter technologies, UV radiation is used to kill the biocontaminant as opposed to removing it from the air stream. While it is possible that these systems could be used in commercial and residential buildings, their application is not yet common.

8.2 Theory of UVGI

UV radiation in wavelengths of 225 to 302 nm is frequently used for microbial disinfection (Kowalski and Bahnfleth, 2000b). UV radiation kills microorganisms by damaging their DNA and, to a lesser extent, causing oxidation of their proteins. DNA absorption of UV radiation is maximal at 254 nm and leads to the hydrolysis of cytosine and the formation of thymine dimers (Snustad et al., 1997). Thymine dimers prevent DNA replication while the hydrolysis of cytosine can lead to base pair mismatches. Protein oxidation occurs when reactive oxygen species are generated by UV radiation and the addition of a chemical such as titanium oxide, which releases significant amounts of oxygen upon exposure to UV light and can facilitate the oxidation process (Lele and Russell, 2005).

Whether or not UV radiation is lethal to a microorganism depends on the dose that microorganism receives. Doses are calculated from the average radiation intensity and exposure time; the dose needed to kill a microorganism is specific to that microorganism (Kowalski and Bahnfleth, 2003). This dose can be approximated mathematically by the following equation (Memarzadeh et al., 2005).

$$\%\text{Survival}=100\exp(-z\,I\,t)$$

where z is the susceptibility factor for the microorganism ($\text{cm}^2/\mu\text{W-s}$), I is the average radiation intensity ($\mu\text{W/cm}^2$), and t is the exposure time (seconds). Effective UVGI doses have also been experimentally determined for many microbial species; however, many were determined for organisms on surfaces rather than in their aerosolized form. Since it is easier to inactivate airborne organisms, some of the published data may overestimate the dose required for an air cleaning UVGI system (Brickner et al., 2003).

To be effective, UV radiation requires direct "line of sight" exposure; therefore, having a fully developed light field is critical. For example, most "in-duct" systems use multiple light sources and reflective panels to create an evenly illuminated exposure zone. Prefilters and routine cleaning of the light sources and reflective panels may also be incorporated to maintain a fully developed light field. Encapsulation of microorganisms in other debris or material can decrease the efficacy of UV radiation. This decrease in efficacy was shown with *Serratia marcescens* suspended in various solutions prior to aerosolization (Lai et al., 2004). The need for direct exposure can be problematic for surface decontamination as well because microorganisms in shaded cracks are not killed.

8.3 Summary of Relevant Studies

Studies in the use of UVGI for air cleaning applications are summarized in Table 17, where the main focus was on those conducted since 1999. A large number of articles discussed the potential application of UVGI in HVAC systems, although the majority of the performance data were for systems using UVGI for upper air inactivation or surface decontamination. Computer modeling and articles with design basics illustrate parameters that factor into selecting a UVGI system specific to each building. Safety concerns over UV exposure were also covered.

Table 17. Summary of UVGI Studies

Basic Scope	Content/Conclusion	Reference
Overview	UVGI is a viable HVAC option; focus has been on tuberculosis (TB) studies, but UVGI can be used to affect other microorganisms; most applications promote combination with mechanical filtration or other to cover range of particle sizes.	Brickner et al., 2003; Kowalski and Bahnfleth, 2005; Kowalski and Bahnfleth, 2003; Kowalski and Bahnfleth, 2002; Kowalski and Bahnfleth, 2000a; Kowalski and Bahnfleth, 2000b
Design Basics and Modeling	Both general and computationally intensive calculations of effectiveness and application specifics.	Brickner et al., 2003; Kowalski, 2003; Kowalski and Bahnfleth, 2000a; Kowalski and Bahnfleth, 2000b
Effectiveness of UVGI	Most were upper-room installations; some effects of temperature and relative humidity; calculated efficiencies for in-duct applications.	Miller and Macher, 2000; Miller, 2002; Peccia et al., 2001; Ko et al., 2002; Xu et al., 2000; Xu et al., 2003; VanOsdell and Foarde, 2002; Kowalski, 2003; Kowalski and Bahnfleth, 2003; Menzies et al., 2003
Safety Considerations	Minimizing UV exposure and ozone production.	Talbot et al., 2002; Nardell, 2002; Kowalski, 2003

8.3.1 Performance and Variables That Affect Performance

Environmental and design variables that affect the performance of UVGI systems are relative humidity, temperature, air velocity and air mixing, lamp selection, the use of reflectors, and combination of UVGI with filtration. Each of these variables is discussed in the following sections.

Relatively humidity, especially at levels greater than 50%, has been documented to impair the UVGI “kill” rate of some microorganisms (VanOsdell and Foarde; 2002; Peccia et al., 2001). Others have reported that relative humidity is not a factor — at least in the 20% to 80% range (Ko et al., 2002). Increased operating temperature can affect biological inactivation by negatively impacting the output of the UV lamps. Temperature was shown by Ko et al. (2002) to have a measurable effect on kill rates.

Air velocity and air mixing can affect the effectiveness of UVGI. The majority of the literature with experimental results dealt with UVGI in upper air cleaning applications. UVGI alone was found to reduce the culturable airborne bacteria between 46% and 80% for *B. subtilis* spores, between 93% and 98% for *M. parafortuitum* and between 96% and 97% for *M. bovis* BCG cells, depending on the ventilation rate (Xu et al., 2003). Incomplete mixing decreased effectiveness by 80% compared to complete mixing conditions (Xu et al., 2000). Air velocity and air mixing in an in-duct system would need to be sufficient to supply the demands of the building but not in such excess as to reduce the effective dose of the incorporated UVGI system. This theory is discussed in more detail by Kowalski (2003), but no experimental data were found in the literature.

The combination of UVGI with filtration is discussed as a viable option to combine the efficiencies of each to compensate for the areas in which the other performs less effectively. Using experimental data on filtration efficiency and calculated UVGI performance, Kowalski (2003) illustrated the effectiveness of combining mechanical filtration with UVGI, as shown in Figure 35. Only microbes with known UVGI rate constants were included, ordered in size from smallest (1) to largest (33), including many BW agents.

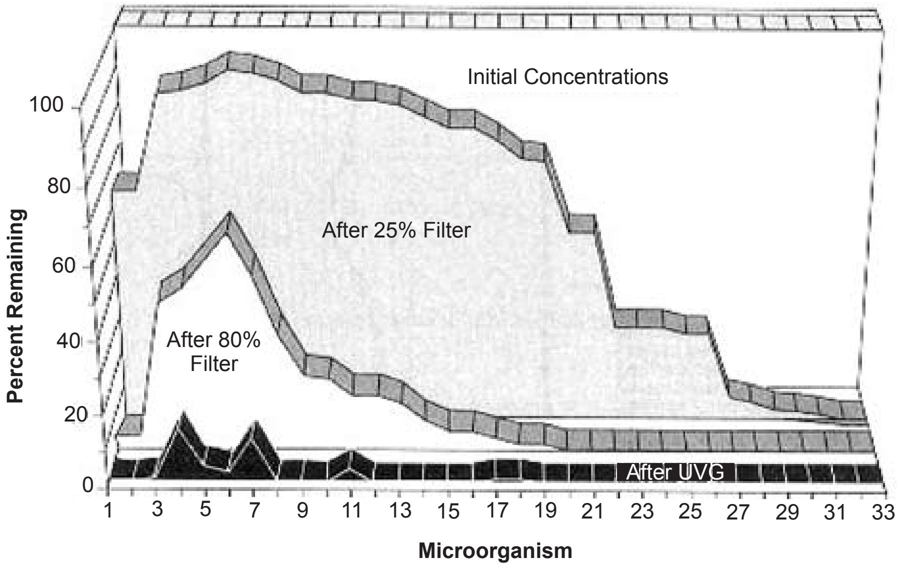


Figure 35. Microbial Populations Before and After Filters and a UVGI System (Kowalski, 2003)

A study performed by Menzies et al. (2003) assessed the reduction in microbial contamination after UVGI was applied to drip pans and cooling coils within the ventilation system of an office building. Although the use of UVGI led to a 99% reduction of microbial contamination on exposed surfaces, airborne microbial levels did not decrease significantly.

Kujundzic et al. (2006) characterized the performance of six in-room air cleaners, including a HEPA filter device, electrostatic filter device, ESP, and air ionizer. Tests were also performed with the HEPA filter and ESP in combination with UVGI. The cleaners were challenged in an 87 m^3 test room with three biological aerosols, two bacterial and one fungal. Cleaner performance was described using the clean air delivery rate (CADR), which represents the amount of particle-free air produced. The HEPA filter and ESP provided the highest removal rates. These rates were increased by a factor of 2 to 3 when used in combination with UVGI. Several of the filtration-based air cleaners were equipped with internal UV lamps to kill bioaerosols that penetrated the filter or to prevent growth on the filter. The authors note that these UV lamps had no effect on the removal rates from the room.

8.3.2 Assessment in an HVAC System

The merits of including a UVGI system in an HVAC system are discussed in detail by Kowalski and Bahnfleth (2000a, 2000b 2002, 2003). Kowalski and Bahnfleth (2003) indicated that a UVGI system was going to be retrofitted into the ventilation system of the administration building of the Memphis Light Gas and Water (MLGW) company to augment the existing air cleaning system; however, no experimental data from this installment were found in the literature.

Design considerations must be made when integrating UVGI into an HVAC system. UVGI in-duct systems need to be appropriately designed to the specific building. Overdesign results in prohibitive costs and high energy consumption, and underdesigned systems are rendered ineffective. Lamp and reflector selection are key in obtaining the appropriate dose for the stated disinfection goal. Economics dictate that the lamp be appropriately sized to the building/application. Kowalski and Bahnfleth have written numerous articles detailing UVGI design basics for air and surface disinfection as well as a model for predicting the rate of air stream disinfection to improve system design (Kowalski, 2003; Kowalski and Bahnfleth, 2003; Kowalski and Bahnfleth, 2002; Kowalski and Bahnfleth, 2000a; Kowalski and Bahnfleth, 2000b). UVGI systems are commonly located downstream from the air intake filter bank but upstream of the cooling coils. Larger particles are more efficiently removed by filters than killed by UVGI, and the use of filters upstream helps maintain a fully developed light field by reducing deposition on the lamps and reflectors. The additional heat created by the UVGI lights must be dissipated through modified HVAC design or an increase in cooling coil performance. Although UVGI systems can be installed in the return air ducts to inactivate any recirculated microorganisms, this type of installation is less common except in specific medial applications.

Kowalski and Bahnfleth (2000a) discuss in detail the four computational aspects of UVGI essential for the accurate modeling of air stream disinfection systems — the exponential decay curve, the lamp intensity field, the direct reflected intensity field, and the inter-reflected intensity field. Model results have been corroborated with laboratory tests within ±15%.

8.3.3 Additional Factors

Safety. Two safety considerations apply when using UVGI for air cleaning applications: UV exposure and ozone production. Literature related to UV exposure cited accidental occupational exposure with unshielded upper-room air installations (Talbot et al., 2002). An upper-room air system needs to be installed at a minimum height with or without additional shielding to reduce UV exposure (Nardell, 2002; Miller et al., 2002). For in-duct applications, UV exposure is less of a concern since personnel and UV lamps would not occupy the same space. Simple precautions would need to be taken by maintenance personnel servicing the system.

In other applications, UV lamps are used specifically to generate ozone, which aids in the destruction of microorganisms. Unfortunately, high levels of ozone can be harmful to health and constitute a respiratory irritant. Non-ozone-producing lamps are available for UVGI systems (Kowalski, 2003), although no other mention of ozone production or the possible effects was encountered in the reviewed literature. Further investigation of the levels of ozone created during UVGI in-duct applications is warranted.

8.4 Critical Assessment

8.4.1 Technology Assessment

The combination of UVGI and mechanical filtration appears to be the most likely use of UVGI due mainly to the fact that UVGI systems would probably be added to a current HVAC system that already employs some type of mechanical filtration. This application is advantageous since UVGI is most effective against biocontaminants in the particle size range where mechanical filtration is less efficient (1 µm and smaller). Since UVGI kills the biocontaminant but does not capture the actual particle, further mechanical filtration downstream of the UVGI system may be necessary.

Retrofit UVGI systems would have to be installed downstream of the original mechanical filtration to aid in maintaining the fully developed light field. Periodic cleaning of the lamps will also be important in establishing the light field in order to maintain the effectiveness of the UVGI system.

Unfortunately, little to no experimental data exist on HVAC applications of UVGI. It is highly recommended that any research in the future be specifically directed to this area so that the benefits of UVGI can be determined. Due to the high initial, operating, and maintenance costs of a UVGI system, the benefits of the system must be profound to outweigh the costs.

8.4.2 Impact on HVAC System

A UVGI air cleaner can be installed in-duct in existing ventilation systems, although modifications are required. The addition of UV bulbs and reflective material in a crossflow configuration adds a negligible pressure drop to the existing HVAC system. Any additional pressure drop on the HVAC system would come from including a higher MERV level prefilter than currently exists in the HVAC system. This additional filter would impact the system as discussed previously under Mechanical Filtration, Section 4.4. Additional power would be required to operate the UVGI lamps as well as cool the air stream from the heat generated by the UVGI system.

8.4.3 Cost Analysis

UVGI, because of the design requirements, typically will not fit into an existing air handler without major modifications. For this reason, the UVGI may be installed outside the air handler, in the ductwork. This arrangement would require redesign of the ductwork system. These systems would also require new electric service to a greater extent than the other filters analyzed here. For the above reasons, the installation cost of these filters is very high. Because of the more complex design of these systems, their initial purchase cost is extremely high. The initial purchase and installation costs for these systems are much higher than for any of the other filters analyzed in this report.

Maintenance costs for these systems are also high as they include cleaning and/or changing the bulbs periodically. The increase in maintenance costs after installing these filters in a typical office building would be 58%. Because they use a large amount of electricity, the operating costs for these systems are also very high; an increase in operating costs of 22% would be observed after installing a UVGI system into a typical office building.

An in-depth cost analysis of UVGI is provided in Section 9.6.

9.0
Cost Analysis

9.1 Approach

When estimating the cost (in dollars) of replacing standard air handler filters with varying types of more protective filters, there are six main factors to consider: (1) the initial (manufacturer's) cost of the new filters, (2) the cost for installation of new filters, (3) the cost of retrofits to the existing system, (4) the cost of other services, (5) yearly operating costs, and (6) yearly maintenance costs.

It is helpful to create a typical office building to provide a model for this approach. Assuming a 100,000 ft^2 (9,290 m^2) office building with four stories and 25,000 ft^2 (2,323 m^2) per story (a typical modern suburban-type office building), and assuming 1 cfm/ft^2 (0.3 $m^3/min/m^2$) (Bell, 2000), results in a 100,000 cfm (2,832 m^3/min) system. Because selection of a system is based on factors too numerous to list and input on the system selection comes from both engineers and owners, there are numerous possible HVAC systems that a building of this size could have. One system for a building of this size would be a variable air volume (VAV) central system, which is becoming increasingly popular because it saves energy. In a VAV system, all heating and cooling is done at centralized air handlers, which consist of VAV terminal boxes for individual zone control, a hot water boiler for heating, and a packaged air cooled chiller for cooling. Since a 100,000 cfm (2,832 m^3/min) air handler unit would be an extremely large custom unit (single custom units are not typical in office buildings in the U.S. because of cost), assume that there are four air handling units (one unit for each floor) of 25,000 cfm (708 m^3/min) each. This system would have both return and outside air mixed within the unit (all the return air from the building comes back to the units). Basing each unit on a Trane Climate Changer (Trane, 2004) unit size 50, the cross-sectional area of each unit would be 75 x 120 inches (191 x 305 cm). Assume that the unit has two fans positioned in parallel, with both operating at 12,500 cfm (354 m^3/min), 5.0 in. w.g. (1.2 kPa), and 1000 RPM, with a 25 HP motor. By consulting the Trane manual, one can also see that the fan's belt can be safely adjusted to 1200 RPM maximum (selections outside the bold lines are unsafe), which gives a static pressure of 7.5 in. w.g. (1.9 kPa). The fan would have 2.5 in. w.g. (0.6 kPa) of extra capacity. The entire HVAC system would be controlled by a direct digital control system, currently the most commonly accepted method of HVAC controls. Assume that the office building is less than one year old and is located in Columbus, Ohio. Equipment of this type is typically located on the roof if space permits. Assume that space permits and all equipment will be located on the roof with adequate space for additional equipment as well. The total first year cost is determined by summing these terms: $C_p + C_I + C_s + C_r + C_o + C_m$. These terms are discussed below.

The initial purchase cost (C_p = Purchase Cost) of the filters depends largely on the types of materials, size, and complexity of filter design. ASHRAE Applications (ASHRAE, 2003) Ch. 36 states, "A reasonable estimate of the capital costs of components may be derived from cost records of recent installations of comparable design or from quotations submitted by manufacturers and contractors or by consulting commercially available cost-estimating guides and software." One such cost estimating guide is provided by R.S. Means (2004). These cost-estimating guides are widely accepted within the construction industry. Manufacturers often give filter costs on a dollars-per-square-foot of filter cross sectional area basis (the area of a filter perpendicular to the air stream).

The installation cost (C_I = Installation Cost) depends on the size and complexity of the filters and how well the filters fit into the existing air handler (how many man-hours required) and who is doing the installation (labor rates). The cost can be incurred by the building owner, an owner-retained mechanical contractor, or in some cases even the manufacturer. These costs can be estimated by multiplying the number of man-hours by the labor rate and adding an overhead rate if a contractor is used. Estimates can also be obtained from mechanical equipment installation estimating books such as *R.S. Means Mechanical Cost Data* (2004).

Service (C_s = Service Cost) from other professionals may be needed, depending on the complexity and size of the installation. Because equipment data can sometimes be inaccurate as fan conditions change over time (dirty filters) and good fan performance data for existing systems are often hard to locate, an air balance contractor may be needed to determine the actual cfm and operating conditions of an existing fan/system. This information is very important as it may determine whether the existing fan will have the capacity to overcome the pressure increase from the new filters (this information would determine whether a new fan is needed or whether the existing fan just needs a speed adjustment). As with any work involving changing some aspect of the air handling system, an air balance is also needed after the installation work is complete. The air balance would be performed by a certified air balance contractor. The services of a design engineer may also be needed if the air handler unit or system has changed or expertise is needed to retrofit the air handler. These costs can be obtained from the professional in question or from estimating books such as *R.S. Means* (2004).

The cost of retrofits (C_r = Retrofit Cost) to the existing system would include the cost of any equipment that must be added to the system or any replacements or changes that must be made to the system to accommodate the new filters. Due to the increase in static pressure that a new filter will cause, a new fan may be needed as a replacement for the existing fan or as a booster fan (to boost the static pressure). In some cases the existing fan may need only a speed adjustment, whether by adjusting the belt drive or in cases of variable frequency drive fans, adjusting the speed directly through a graphical user interface. Depending on the type of new filter, the filter may be larger in size or require a different face velocity than the existing filter(s). The existing air handler housing may need to change or a special housing may be needed for the new filter. The change in filter size from smaller to larger may also make it necessary to add directional or straightening air vanes to existing air handlers because of the reduced space in the air handler housing. Some filters may require electric service with the addition of new electrical equipment. With some filters, a new filter monitoring system might be required to monitor the filter's cleanliness. In buildings where humidity monitoring is important, a new humidifier may be needed to compensate for the loss of humidity that some filters may cause. The costs of the above-mentioned changes to the system can be estimated from the installers (of the equipment) or from estimating books such as *R.S. Means* (2004).

The operating costs (C_o = Operating Costs) include costs incurred by the operation of the new filters or adjustments that must be made to the system as a result of the new filters. Electrical power usage cost will increase if equipment such as a new fan, electronic air filter, or humidifier is installed. The cost of other utilities such as steam and/or water for a humidifier could increase. Operating costs can be obtained from a calculation of the expected energy usage multiplied by the utility rate estimated or obtained from local utilities companies. Operating (as well as maintenance) costs can also be calculated by computer programs marketed by HVAC equipment manufacturers as well as government agencies such as the Department of Energy (DOE). The National Institute of Science and Technology (NIST) has created a program called the Building Life-Cycle Cost Program (BLCC) (DOE, 2007). Operating costs can be determined by comparing data from previous studies.

To determine the overall building energy cost for comparison purposes, it is helpful to consider the DOE/Energy Information Administration (EIA) 1998 Commercial Buildings Energy Consumption Survey, which reports the consumption and expenditures of commercial buildings during 1995. Data from this study (reprinted in Wang, 2001) reveal that for a central system of the type described above, the heating energy intensity (usage per year) is 29.0 kBTU/ft^2/year. This study also reveals that the cooling energy intensity for a central system is 10.0 kBTU/ft2/year.

Applying these numbers to our model:

<u>Heating energy</u>: 100,000 ft^2 x 29 kBTU/ft^2/year = 2,900,000 kBTU/year

Assuming natural gas is used with a cost of $0.00007/BTU, the total heating cost is:

2,900,000,000 BTU/year x $0.00007/BTU = $203,000/year

<u>Cooling energy</u>: 100,000 ft^2 x 10 kBTU/ft2/year = 1,000,000 kBTU/year

Convert to KWH (cooling will be an electrical utility):

$$\frac{1{,}000{,}000{,}000 \text{ BTU/year}}{3{,}413 \text{ BTU/KWH}} = 292{,}997 \text{ KWH/year}$$

Assuming $0.13/KWH, the total operating cost of the cooling system is:

292,997 KWH/year x $0.13/KWH = $38,090

<u>Total building operating cost</u>: $38,090 + $203,000 = $241,090/year

Maintenance (C_m = Maintenance Cost) includes the cost of upkeep of the filters or any equipment that was added to accommodate the filters. Some filters may need to be cleaned or have parts replaced on a regular basis. These costs can be incurred by the owner, through a maintenance contract with a mechanical contractor, or in some cases by the manufacturer. They can be estimated using data provided by the filter manufacturer, using data from various studies, or by multiplying the number of man-hours by the labor rate.

To determine overall building maintenance costs for comparison purposes, one can use the following equation from ASHRAE (2003):

$$C_{83} = A + h + c + d + S_B$$

where:

A = age adjustment = 0.0018n

n = number of years the system has been in use

h = heating adjustment

c = cooling adjustment

d = distribution system adjustment

S_B = mean maintenance cost

C_{83} = cost in 1983 dollars

The cost in 1983 dollars can be converted (ASHRAE, 2004) to 2005 dollars (C05) by using consumer price index data (CPI) provided by the U.S. Department of Labor (DOL, 2007).

$$C_{05} = CPI_{05} / CPI_{83} \text{ x } C_{83}$$

Values for the preceding equations were found in works by Bell (2000), Dohrmann and Alereza (1986), and ASHRAE (2003) and are listed below.

A = 0, n=0 (new building)

h = 0.0077 \$/ft^2 or 0.083 \$/m^2 (fire tube boilers)

c = -0.04 \$/ft$_2$ or -0.43 \$/m^2 (reciprocating chiller)

d = -0.0446 \$/ft^2 or -0.48 \$/m^2 (multi-zone distribution system)

S_B = 0.32 \$/ft^2 (3.4 \$/m2) per year (mean maintenance cost)

C_{83} = cost in 1983 dollars

$$C_{83} = 0 + 0.0077 - 0.04 - 0.0446 + 0.32 = 0.2431 \text{ \$/ft}^2 \ (2.617 \text{ \$/m}^2)$$

$$C_{05} = 195.3 / 99.6 \times 0.2431 = 0.4767 \text{ \$/ft}^2 \ (5.129 \text{ \$/m}^2)$$

Considering the 100,000 ft^2 (9,290 m2) building, the total maintenance cost is:

$$5.129 \text{ \$/m}^2 \times 9{,}290 \text{ m}^2 = \$\ 47{,}648\text{/year}$$

9.2 Model Estimation for Mechanical Filtration

Using the typical office building model described above, assume that the existing filters are replaced by high efficiency filters with MERV 14 rating and prefilters with MERV 8. Two new pressure gauges would be used to measure pressure drop across the filter. These gauges would have interfaces to the building control system. Because the existing filter would have roughly the same static pressure as the prefilter, the only addition in static pressure to the system is from the MERV 14 filter. This filter would typically be replaced when the pressure drop through the filters reached 1 in. w.g. (249 Pa). The 1 in. w.g. (249 Pa) is safely below the excess of 2.5 in. w.g. (623 Pa) inherent in the fan selection, so a new booster fan would not be needed (the belt would be adjusted to 1100 RPM, which would give 6 in. w.g. [1.5 kPa] static pressure capacity). In this case, the fan is on a variable frequency drive, which means that the fan does not operate at full capacity. The filters installed in the existing air handling unit have a face velocity of 400 fpm, which is below the generally recommended maximum face velocity for commercial air filters of 500 fpm.

9.2.1 Initial Purchase Cost (C_p)

Item	Cost
MERV 8 filters (n=16)	$ 258
MERV 14 filters (n=16)	$ 1,687
New pressure gauges (2) and controls	$ 820
Delivery	$ 100
Total 1 unit	$ 2,865
Total whole building (4 units) C_p	$11,460

The above data were acquired from confidential discussions with a leading air filter manufacturer. It was assumed that 4 air handlers would be procured, each delivering 25,000 cfm, so that the 100,000 cfm required for the building could be achieved.

9.2.2 Installation Cost (C_i)

Item	Cost
Install MERV 8 filters	$ 72
Install MERV 14 filters	$ 240
Install gauges/controls	$ 600
Total 1 unit	$ 912
Total whole building (4 units) C_i	$3,648

Filter installation costs were estimated using data from the report entitled "Performance and Costs of Particle Air Filtration Technologies" (Faulkner et al., 2002).

9.2.3 Service Cost (C_s)

Item	Cost
Engineering fees	$3,650
Air balance	$4,500
Total whole building (4 units) C_s	$8,150

The air handling units must be rebalanced and possibly have their belts adjusted (to speed up the fan) because of the additional static pressure added by the filters. Engineering fees are for the investigation of the system, planning, and design of air handler modifications. The engineering fees estimation assumes a $50,000 total project cost. Both numbers were estimated using *R.S. Means* (2004).

9.2.4 Retrofit Cost (C_r)

Item	Cost
Remove existing filters	$ 72
New access door	$ 202
Total 1 unit	$ 274
Total whole building (4 units) C_r	$1,096

Labor cost to remove existing filters was based on data from "Performance and Costs of Particle Air Filtration Technologies" (Faulkner et al., 2002). Assuming the existing access door is not located correctly for the new filter or big enough to accommodate it, adding a new access door would be necessary. The cost of a new access door was estimated from *R.S. Means* (2004).

9.2.5 Operating Cost (C_o)

Item	Cost
Fan power	$ 3,519
Total whole building (4 units) C_o	$14,076

The fan power operating cost increase is due to the additional electrical power required to operate the fan at its new pressure. This power increase is calculated from eq. 25 of the *Handbook of Air Conditioning and Refrigeration* (Wang, 2001), given below:

$$P_f = \frac{\Delta p\ V}{6356\ \eta_f\ \eta_m\ \eta_d}$$

where:

P_f = fan energy use in hp (increase due to new filter)

Δp = static pressure drop of filter (in. w.g.) = 5 in. w.g. (1.2 kPa)

V = total system volume flow rate (cfm) = 25,000 cfm (708 m^3/min)

$\eta_f\ \eta_m\ \eta_d$ = combined fan, motor, and drive efficiency (for a VAV central system, this value is 0.55, from Table 25.1 [Wang, 2001])

Power is then converted to yearly dollars using eq. 5 from Faulkner et al. (2002):

$$\text{Energy Cost} = (\text{Fan Power})(\text{Fan Operating Time})(\text{Electricity Price})$$

In the energy cost calculation, the fan is assumed to be running continuously 24 hours a day, 365 days per year. The electricity price is the local price in Columbus, Ohio, using data from the DOE's Energy Information Administration Table 5.6.A., "Average Retail Price of Electricity to Ultimate Customers by End-Use Sector" (DOE, 2004).

9.2.6 Maintenance Cost (C_m)

Item	Cost
MERV 8	$ 330
MERV 14	$1,927
Total 1 unit	$2,257
Total whole building (4 units) C_m	$9,028

Maintenance costs include the cost of changing both filter banks. It is assumed that the filters will be changed once per year.

9.2.7 Mechanical Filtration Cost Summary

Item	Cost
Total 1st year	$47,458
Total yearly operations and maintenance (O+M)	$23,104
Energy increase	6%
Maintenance increase	19%

The cost for the first year, including initial costs and operation (maintenance only requires yearly changing of the filter) in our model is:

$$\text{Total 1}^{\text{st}}\text{ Year Cost} = C_p + C_I + C_s + C_r + C_o + C_m$$

Using this equation and the above data, the first-year cost for installing mechanical filtration in the model building is $47,458.

The yearly costs (for subsequent years after the first year) can be estimated by the following:

$$\text{Total yearly cost} = C_o + C_m$$

The total yearly cost in the above example is $23,104. This yearly cost incurred after the first year can be useful in life-cycle cost analysis.

For the purpose of extrapolating these data to other buildings with similar HVAC systems, it is helpful to compare yearly cost to total building yearly operating and maintenance cost. By calculating the energy increase due to the filters as a percentage of the above total building energy consumption, one can see that the increase in operating costs is 6% of the total building energy costs. In a similar manner, the maintenance cost increase is 19% of the estimated total building maintenance cost.

9.3 Model Estimation for Electrostatically Enhanced Filtration (EEF)

Using the typical office building model described above, it was assumed that the existing filters were replaced by an electrostatically enhanced filtration system. A MERV 8 prefilter would be used before the EEF to keep the EEF clean from large particles. The EEF would add 1 in. w.g. (249 Pa) of static pressure when dirty, which allows the same fan to be used, per the above-mentioned criteria (under 2.5 in. w.g.) (623 Pa). The filters installed in the existing air handling unit have a face velocity of 400 fpm, which is acceptable because it is below the maximum recommended velocity of 500 fpm.

9.3.1 Initial Purchase Cost (C_p)

Item	Cost
EEF final filter	$22,500
MERV 8 (prefilter)	$ 258
Delivery	$ 100
New pressure gauges (2) and controls	$ 820
Total 1 unit	$23,678
Total whole building (4 units) C_p	$94,712

The above data were obtained from confidential discussions with a leading manufacturer. The EEF final filter cost includes the cost of control modules within the filter system.

9.3.2 Installation Cost (C_i)

Item	Cost
Install EEF filter	$18,000
Install MERV 8 filter	$ 72
Install gauges/controls	$ 600
Total 1 unit	$18,672
Total whole building (4 units) C_i	$74,688

Estimates shown above were obtained from confidential information provided by a leading manufacturer. The "Install EFF filter" includes the cost of modifications to the existing system to fit the control modules.

9.3.3 Service Cost (C_s)

Item	Cost
Engineering fees	$4,800
Air balance	$4,500
Total whole building (4 units) C_s	$9,300

It is assumed that the air handling units must be rebalanced and possibly have their belts adjusted (to speed up the fan) because of the additional static pressure added by the filters. Engineering fees encompass the investigation of the system, planning, and design of air handler modifications. The engineering fees estimation assumes a $100,000 total project cost. The project cost may actually be more, but typically engineering fees for projects of this size would not be based on the cost of the equipment (only a small portion of the square footage of the building is being worked on). Both numbers are estimated using *R.S. Means* (2004).

9.3.4 Retrofit Cost (C_r)

Item	Cost
Remove existing filters	$ 72
New access door	$ 202
New electric service	$ 496
Total 1 unit	$ 770
Total whole building (4 units) C_r	$3,080

Labor cost to remove existing filters was based on data from "Performance and Costs of Particle Air Filtration Technologies" (Faulkner et al., 2002). Assuming the existing access door is not located correctly or the access door is not big enough to accommodate a new filter, a new access door would have to be added. The cost of a new access door is estimated from R.S. Means (2004). New electric service includes the cost of wiring, junction boxes, and disconnect switches, and assumes that there is a spare breaker or breaker space in a panel relatively close to the air handler.

9.3.5 Operating Cost (C_o)

Item	Cost
Fan power	$ 3,519
EEF power	$ 198
Total 1 unit	$ 3,717
Total whole building (4 units) C_o	$14,868

The EEF requires 15 watts per filter with 20 filters. All calculations were made in a manner similar to Section 9.2.5.

9.3.6 Maintenance Cost (C_m)

Item	Cost
EEF filters (change pads)	$ 2,576
MERV 8 (prefilter)	$ 330
Total 1 unit	$ 2,906
Total whole building (4 units) C_m	$11,624

The above cost includes the cost of changing the EEF filter pads and the cost of changing the prefilters.

9.3.7 EEF Filtration Cost Summary

Item	Cost
Total 1st year	$208,272
Total yearly operations and maintenance (O+M)	$26,492
Energy increase	6%
Maintenance increase	24%

The above data were calculated in the same manner as described in Section 9.2.7.

9.4 Model Estimation for Electret Media Filtration (EMF)

Using the typical office building model described above, it was assumed that the existing filters were replaced by electret media filters with prefilters. A MERV 8 prefilter would be used before the EMF to keep the EMF clean from large particles. The EMF would add 1.5 in. w.g. (374 Pa) of static pressure when dirty, which allows the same fan to be used per the above-mentioned criteria (under 2.5 in. w.g.) (623 Pa). The fan would have its speed adjusted to 1150 RPM, which would give 6.5 in. w.g. (1.6 kPa) total static pressure. The new filters installed in the existing air handling unit have a face velocity of 390 fpm, which is acceptable because it is below the maximum recommended velocity of 500 fpm.

9.4.1 Initial Purchase Cost (C_p)

Item	Cost
Electret filters (n=16)	$ 2,500
MERV 8 (prefilters) (n=16)	$ 258
Delivery	$ 100
New pressure gauges (2) and controls	$ 820
Total 1 unit	$ 3,678
Total whole building (4 units) C_p	$14,712

The above data were obtained through confidential discussions with a leading manufacturer.

9.4.2 Installation Cost (C_i)

Item	Cost
Install electret filters	$ 160
Install MERV 8 (prefilters)	$ 72
Install gauges and controls	$ 600
Total 1 unit	$ 832
Total whole building (4 units)	$3,328

Filter installation costs were estimated using data from the report entitled "Performance and Costs of Particle Air Filtration Technologies" (Faulkner et al., 2002).

9.4.3 Service Cost (C_s)

Item	Cost
Engineering fees	$3,650
Air balance	$4,500
Total whole building (4 units) C_s	$8,150

The air handling units must be rebalanced and possibly have their belts adjusted (to speed up the fan) because of the additional static pressure added by the filters. Engineering fees are for the investigation of the system, planning, and design of air handler modifications. The engineering fees estimation assumes a $50,000 total project cost. The project cost may actually be more, but typically engineering fees for projects of this size would not be based on the cost of the equipment (only a small portion of the square footage of the building is being worked on). Both numbers are estimated using *R.S. Means* (2004).

9.4.4 Retrofit Cost (C_r)

Item	Cost
Remove existing filters	$ 72
New access door	$ 202
Total 1 unit	$ 274
Total whole building (4 units) C_r	$1,096

Labor cost to remove existing filters was based on data from “Performance and Costs of Particle Air Filtration Technologies” (Faulkner et al., 2002). Adding a new access door would be necessary, assuming the existing access door is not located correctly or is not big enough to accommodate new filters. The cost of a new access door is estimated from *R.S. Means* (2004).

9.4.5 Operating Cost (C_o)

Item	Cost
Fan power	$ 5,278
Total whole building (4 units) C_o	$21,112

All calculations were made in a manner similar to Section 9.2.5.

9.4.6 Maintenance Cost (C_m)

Item	Cost
Change electret (every 2 years)	$1,330
Change prefilters (every year)	$ 330
Total 1 unit	$1,660
Total whole building (4 units) C_m	$6,640

The above electret filter cost represents the average yearly cost to change the filters every two years as recommended (Manz, 2005).

9.4.7 Electret Media Filtration Cost Summary

Item	Cost
Total 1st year	$55,038
Total yearly operations and maintenance (O+M)	$27,752
Energy increase	9%
Maintenance increase	14%

The above data were calculated in the same manner as described in Section 9.2.7.

9.5 Model Estimation for Electrostatic Precipitation

In the electrostatic precipitation example, the electrostatic precipitators or electronic air cleaners (as they are commonly called) are mounted in the ductwork (outside of the air handling unit). The size of the air cleaners and their geometry make it difficult to fit into an existing air handler. Because they are mounted in the existing ductwork, the ductwork would have to be reconfigured. Fourteen air cleaners would be used with a velocity of 515 fpm (2.62 m/s), which is acceptable according to the manufacturer’s recommendation of 576 fpm (2.93 m/s) maximum. The air cleaners in this example are based on electronic air cleaners from a leading manufacturer. The pressure drop for these filters is 0.5 in. w.g. (125 Pa) when dirty. This pressure drop requires the fan to be adjusted to 1049 RPM to give 5.5 in. w.g. (1.4 kPa) of total static pressure.

9.5.1 Initial Purchase Cost (C_p)

Item	Cost
Electronic air cleaners (n=14)	$11,410
Delivery	$ 1,000
New pressure gauges (2) and controls	$ 820
Total 1 unit	$13,230
Total whole building (4 units) C_p	$52,920

Electronic filter cost data were estimated using *R.S. Means* (2004) and retail prices for the electronic air cleaner.

9.5.2 Installation Cost (C_i)

Item	Cost
Install electronic air cleaners (n=14)	$ 4,340
Install new pressure gauges and controls	$ 600
Total 1 unit	$ 4,940
Total whole building (4 units)	$19,760

Installation cost data were estimated using *R.S. Means* (2004).

9.5.3 Service Cost (C_s)

Item	Cost
Engineering fees	$ 9,000
Air balance	$ 4,500
Total whole building (4 units) Cs	$13,500

The air handling units must be rebalanced and possibly have their belts adjusted (to speed up the fan) because of the additional static pressure added by the electronic air cleaners. Engineering fees are for the investigation of the system, planning, and design of air handler modifications. The engineering fees estimation assumes a $100,000 total project cost and a more complex design (because of the installation of the air cleaners in the ductwork). The project cost may actually be more, but typically engineering fees for projects of this size would not be based on the cost of the equipment (only a small portion of the square footage of the building is being worked on). Both numbers are estimated using *R.S. Means* (2004).

9.5.4 Retrofit Cost (C_r)

Item	Cost
Re-work/install new duct transitions	$ 7,375
New electrical service	$ 1,488
Total 1 unit	$ 8,863
Total whole building (4 units) C_r	$35,452

The above estimations were based on data provided by *R.S. Means* (2004). New electric service includes the cost of wiring, junction boxes, and disconnect switches and assumes that there is a spare breaker or breaker space in a panel relatively close to the air handler.

9.5.5 Operating Cost (C_o)

Item	Cost
Power to units	$ 332
Fan power	$1,715
Total 1 unit	$2,047
Total whole building (4 units) C_o	$8,188

Power to units is the energy required to operate the air cleaner at 36 watts per filter. Data were taken from manufacturer's data. All calculations were made in a manner similar to Section 9.2.5.

9.5.6 Maintenance Cost (C_m)

Item	Cost
Wash prefilters	$1,400
Total 1 unit	$1,400
Total whole building (4 units) C_m	$5,600

The air cleaners used in this model had washable (reusable) filters built into the air cleaners. Data were estimated using *R.S. Means* (2004).

9.5.7 Electrostatic Precipitation Cost Summary

Item	Cost
Total 1st year	$135,420
Total yearly operations and maintenance (O+M)	$13,788
Energy increase	3%
Maintenance increase	12%

The above data were calculated in the same manner as described in Section 9.2.7.

9.6 Model Estimation for UVGI

This estimation is based on a commercial UVGI system that is 36 x 48 x 72 inches (91 x 122 x 183 cm) in size and has built-in prefilters. Because the size of the system is different from the size of the air handler and the system cannot fit into the air handler, the system would have to be located outside of the air handler (on the supply side). This arrangement requires reworking the ductwork and assumes that there is enough space in the supply duct exiting the air handler. The pressure drop across the UVGI is low enough to be negligible; however, the prefilter would add 1 in. w.g. (249 Pa) static pressure to the system. The 1 in. w.g. (249 Pa) is safely below the excess of 2 in. w.g. (498 Pa) inherent in the fan selection, so a new booster fan would not be needed (the belt would be adjusted to 1100 RPM, which would give 6 in. w.g. [1.5 kPa] static pressure capacity).

9.6.1 Initial Purchase Cost (C_p)

Item	Cost
UVGI filter	$ 253,125
MERV 13 prefilter (n=16)	$ 1,927
Delivery	$ 1,000
New pressure gauges (2) and controls	$ 820
Total 1 unit	$ 256,872
Total whole building (4 units) Cp	$1,027,488

The above costs were based on data provided during confidential discussions with a commercial vendor.

9.6.2 Installation Cost (C_i)

Item	Cost
Install UVGI filter/housing/prefilter	$ 7,500
Install gauges/controls	$ 600
Total 1 unit	$ 8,100
Total whole building (4 units)	$32,400

The above costs were based on data provided during confidential discussions with a commercial vendor.

9.6.3 Service Cost (C_s)

Item	Cost
Engineering fees	$4,800
Air balance	$4,500
Total whole building (4 units) C_s	$9,300

The air handling units must be rebalanced and possibly have their belts adjusted (to speed up the fan) because of the additional static pressure added by the filters. Engineering fees are for the investigation of the system, planning, and design of air handler/ductwork modifications. The engineering fees estimation assumes a $100,000 total project cost. The project cost may actually be more, but typically engineering fees for projects of this size would not be based on the cost of the equipment (only a small portion of the square footage of the building is being worked on). Both numbers are estimated using *R.S. Means* (2004).

9.6.4 Retrofit Cost (C_r)

Item	Cost
Re-work/install new duct transitions	$ 9,375
New electrical service	$ 3,600
Total 1 unit	$12,975
Total whole building (4 units) C_r	$51,900

The above costs were based on data provided during confidential discussions with a vendor and assumes that there is adequate power in the building as well as a spare breaker or breaker space in a panel close to the existing air handler.

9.6.5 Operating Cost (C_o)

Item	Cost
UVGI filter electric power	$ 9,894
Fan power	$ 3,519
Total 1 unit	$13,503
Total whole building (4 units) C_o	$53,652

UVGI filter electric power is the power required to operate the UVGI system and is based on data provided during confidential discussions with a vendor.

9.6.6 Maintenance Cost (C_m)

Item	Cost
Clean UV bulbs	$ 375
Replace bulbs	$ 4,623
Replace prefilter	$ 1,927
Total 1 unit	$ 6,925
Total whole building (4 units) C_m	$27,700

The above costs represent regular maintenance as recommended by a leading vendor. The vendor recommends cleaning the bulbs every 9 months and replacing the bulbs every 18 months (costs shown above are average per year based on this schedule).

9.6.7 UVGI Filtration Cost Summary

Item	Cost
Total 1st year	$1,202,440
Total yearly operations and maintenance (O+M)	$ 81,352
Energy increase	22%
Maintenance increase	58%

The above data were calculated in the same manner as described in Section 9.2.7.

10.0
Conclusions

An open literature survey of air cleaning technologies for building HVAC applications was conducted. We reviewed the literature and conducted a critical assessment, which included an analysis of the cost and physical impacts of the air cleaning device on building operation. Summaries of each technology, including recent research, were presented.

The critical review focused on air cleaning technologies relevant for building HVAC applications, primarily (but not exclusively) those for particle removal. The five technologies assessed in the report are as follows:

- Fibrous filters (mechanical filters)
- Electrostatically enhanced filters
- Electrets
- Electrostatic precipitators
- Ultraviolet germicidal irradiation

The typical HVAC filtration system in a building is a relatively low (<90%) efficiency fibrous filter that is intended to remove particles to keep the remainder of the HVAC system clean and to remove nuisance dust for the occupants. Technologies exist that can improve particulate removal, which will be needed if the HVAC filtration system is to mitigate the hazard associated with an intentional biological agent release. The analysis to determine which technology to use for a particular building HVAC system will need to be made on a case-by-case basis and will include factors such as cost (initial and operating), level of protection desired, and coverage (how much of the building to protect).

Based on the assessment discussed in this report, mature technologies exist to enhance particle removal without impacting the entire HVAC system—that is, without requiring extensive retrofits or significant duct modifications. Operating costs may increase because the technology is more expensive to maintain or operate. The specific impacts of these technologies on operation and cost are discussed and summarized in each technology's critical assessment in the body of this report.

Many data gaps need to be addressed. Two examples of gaps in data are in-use operational data and the impact that particle reduction in an HVAC system has on particulate levels within the building. Another gap or question is related to how air infiltration or leakage impact building contaminant levels.

With respect to electrostatic precipitators for residential and commercial applications, some data gaps exist in the literature. Because ESP devices generally have lower pressure drops than traditional mechanical filtration, pressure drop is not generally reported. Many studies also do not report ozone concentrations or generation rates, important factors when considering an ESP technology because of human exposure issues. Further difficulties with the available literature were the diverse types of ESP devices considered; many were not designed for in-duct use in residential and commercial HVAC applications and even those that were specific for this application varied in design. Authors also disagreed about the effects of dust loading on the performance degradation of ESPs. The work of Hanley et al. (2002) should be continued to further quantify performance degradation as a function of service life.

The UVGI literature lacked experimental data in HVAC applications. Kowalski and Bahnfleth (2003) indicated that data are being collected in a commercial setting for a retrofit UVGI application. However, those data were not located or are not yet available. Again, standardizing some test parameters may help generate comparable data on other factors that affect UVGI performance.

Electrostatically enhanced filter technologies appear to be a relatively new and small player in the residential and commercial HVAC market. Additional literature review may locate more studies of this technology. Three studies obtained in the current effort were helpful but not exhaustive. There is a gap in data for filter pressure drops for these types of devices. Further quantification of fiber diameters for the filters used and comparison with mechanical filters that are not electrostatically enhanced should be examined to quantify the reduction in pressure drop at equal collection efficiencies that can be achieved with electrostatically enhanced filtration.

Many data exist regarding the application and performance of air cleaning technologies, but data specific to the impact of air cleaning technologies on residential and commercial environments are sparse. As more studies are conducted to examine the impact of HVAC air cleaning technologies on indoor air quality, it would be helpful to develop a sort of classification or standard for this type of testing. While there will always be site-specific differences, certain factors such as duration of the test, baseline conditions, and flow rates could be standardized for air cleaner evaluation. Studies that incorporate a wide range of filters or air cleaner technologies with different efficiencies would prove more valuable.

11.0

References

Agranovski, I.E., R.D. Braddock, and T. Myojo. “Comparative Study of the Performance of Nine Filters Utilized in Filtration of Aerosols by Bubbling,” *Aerosol Science and Technology* 35(4): 852–859 (2001).

Agranovski, I.E., R. Huang, O. Pyankov, I. Altman, and S.A. Grinshpun. “Enhancement of the Performance of Low-Efficiency HVAC Filters Due to Continuous Unipolar Ion Emission,” *Aerosol Science and Technology* 40(11): 963–968 (2006).

ANSI/ASHRAE (American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers). ANSI/ASHRAE Standard 52.1-1992, “Gravimetric and Dust-Spot Procedures for Testing Air-Cleaning Devices Used in General Ventilation for Removing Particulate Matter,” Atlanta, GA, 1992.

ANSI/ASHRAE (American National Standards Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers). ANSI/ASHRAE Standard 52.2-1999, “Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size,” Atlanta, GA, 1999.

Arnold, B. and D. Myers. “Electret Media for HVAC Filtration Applications,” Paper presented at the AFS Indoor Air Quality-Filtration Conference Proceedings. Cincinnati, OH, November 14–15, 2002.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). *ASHRAE Handbook 2003: HVAC Applications.* Atlanta, Georgia: ASHRAE, Inc., 2003.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). *ASHRAE Handbook 2004: HVAC Systems and Equipment.* Atlanta, Georgia: ASHRAE, Inc., 2004.

Balazy, A., A. Podgorski, and L. Gradon. “Filtration of Nano-sized Aerosol Particles in Fibrous Filters. I - Experimental Results,” *Journal of Aerosol Science* 35: S967–S980 (2004).

Balazy, A., M. Toivola, T. Reponen, Z. Podgorski, A. Zimmer, and S.A. Grinshpun. “Manikin-Based Performance Evaluation of N95 Filtering-Facepiece Respirators Challenged with Nanoparticles,” *Annals of Occupational Hygiene* 50(3): 259–269 (2005).

Barrett, L.W. and A.D. Rousseau. “Aerosol Loading Performance of Electret Filter Media,” *American Industrial Hygiene Association Journal* 59: 532–539 (1998).

Bell, A.A., Jr. *HVAC Equations Data and Rules of Thumb.* New York, New York: McGraw-Hill, 2000.

Brickner, P.W., R.L. Vincent, M. First, E. Nardell, M. Murray, and W. Kaufman. “The Application of Ultraviolet Germicidal Irradiation to Control Transmission of Airborne Disease: Bioterrorism Countermeasure,” *Public Health Reports* 118: 99 (March–April 2003).

Brosseau, L.M., M.J. Ellenbecker, and J.S. Evans. “Collection of Silica and Asbestos Aerosols by Respirators at Steady and Cyclic Flow,” *American Industrial Hygiene Association Journal* 51(8): 420–426 (1990).

Brosseau, L.M., S.K. Chen, D. Vesley, and J.H. Vincent. “System Design and Test Method for Measuring Respirator Filter Efficiency Using Mycobacterium Aerosols,” *Journal of Aerosol Science* 25(8): 1567–1577 (1994).

Brown, R.C. “Capture of Dust Particles in Filters by Line-Dipole Charged Fibers,” *Journal of Aerosol Science* 12: 349–356 (1981).

Brown, R.C. “Filtration in Industrial Hygiene,” *American Industrial Hygiene Association Journal* 62(5): 633–643 (September–October 2001).

Brown, R.C., D. Wake, R. Gray, D.B. Blackford, and G.J. Bostock. “Effect of Industrial Aerosols on the Performance of Electrically Charged Filter Material,” *Annals of Occupational Hygiene* 32(3): 271–294 (1988).

Burroughs, B.H. “The Role of Filtration Efficiency in the Cleanliness of HVAC Systems Phase III – An Extended Field Study of the Cleanliness of HVAC Systems Based Upon the Efficiency Level of the Air Filtration System,” Paper presented at the *Ninth World Filtration Congress*, New Orleans, LA, April 18–24, 2004.

Carlsson, T. “Indoor Air Filtration: Why Use Polymer Based Filter Media?” *Filtration & Separation* 38(2): 30–32 (March 2001).

Carpin, J., R. Doherty, and P. Gardner. “Fractional Penetrations for Select Commercial Electrostatic Filter Media in the Sub-Micron Particle Size Range,” Proceedings of the 1996 Edgewood Research, Development and Engineering Center (ERDEC) Scientific Conference on Chemical and Biological Defense Research, Paper CB-103985, AD-A334105, pp. 511–517, 1997.

Carrera, M., R.O. Zandomeni, J. Fitzgibbon and J.L. Sagripanti. “Difference Between the Spore Sizes of Bacillus anthracis and Other Bacillus Species,” Journal of Applied Microbiology (2006).

Centers for Disease Control and Prevention (CDC). “Filtration and Air Cleaning Principles,” *Guidance for Protecting Building Environments from Airborne Chemical, Biological, or Radiological Attacks.* http://www.cdc.gov/niosh/docs/2003-136/2003-136c.html (May 2005).

Chambers, F.W., A. Al-Sarkhi, and S. Yao. “Velocity Distribution Effects in Air Filter Testing,” *Particulate Science and Technology* 19(1): 1–21 (2001).

Chen, C., S. Huang, C. Chang, and C. Chen. “Penetration of 4.5 nm to 10 µm Aerosol Particles Through Fibrous Filters,” Poster presented at American Industrial Hygiene Conference and Exhibition, Chicago, IL (2006).

Chen, S-K., D. Vesley, L.M. Brosseau, and J.H. Vincent. “Evaluation of Single-use Masks and Respirators for Protection of Healthcare Workers Against Mycobacterial Aerosols,” *American Journal of Infection Control* 22(2): 65–74 (1994).

Chimack, M. J. and D. Sellers. “Using Extended Surface Air Filters in Heating Ventilation and Air Conditioning Systems: Reducing Utility Maintenance Costs While Benefiting the Environment,” In the American Council for Energy Efficient Economy’s *Proceedings of the American Council for an Energy Efficient Economy Summer Study on Energy Efficiency in Buildings* 3: 377–388, Washington, D.C., 2000.

Cooper, C. D. and Alley, F. C. “Air Pollution Control: A Design Approach”. PWS Publishers, 1986.

Croxford, B., K.W. Tham, A. Young, T. Oreszczyn, and D. Wyon. “A Study of Local Electrostatic Filtration and Main Pre-Filtration on Airborne and Surface Dust Levels in Air-Conditioned Office Premises,” *Indoor Air* 10(3): 170–177 (September 2000).

DOE (Department of Energy), Energy Information Administration. “Table 5.6.A. Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State, July 2004 and 2003 (Cents per kilowatt-hour),” *Electric Power Monthly* Data For: July 2004, Report Released: October 19, 2004. http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html (accessed April 2005).

DOE (Department of Energy), Federal Energy Management Program. “Building Life-Cycle Cost (BLCC) Programs,” *Information Resources*. http://www1.eere.energy.gov/femp/information/download_blcc.html (accessed April 2007).

DOL (Department of Labor), Bureau of Labor Statistics. “2005 Consumer Price Index Detailed Report Tables,” Consumer Prices Indexes. http://www.bls.gov/cpi/cpid05av.pdf (accessed April 2007).

Drouin, B. “Triboelectric Blend Enhances Filtration,” *Filtration & Separation* 37(8): 20–23 (November 2000).

Drouin, B. “Enhanced Air Filtration Performance with a New Triboelectric Blend,” Paper presented at the American Filtration and Separations Society (AFS) Indoor Air Quality-Filtration Conference. Cincinnati, OH, November 14–15, 2002.

Emmerich, S.J., and S.J. Nabinger. “Measurement and Simulation of the IAQ Impact of Particle Air Cleaners in a Single-Zone Building,” *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research* 7(3): 223–244 (July 2001).

Faulkner, D., W. Fisk, J. Palonen, and O. Seppanen. “Performance and Costs of Particle Air Filtration Technologies,” *Indoor Air* 12(4): 223–234 (December 2002).

First, M.W., E.A. Nardell, W. Chaisson, and R. Riley. “Guidelines for the Application of Upper-Room Ultraviolet Germicidal Irradiation for Preventing Transmission of Airborne Contagion—Part I: Basic Principles,” *In ASHRAE Transactions: Symposia*, Paper CH-99-12-1, The 1999 Winter Meeting, Chicago 105(1): 869–876 (1999).

Fuchs, K., A. Fuchs, and S. Koeger. “NBC-Building Protection System and Method,” U.S. Patent US 2004/0144104 A1 (2004).

Fugler, D., D. Bowser, and W. Kwan. “The Effects of Improved Residential Furnace Filtration on Airborne Particles,” *ASHRAE Transactions: Research* 106(1): 317–326 (2000).

Grabarczyk, Z. “Effectiveness of Indoor Air Cleaning with Corona Ionizers,” *Journal of Electrostatics* 51–52: 278–283 (May 2001).

Hanley, J.T., D.L. Frank, M.K. Owen, D.S. Ensor, and L.E. Sparks. “Improved Test Methods for Electronic Air Cleaners,” Paper presented at Indoor Air 2002, 9th International Conference on Indoor Air Quality and Climate. Monterey, California, June 30 – July 5, 2002.

Hanley, J.T., D.S. Ensor, K.K. Foarde, and L.E. Sparks. “The Effect of Loading Dust Type on the Filtration Efficiency of Electrostatically Charged Filters,” Indoor Air 99 in Edinburgh, Scotland, August, 1999.

Hanley, J.T. and M.K. Owen. “Develop a New Loading Dust and Dust Loading Procedures for the ASHRAE Filter Test Standards 52.1 and 52.2, Final Report,” ASHRAE Project No. 1190-RP, August 2003.

Hanley J.T., and K.K. Foarde. “Validation of Respirator Filter Efficacy,” RTI International Project No. 08621, 2003.

Harrington, M. “Experimental Study of Nanoparticle Penetration Through Various Filter Media,” *2005 National Nanotechnology Infrastructure Network (NNIN) Research Experience for Undergraduates (REU) Research Accomplishments,* 42–43 (2005).

Hawkins, B.E. and K.C. Hofacre. “Tasks 7 & 8: Experimental and Theoretical Analysis of Important Parameters for Determining Impact of a Chemical/Biological Attack on a Building,” Contract No. GS-10F-0275K, Task No. 8, Battelle report submitted to U.S. Environmental Protection Agency for final review, 2007.

Heim, M., B.J. Mullins, M. Wild, J. Meyer, and G. Kasper. “Filtration Efficiency of Aerosol Particles Below 20 Nanometers,” *Aerosol Science and Technology* 39(8): 782–789 (2005).

Hofacre, K.C., A.W. Richardson, A. Wang, and B.L. Sheridan. “First Generation Mask Filter Prototype Design Analysis, Final Report,” Contract No. SP0900-94-D-0002, Task No. 229, Submitted to U.S. Army Edgewood Chemical Biological Center, May, 1999.

Hofacre, K.C., P.M. Schumacher, R.T. Hecker, and T.L. Forney. “Filtration Efficiency Assessment of HEPA Filters Against a Bioaerosol Challenge,” Battelle Contract No. SP0900-94-D-0002, 1996.

Homeyer, S.T., J. Walenga, and C. Cavalca. “Indoor Air Purification System,” U.S. Patent US 6,280,691 B1 (2001).

Homonoff, E. “North American Filtration Markets: 2003–2008,” Paper presented at Filtration 2004 International Conference and Exposition. Philadelphia, PA, December 7–9, 2004.

Howard-Reed, C., L.A. Wallace, and S.J. Emmerich. “Effect of Ventilation Systems and Air Filters on Decay Rates of Particles Produced by Indoor Sources in an Occupied Townhouse,” *Atmospheric Environment* 37(38): 5295–5306 (December 2003).

Huang, S.H. and C.C. Chen. “Filtration Characteristics of a Miniature Electrostatic Precipitator,” *Aerosol Science and Technology* 35(4): 792–804 (October 1, 2001).

Huang, S.H. and C.C. Chen. “Ultrafine Aerosol Penetration Through Electrostatic Precipitators,” *Environmental Science and Technology* 36: 4625–4632 (2002).

IEST (Institute of Environmental Sciences and Technology). “HEPA and ULPA Filters,” Recommended Practice (RP) CC001.3, 1993.

Jankowska, E., T. Reponen, K. Willeke, S.A. Grinshpun, and K. Choi. “Collection of Fungal Spores on Air Filters and Spore Reentrainment from Filters into Air,” *Journal of Aerosol Science* 31(8): 969–978, 2000.

Janssen, L.L., J.O. Bidwell, H.E. Mullins, and T.J. Nelson. “Efficiency of Degraded Electret Filters: Part I – Laboratory Testing Against NaCl and DOP Before and After Exposure to Workplace Aerosols,” *Journal of the International Society for Respiratory Protection* 20: 71–80 (Fall/Winter 2003a).

Janssen, L.L., J.O. Bidwell, H.E. Mullins, and T. J. Nelson. “Efficiency of Degraded Electret Filters: Part II – Field Testing Against Workplace Aerosols,” *Journal of the International Society for Respiratory Protection* 20: 81–90 (Fall/Winter 2003b).

Japuntich, D., L.M. Franklin, D.Y. Pui, T.H. Kuehn, S.C. Kim, and A.S. Viner. “A Comparison of Two Nano-Sized Particle Air Filtration Tests in the Diameter Range of 10 to 400 Nanometers,” *Journal of Nanoparticle Research,* 10 November (2006).

Ji, J.H., G.N. Bae, S.H. Kang, and J. Hwang. “Effect of Particle Loading on the Collection Performance of an Electret Cabin Air Filter for Submicron Aerosols,” *Journal of Aerosol Science* 34: 1493–1504 (2003).

Kemp, P.C., H.G. Neumeister-Kemp, G. Lysek, and F. Murray. “Survival and Growth of Micro-Organisms on Air Filtration Media During Initial Loading,” *Atmospheric Environment*, 35(28): 4739–4749 (2001).

Kim, C.S., L. Bao, K. Okuyama, M. Shimada, and H. Niinuma. “Filtration Efficiency of a Fibrous Filter for Nanoparticles,” *Journal of Nanoparticle Research* 8: 215–221 (2006).

Kim, S., M. Harrington, and D. Pui. “Experimental Study of Nanoparticles Penetration Through Commercial Filter Media,” *Journal of Nanoparticle Research* 9(1): 117–125 (2007).

Ko, G., M.W. First, and H.A. Burge. “The Characterization of Upper Room Ultraviolet Germicidal Irradiation in Inactivating Airborne Microorganisms,” *Environmental Health Perspectives* 110(1): 95–101 (January 2002).

Kogan, V., C. Harto, D.J. Hesse, and K. Hofacre. “Task 4: Evaluation of In-Room Air Cleaners,” Contract No. GS-10F-0275K, Task No. 4, Battelle report submitted to U.S. Environmental Protection Agency for final review, 2007.

Kowalski, W.J. *Immune Building Systems Technology.* New York: McGraw-Hill, 2003.

Kowalski, W.J. and W.P. Bahnfleth. “Effective UVGI System Design Through Improved Modeling,” In *ASHRAE Transactions: Symposia*, Paper MN-00-11-1, The 2000 Annual Meeting, Minneapolis 106(2): 721–730 (2000a).

Kowalski, W.J. and W.P. Bahnfleth. “UVGI Design Basics for Air and Surface Disinfection,” *HPAC Engineering* 72(1): 100–110 (January 2000b).

Kowalski, W.J. and W.P. Bahnfleth. “Airborne-Microbe Filtration in Indoor Environments,” *HPAC Engineering* 74(1): 57–69 (January 2002).

Kowalski, W.J. and W.P. Bahnfleth. “Immune-Building Technology and Bioterrorism Defense,” *HPAC Engineering* 75(1): 57–62 (January 2003).

Kühn, K.P. and I.F. Chaberny. “Ultraviolet Germicidal Irradiation of Office Ventilation Systems Reduces Work-Related Mucosal and Respiratory Symptoms,” Evidence-based Healthcare 8: 148–149 (2004).

Kujundzic, E., M. Fatimah, C.J. Howard, M. Hernandez, and S.L. Miller. “UV Air Cleaners and Upper-Room Air Ultraviolet Germicidal Irradiation for Controlling Airborne Bacteria and Fungal Spores,” *Journal of Occupational and Environmental Hygiene* 3: 536–546 (2006).

Lai, K.M., H.A. Burge, and M.W. First. “Size and UV Germicidal Irradiation Susceptibility of Serratia Marcescens When Aerosolized From Different Suspending Media 1,” *Applied and Environmental Microbiology* 70: 2021–2027 (2004).

Lathrache, R., and H. Fissan. “Enhancement of Particle Deposition in Filters Due to Electrostatic Effects,” *Filtration and Separation* 24: 418–422 (1987).

Lee, M., Y. Otani, N. Namiki, and H. Emi. “Prediction of Collection Efficiency of High-Performance Electret Filters,” *Journal of Chemical Engineering of Japan* 35(1): 57–62 (2002).

Lee, B.U., M. Yermakov, and S.A. Grinshpun. “Removal of Fine and Ultrafine Particles from Indoor Air Environments by the Unipolar Ion Emission,” *Atmospheric Environment* 38: 4815–4823 (2004a).

Lee, B.U., M. Yermakov, and S.A. Grinshpun. “Unipolar Ion Emission Enhances Respiratory Protection Against Fine and Ultrafine Particles,” *Journal of Aerosol Science* 35: 1359–1368 (2004b).

Lehtimäki, M. “Development of Test Methods for Electret Filters,” *Nordtest, NT Technical Report 320.* 57 p. NT project No. 1164–94, 1996.

Lehtimäki, M. and K. Heinonen. “Reliability of Electret Filters,” *Building and Environment* 29(3): 353–355 (1994).

Lele, B.S. and A. J. Russell. “Enhancing Enzyme Stability Against TiO2-UV Induced Inactivation,” *Biomacromolecules* 6: 475–482 (2005).

Letts, G.L., P.C. Raynor, and R. L. Schumann. “Selecting Fiber Materials to Improve Mist Filters,” *Aerosol Science* 34: 1481–1492 (2003).

Lifshutz, N. “Performance Decay in Synthetic Electret Filter Media,” *Advances in Filtration and Separation Technology* 11: 307–311 (1997).

Liu, B.Y.H. and F. J. Romay. “Assessment of Methodologies for the Test and Evaluation of Electret Filter Media,” Final Report for Edgewood Research, Development and Engineering Center (ERDEC) U.S. Army Research Office (1997).

Mainelis, G., S.A. Grinshpun, K. Willeke, T. Reponen, V. Ulevicius, and P.J. Hintz. “Collection of Airborne Microorganisms by Electrostatic Precipitation,” *Aerosol Science and Technology* 30(2): 127–144 (February 1999).

Mainelis, G., K. Willeke, P. Baron, T. Reponen, S.A. Grinshpun, R.L. Górny, and S. Trakumas. “Electrical Charges on Airborne Microorganisms,” *Journal of Aerosol Science* 32: 1087–1110 (2001).

Mainelis, G., A. Adhikari, K. Willeke, S. Lee, T. Reponen, and S.A. Grinshpun. “Collection of Airborne Microorganisms by a New Electrostatic Precipitator,” *Aerosol Science* 33: 1417–1432 (2002a).

Mainelis, G., R.L. Górny, T. Reponen, M. Trunov, S.A. Grinshpun, P. Baron, J. Yadav, and K. Willeke. “Effect of Electrical Charges and Fields on Injury and Viability of Airborne Bacteria,” *Biotechnology and Bioengineering* 79: 229–241 (2002b).

Mainelis, G., K. Willeke, A. Adhikari, T. Reponen, V. Ulevicius, and P.J. Hintz. “Design and Collection Efficiency of a New Electrostatic Precipitator for Biological Aerosol Collection,” *Aerosol Science and Technology* 36: 1073–1085 (2002c).

Manz, A., Freudenberg Nonwovens. Personal Communication, April to June 2005.

Mayya, Y.S., B.K. Sapra, A. Khan and F. Sunny. “Aerosol Removal by Unipolar Ionization in Indoor Environments,” *Aerosol Science* 35: 923–941 (2004).

McCullough, N.V, L.M. Brosseau, and D. Vesley. “Collection of Three Bacterial Aerosols by Respirator and Surgical Mask Filters Under Varying Conditions of Flow and Relative Humidity.” *Annals of Occupational Hygiene* 41(6): 677–690 (1997).

Memarzadeh, F., Z. Jiang, and W., Xu. “Analysis of Efficacy of UVGI Inactivation of Airborne Organisms Using Eulerian and Lagrangian Approaches,” March 24, 2005, http://www.vigilairsystems.com/what/uvgilibrarypage.

Menzies, D., J. Popa, J.A. Hanley, T. Rand, and D.K. Milton. “Effect of Ultraviolet Germicidal Lights Installed in Office Ventilation Systems on Workers’ Health and Wellbeing: Double-Blind Multiple Crossover Trial,” *The Lancet* 362(9398): 1785–1791 (November 29, 2003).

Miller, J.D. “Defensive Filtration,” *ASHRAE Journal* 44(12): 18–23 (December 2002).

Miller, S.L. and J.M. Macher. “Evaluation of a Methodology for Quantifying the Effect of Room Air Ultraviolet Germicidal Irradiation on Airborne Bacteria,” *Aerosol Science and Technolog*y 33: 274–295 (2000).

Miller, S.L., M. Hernandez, K. Fennelly, J. Martyny, J. Macher, E. Kujundzic, P. Xu, P. Fabian, J. Peccia, and C. Howard. “Efficacy of Ultraviolet Irradiation in Controlling the Spread of Tuberculosis,” Final Report submitted to Centers for Disease Control and Prevention, NIOSH under NIOSH Contract No. 200-97-2602. pp. 1–80 (October 14, 2002).

Morawska, L., V. Agranovski, Z. Ristovski, and M. Jamriska. “Effect of Face Velocity and the Nature of Aerosol on the Collection of Submicrometer Particles by Electrostatic Precipitator,” *Indoor Air* 12(2): 129–137 (June 2002).

Musser, A., W. Kowalski, and W. Bahnfleth. “Stack and Mechanical System Effects on Dispersion of Biological Agents in a Tall Building,” *In Proceedings of IMECE2002*, American Society of Mechanical Engineers (ASME) International Mechanical Engineering Congress and Exposition, Paper IMECE2002-33862: 119–126. New Orleans, LA, November 17–22, 2002.

Myers, D.L. and B.D. Arnold. “Electret Media for HVAC Filtration Applications,” Paper presented at INTC 2003, International Nonwovens Technical Conference, Conference Proceedings, pp. 602–630 (2003).

Nardell, E.A. “Use and Misuse of Germicidal UV Air Disinfection for TB in High-Prevalence Settings,” *The International Journal of Tuberculosis and Lung Disease* 6(8): 647–648 (August 2002).

National Research Council Committee on Toxicology. “Emergency and Continuous Exposure Limits for Selected Airborne Contaminants.” Volume 1. Washington, DC: National Academy Press, 1984.

Nifuku, M., Y. Zhou, A. Kisiel, T. Kobayahsi, and H. Katoh. “Charging Characteristics for Electret Filter Materials,” *Journal of Electrostatics* 51/52: 200–205 (2001).

Oglesby, S., and G.B. Nichols. *A Manual of Electrostatic Precipitator Technology.* Part I. Final Report from Southern Research Institute to National Air Pollution Control Administration, Division of Process Control Engineering, APTD-0610 (August 25, 1970).

Otani, Y., H. Emi, and J. Mori. “Initial Collection Efficiency of Electret Filter and Its Durability for Solid and Liquid Particles,” *KONA Powder and Particles* 11: 207–214 (1993).

Owen, M.K., D.S. Ensor, and L.E. Sparks. “Airborne Particle Sizes and Sources Found in Indoor Air,” *Atmospheric Environment* 26A(12): 2149–2162 (1992).

Owen, M.K., J.T. Hanley, D.S. Ensor, and L.E. Sparks. “Residential and Commercial Air Filter Efficiencies,” Paper presented at the *Annual Air and Waste Management Association Conference*, San Diego, CA, 2003.

Park, H.S., H.J. Chang, and K.W. Lee. “Analytic Solution for Collection Efficiency of Electrostatic Precipitators for Polydisperse Aerosols,” *Environmental Engineering Science* 21(4): 451–461 (2004).

Park, Y.O., S.J. Park, I.K. Shin, and H.U. Jung. “Development of a Cartridge Filter Combining a Dielectric Filter with an Electrostatic Precipitator,” *Presentation* 2002.

Peccia, J., H.M. Werth, S. Miller, and M. Hernandez. “Effects of Relative Humidity on the Ultraviolet Induced Inactivation of Airborne Bacteria,” *Aerosol Science and Technology* 35: 728–740 (2001).

Peters, T., M. Boundy, and D. Leith. “Influence of Upstream Flow Characteristics on Filter Efficiency,” *Filtration & Separation* 38(10): 41-47 (December 2001).

Pich, J. *Fundamentals of Aerosol Science*, (D.T. Shaw, ed.). New York: Wiley Interscience, 1978.

Pich, J., H. Emi, and C. Kanaoka. “Coulombic Deposition Mechanism in Electret Filters,” *Journal of Aerosol Science* 18: 29–35 (1987).

Pierce, M.E. and N. Lifshutz. “New Developments in Synthetic ASHRAE Filtration Media,” *Tappi Journal* 80: 142–145 (1997).

Qian Y., K. Willeke, S.A. Grinshpun, and J. Donnelly. “Performance of N95 Respirators: Reaerosolization of Bacteria and Solid Particles,” *American Industrial Hygiene Association Journal* 58(12): 876–80 (1997a).

Qian, Y., K. Willeke, V. Ulevicius, and S. Grinshpun. “Particle Reentrainment from Fibrous Filters,” *Aerosol Science and Technology* 27: 394–404 (1997b).

Qian Y., K. Willeke, S.A. Grinshpun, J. Donnelly, and C.C. Coffey. “Performance of N95 Respirators: Filtration Efficiency for Airborne Microbial and Inert Particles,” *American Industrial Hygiene Association Journal* 59: 128–132 (1998).

Raynor, P.C. and S.J. Chae. “Effects of Particle Loading on Electrostatically Charged Filters in an HVAC System,” Paper presented at the AFS Indoor Air Quality-Filtration Conference Proceedings. Cincinnati, OH, November 14–15, 2002.

Raynor, P.C. and S.J. Chae. “Dust Loading on Electrostatically Charged Filters in a Standard Test and a Real HVAC System,” *Filtration & Separation* 40(2): 35–39 (March 2003).

Richardson, G., D.J. Harwood, S.A. Eick, F. Dobbs, and K.G. Rosen. “Reduction of Fine Airborne Particulates (PM3) in a Small City Centre Office, by Altering Electrostatic Forces,” *The Science of the Total Environment* 269: 145–155 (2001).

Rivers, R.D. and D.J. Murphy, Jr. “Air Filter Performance Under Variable Air Volume Conditions,” *ASHRAE Transactions* 106: 131–144 (2000).

Romay, F.J. and B.Y.H. Liu. “Degradation of Electret Filters During DOP Aerosol Loading,” In *Advances in Filtration and Separation Technology*, v12, Advancing Filtration Solutions, St. Louis, Missouri: American Filtration & Separations Society, pp. 193–200, May 4–7, 1998a.

Romay, F. J., B.Y.H. Liu, and S.J. Chae. “Experimental Study of Electrostatic Capture Mechanisms in Commercial Electret Filters,” *Aerosol Science and Technology* 28: 224–234 (1998b).

Romay, F. J., B.Y.H., Liu, and S.J. Chae. “Electrostatic Particle Capture in Commercial Electret Filters,” *Advances in Filtration and Separation Technology* 11: 126–133 (1997).

Rose, H.E., and A.J. Wood. *An Introduction of Electrostatic Precipitation in Theory and Practice.* London, Great Britain: Constable and Company Ltd., 1956.

Rousseau, A.D., M.E. Jones, and B.Z. Mei. “Electret Articles and Filters with Increased Oily Mist Resistance,” European Patent Application EP 1402934 A1 (1998).

Roth, C., E. Karg, K. Sommerer, and J. Wiegand. “Ultrafine Ambient Particles Can Be Used to Measure the Efficiency of High Volume Filters,” *Journal of Aerosol Science*, 30, S751–S752 (1999).

R.S. Means Company. *R.S. Means Mechanical Cost Data*, 25th Annual Edition. Kingston, Massachusetts: R.S. Means Company, Inc., 2004.

Rudnick, S. N. “Optimizing the Design of Room Air Filters for the Removal of Submicrometer Particles,” *Aerosol Science and Technology* 38(9): 861–869 (2004).

Snustad, D.P., M.J. Simmons, and J.B. Jenkins. *Principles of Genetics.* John Wiley and Sons, Inc., 1997.

Stafford, R.G., H.J. Ettinger, and T.J. Rowland, “Respirator Cartridge Filter Efficiency Under Cyclic- and Steady-Flow Conditions,” *American Industrial Hygiene Association Journal* May: 182–192 (1973).

StrionAir, Inc. “Products: How It Works,” http://www.strionair.com/operation.asp. (April 2005).

Talbot, E.A., P. Jensen, H.J. Moffat, and C.D. Wells. “Occupational Risk from Ultraviolet Germicidal Irradiation (UVGI) Lamps,” *International Journal of Tuberculosis and Lung Disease* 6: 738–741 (2002).

Tennal, K.B., M.K. Mazumder, and A. Siag. "Effect of Loading with an Oil Aerosol on the Collection Efficiency of an Electret Filter," *Particulate Science and Technology* 9: 19–29 (1991).

Thorpe, A. and R.C. Brown. "Performance of Electrically Augmented Fibrous Filters, Measured with Monodisperse Aerosols," *Aerosol Science and Technology* 37: 231–245 (2003).

Trane Company, The. "Quick Selection Guide, July 2004, M-Series and T-Series Climate Changer Air Handlers, Fan Performance Data for Sizes 3 Through 30, December 2001," www.trane.com/commercial/equipment/ProductDetails.aspx?prod=19.

Tsai, P.P., H. Schreuder-Gibson, and P. Gibson. "Different Electrostatic Methods for Making Electret Filters," *Journal of Electrostatics* 54: 333–341 (2002).

US Environmental Protection Agency, National Homeland Security Research Center. Verification reports for the evaluation of filtration media in HVAC systems. Available at http://www.epa.gov/nhsrc/tte_ventmediaair.html

VanOsdell, D. and K. Foarde. "Defining the Effectiveness of UV Lamps Installed in Circulating Air Ductwork," RTI International Final Report ARTI-21CR/610-40030-01 prepared for the Air Conditioning and Refrigeration Technology Institute (November 2002).

Wake, D., A.C. Bowry, B. Crook, and R.C Brown. "Performance of Respirator Filters and Surgical Masks Against Bacterial Aerosols," *Journal of Aerosol Science* 28(7): 1311–1329 (1997).

Wallace, L.A., S.J. Emmerich, and C. Howard-Reed. "Effect of Central Fans and In-duct Filters on Deposition Rates of Ultrafine and Fine Particles in an Occupied Townhouse," *Atmospheric Environment* 38(3): 405–413 (2004).

Walsh, D.C. and J.I.T. Stenhouse. "The Effect of Particle Size, Charge, and Composition on the Loading Characteristics of an Electrically Active Fibrous Filter Material," *Journal of Aerosol Science* 28(2): 307–321 (1997).

Walsh, D.C. and J.I.T. Stenhouse. "Parameters Affecting the Loading Behavior and Degradation of Electrically Active Filter Materials," *Aerosol Science and Technology* 29: 419–432 (1998).

Wang, A. and K.C. Hofacre. "Task 6: Advanced Air Filtration System Development," Contract No. GS-10F-0275K, Task No. 6, Battelle report submitted to U.S. Environmental Protection Agency for final review, 2007.

Wang, C.S. "Electrostatic Forces in Fibrous Filters – A Review," *Powder Technology* 118: 166–170 (2001).

Wang, H. C. and G. Kasper. "Filtration Efficiency of Nanometer-size Aerosol Particles," *Journal of Aerosol Science* 22(1): 31–41 (1991).

Wang, J., D. Chen, and D. Pui. "Modeling of Filtration Efficiency of Nanpoarticles in Standard Filter Media," *Journal of Nanoparticle Research* 9(1): 109–115 (2007).

Wang, S.K. *Handbook of Air Conditioning and Refrigeration*, Second Edition. New York, New York: McGraw-Hill, 2001.

Ward, M., J.A. Siegel, and R.L. Corsi. "Stand-Alone Air Cleaners: Evaluation and Implications," Paper presented at the *Annual Air and Waste Management Association Conference.* San Diego, CA, 2003.

White, H.J. *Industrial Electrostatic Precipitation.* Reading, Massachusetts: Addison-Wesley Publishing Company, Inc., 1963.

Willeke, K., Y. Qian, J. Donnelly, S. Grinshpun, and V. Ulevicius. "Penetration of Airborne Microorganisms through a Surgical Mask and a Dust/Mist Respirator," *American Industrial Hygiene Association Journal* 57: 348–355 (1996).

Xu, P., J. Peccia, P. Fabian, J.W. Martyny, K.P. Fennelly, M. Hernandez, and S.L. Miller. "Efficacy of Ultraviolet Germicidal Irradiation of Upper-Room Air in Inactivating Airborne Bacterial Spores and Mycobacteria in Full-Scale Studies," *Atmospheric Environment* 37: 405–419 (2003).

Xu, P., J. Peccia, M. Hernandez, and S.L. Miller. "The Efficacy of Upper Room Ultraviolet Germicidal Irradiation in Inactivating Airborne Microorganisms Under Incomplete Mixing Conditions," Paper presented at the U.S. EPA's Engineering Solutions to Indoor Air Quality Problems Conference, Proceedings, Research Triangle Park, NC, July 2000.

Yang, S. and G.W.M. Lee. "Filtration Characteristics of a Fibrous Filter Pretreated with Anionic Surfactants for Monodisperse Solid Aerosols," *Journal of Aerosol Science* 36: 419–437 (2005).

Yao, M. and G. Mainelis. "Utilization of Natural Electrical Charges on Airborne Microorganisms for their Collection by Electrostatic Means," *Aerosol Science* 37: 513–527 (2006).

Zukeran, A., P.C. Lioy, A. Chakrabarti, A.A. Berezin, S. Jayaram, J.D. Cross, T. Ito, and J. Chang. "Collection Efficiency of Ultrafine Particles by an Electrostatic Precipitator Under DC and Pulse Operating Modes," *Institute of Electrical and Electronics Engineers (IEEE) Transactions on Industry Applications* 35(5): 1184–1191 (September/October 1999).

Appendix A
Databases and Conferences Searched for Relevant Information

Area	Source Reviewed
Published technical literature	• Defense Technical Information Center's (DTIC's) Database • Technical Report (TR) Database • The Research Summaries (RS) Database • Chemical and Biological Defense Information Analysis Center (CBIAC) Bibliographic Database • Dialog Database (including but not limited to): Journal of Aerosol Science Atmospheric Environment Aerosol Science & Technology Building & Environment ASHRAE Journal Journal of the Air & Waste Management Association Journal of the Air Pollution Control Association (JAPCA) Air & Waste Indoor Air Filtration and Separation HPAC Heat. Piping. AirCond. Eng. Journal of the Chemical Engineering of Japan Journal of the Institute of Environmental Sciences and Technology (IEST) Powder Technology Particulate Science and Technology • Internet resources available from the following agencies: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) American Society of Mechanical Engineers (ASME) Occupational Safety and Health Administration (OSHA) National Institute for Occupational Safety and Health (NIOSH) Environmental Protection Agency (EPA) Department of Health and Human Services (DHHS) Centers for Disease Control and Prevention (CDC) Edgewood Chemical Biological Center (ECBC)
Conference proceedings	• 2002 Indoor Air Quality-Filtration Conference, November 14–15, 2002, AFS Society, Cincinnati, OH. • World Filtration Congress 9 Proceedings CD-ROM, AFS Society, April 18–24, 2004, New Orleans, LA. • First NSF International Conference on Indoor Air Health Proceedings, National Sanitation Foundation, May 3–5, 1999. • Second NSF International Conference on Indoor Air Health Proceedings, National Sanitation Foundation, January 2001, Miami, FL.
Manufacturer's literature	• Market Survey and Evaluation of Filters for Enhanced SIP Applications," U.S. Army Soldier Biological and Chemical Command (SBCCOM), Aberdeen Proving Ground, MD, October 2001. • Market Survey and Evaluation of Filters for Large Area Shelter-in-Place Applications," U.S. Army Research Development and Engineering Command (RDECOM) Chemical Stockpile Emergency Preparedness Program (CSEPP), Aberdeen Proving Ground, MD, May 2004. • U.S. Commercial and Industrial Air Filtration Markets, Frost & Sullivan, March 29, 2001. • World HVAC Equipment to 2006, Freedonia Group, May 1, 2002. • Growing Markets for Nonwoven Filter Media, Business Communications Company, December 1, 2002.

EPA
United States
Environmental Protection
Agency

PRESORTED STANDARD
POSTAGE & FEES PAID
EPA
PERMIT NO. G-35

Office of Research and Development
National Homeland Security Research Center
Cincinnati, OH 45268

Official Business
Penalty for Private Use
$300

Recycled/Recyclable
Printed with vegetable-based ink on
paper that contains a minimum of
50% post-consumer fiber content
processed chlorine free