Assessment of Advanced Air Purification Technologies

Filtration and Hybrid Systems for Residential and Commercial Applications

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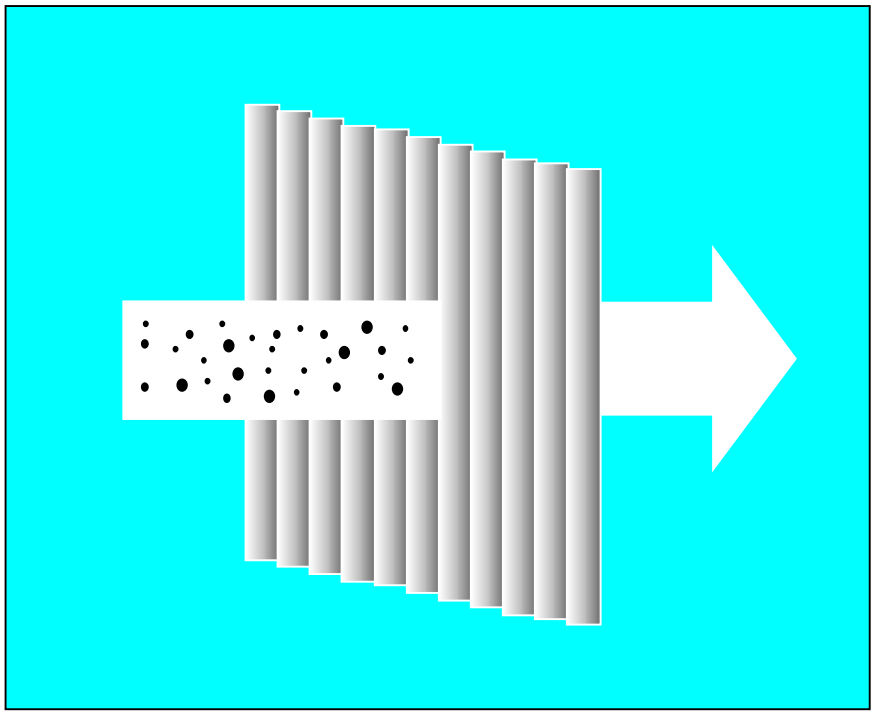

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Technical Update, January 2003

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REPORT SUMMARY

Indoor air contaminants, such as microorganisms, allergens, environmental tobacco smoke, and volatile organic compounds, can cause health- and productivity-related problems for the occupants of the indoor space. Children, elderly adults, and people with deficient immune systems are especially likely to be affected by contaminated air. There are three primary measures to control indoor air contamination. The first is to eliminate the contaminant source. The second is to control ventilation within the space, which involves dilution and/or isolation of the contaminated air. The third is to remove contaminants from the air. Contaminant removal consists of either simply removing the contaminants, or removing and then destroying the captured contaminants. This report addresses the third measure. It specifically focuses on how to remove contaminants from indoor air in residential and commercial buildings by the use of air filtration and hybrid technologies. The technologies investigated include advanced media filters, filters with anti-microbial agents, electrostatically enhanced filters and air cleaners, plasma sterilized filters, and media filters combined with ultraviolet germicidal irradiation and/or gas sorption.

Background

During the last 15 years, EPRI has undertaken numerous efforts geared toward characterizing indoor air in industrial, commercial, and residential buildings. This report expands upon past work by EPRI to include an assessment of commercially available and emerging air purification technologies for residential and commercial buildings. It specifically evaluates those air purification technologies that entail media filtration, either alone or in conjunction with additional control strategies. It also identifies drivers and barriers to successful adoption and commercialization of these technologies, and provides recommendations to ensure that residential and commercial customers make informed decisions when selecting air purification systems for their buildings.

Objectives

- To provide an overview of why indoor air quality is important and how air purification technologies can address indoor air quality problems
- To assess the most viable air filtration and hybrid technologies, either commercially available or emerging, for residential and commercial buildings
- To identify market drivers and barriers to successful integration of air purification technologies in residential and commercial markets
- To provide recommendations for how energy companies can assist residential and commercial customers in selecting air purification systems to improve indoor air quality

Approach

The project team identified and evaluated commercially available and emerging air purification systems targeted for residential and commercial buildings. Among the commercially available technologies, the project team assessed five groups of technologies that entail air filtration, either alone or in conjunction with additional control strategies: 1) HEPA filtration, 2) filters containing anti-microbial agents, 3) electrostatically enhanced filters and systems, 4) media filtration combined with ultraviolet germicidal irradiation, and 5) media filtration combined with gas sorption. The project team also identified and evaluated three types of new filtration systems that are still in the research and development stage, but show promise for solving some of today's indoor air purification problems: 1) electrostatically enhanced filtration with plasma sterilization, 2) nanofibrous filters, and 3) nanoporous filters. For each technology, the team compiled data on the technological process, current and potential applications, developmental status, primary merits and limitations, representative manufacturers, and estimated costs. The project team also sought to highlight key market drivers and barriers related to successful integration of air purification technologies in residential and commercial buildings. Based on this effort, the project team developed recommendations for how energy companies can work with residential and commercial customers to address indoor air quality needs and to select appropriate air purification products.

Results

This report includes an assessment of air purification systems that represent a diverse group of technologies—from media filtration alone to electrostatically enhanced filtration with or without plasma sterilization to new filtration systems based on nanomaterials, such as nanofibrous filters and nanoporous filters. The findings during the assessment phase yielded a variety of recommendations for how energy companies can pursue the subject of air purification further. If implemented, these recommendations will serve to educate residential and commercial customers in improving indoor air quality—this will be a valuable service. Specifically, one recommendation is to develop general fact sheets on indoor air quality and air purification technologies for residential and commercial buildings. Another recommendation is to develop building-and-application-specific fact sheets that address chemical and biological attack threats, and the specific indoor air quality needs of schools and healthcare facilities. This report also provides recommendations for which emerging air purification technologies to study further through demonstration and collaborative research projects, such as the electrostatically enhanced filtration system with plasma sterilization and the nanofibrous filters.

EPRI Perspective

EPRI has been studying indoor air and its effects on building occupants for 15 years. Earlier studies include a manual on indoor air, a report on residential air cleaners, and a report on indoor air quality health effects. Numerous reports and newsletters on indoor air quality in various types of commercial buildings followed these first studies. The present report provides an update to the EPRI material listed below. For those energy companies interested in improving indoor air quality in their residential and commercial customers' buildings, this report is a very valuable source of information.

Manual on Indoor Air (EM-3469)

Residential Indoor Air Cleaners (CU.3042.3.92)

Indoor Air Quality Health Effects Primer (CR-106639)

Power Prescription ™ Indoor Air Quality (various volumes and numbers)

Indoor Air Quality During Building Construction in Healthcare Facilities (TB-112232)

Educational Facilities Guidebook (TR-107123)

Educational Facilities Guidebook, Second Edition (1001086)

Keywords
Indoor air quality
Air purification
Indoor air contaminants
Media filtration
Residential
Commercial

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INTRODUCTION

1.1 Relevancy

We spend about 90 percent of our time indoors where contaminant levels may be higher than those outside. Poor indoor air quality is estimated to cause hundreds of thousands of respiratory health problems and thousands of cancer deaths each year.[1] New reports also have confirmed that indoor air contaminants, such as allergens, microorganisms, and chemicals are triggers for asthma.[2] In the United States alone, an estimated 17 million people suffer from asthma. Children in particular are prone to develop asthma; this is because, per pound of body weight, they breathe more air and ingest more material than do adults. Children also more readily absorb a greater quantity of contaminants due to their developing systems. In addition to causing illness, poor indoor air quality may also inhibit a person's ability to perform. Studies have shown that improved indoor air quality leads to greater productivity in the workplace.[3] Another threat to indoor air purity is related to acts of chemical and biological terrorism. Anthrax scares and an overall increased awareness of potential terrorist actions have resulted in a movement toward creating more resistant indoor environments. The air purification systems reviewed in this report are part of the solution to these indoor air quality problems.

1.2 Scope

Controlling indoor air contamination involves three main steps. The most effective approach is to eliminate the source of contamination. If the source cannot be fully eliminated, the level of contaminants should be reduced as much as possible. The next essential step is to have adequate and well-controlled ventilation of the space. This step acts to dilute the air, thus reducing the concentration of contaminants. The third approach, which is addressed in this report, is to remove the contaminants from the indoor air by using an air purification system.

This report contains assessments of selected commercially available and emerging technologies for air purification. The types of air purification technologies addressed are those that are based either entirely on air filtration, or on combinations of air filtration and other pollutant control strategies. Further, the assessment focuses on products applicable to the residential and commercial markets. The treatments of individual technology families provide a summary of the technical processes involved, existing and potential applications, developmental status, merits and limitations, manufacturers, and estimated costs. The discussions are not intended to contain

[1] *Healthy Buildings, Healthy People: A Vision For The 21st Century*, EPA-402-K-01-003, EPA, Washington, DC: October 2001.
[2] Ibid.
[3] William J. Fisk, "How IEQ Affects Health, Productivity," *ASHRAE Journal*, May 2002.

an exhaustive review of all specific products. Rather, they are meant to provide meaningful summaries of viable technologies, lists of representative manufacturers, and approximate ranges of costs. The report also contains descriptions of the main drivers and barriers associated with widespread implementation of air purification technologies in residential and commercial buildings. Lastly, it lists recommended actions for energy companies to pursue. If implemented, these actions will help their residential and commercial customers bypass, or at least navigate themselves through, often confusing data surrounding air purification systems. The actions will also result in useful fact sheets, web pages, seminars, and collaborative research and demonstration efforts.

1.3 Previous EPRI Work

During the last fifteen years, EPRI has been studying indoor air and its effect on building occupants. As early as 1984, EPRI published a manual on indoor air, which provided a reference guide on indoor air quality and its relationship to air exchange and energy use in residential buildings.[1] EPRI followed that effort with a report on residential air cleaners, which describes typical air contaminants found in homes and various types of air cleaning systems.[2] A few years later, EPRI published a report on indoor air quality health effects, which discusses sick building syndrome and building-related illness, as well as volatile organic compounds, environmental tobacco smoke, radon, and asbestos.[3] These initial efforts were followed by numerous EPRI reports and newsletters studying indoor air quality in various types of commercial settings, such as healthcare facilities[4,5,6] and educational buildings.[7,8]

1.4 Objectives

The purpose of this study is to identify and assess air purification technologies for the residential and commercial markets. In particular, the study has the following objectives:

- To summarize important indoor air contaminants, and to explain how air purification technologies can mitigate poor indoor air quality
- To evaluate viable commercially available and emerging air filtration and hybrid technologies for the residential and commercial markets
- To highlight the primary drivers and barriers influencing successful market penetration of air purification technologies in residential and commercial markets
- To recommend ways in which energy companies can help their residential and commercial customers understand and select appropriate air purification technologies

[1] *Manual on Indoor Air*. EPRI, Palo Alto, CA: 1984. EM-3469.
[2] *Residential Indoor Air Cleaners*, EPRI, Palo Alto, CA: 1992. CU.3042.3.92.
[3] *Indoor Air Quality Health Effects Primer*. EPRI, Palo Alto, CA: 1996. CR-106639.
[4] *Power Prescription ™ Indoor Air Quality: Various volumes and numbers*. EPRI, Palo Alto, CA: 1996-1997.
[5] *Power Prescription (TM) for Healthcare: Various volumes and numbers*. EPRI, Palo Alto, CA: 1999.
[6] *Indoor Air Quality During Building Construction in Healthcare Facilities.* EPRI, Palo Alto, CA: 1998. TB-112232
[7] *Educational Facilities Guidebook*. EPRI, Palo Alto, CA: 1996. TR-107123.
[8] *Educational Facilities Guidebook, Second Edition.* EPRI, Palo Alto, CA: 2000. 1001086.

1.5 Report Organization

Chapter 2 provides a perspective on the importance of air purification technologies to the residential and commercial sectors. This chapter describes the types of particulate and gaseous contaminants commonly found in homes and commercial buildings. It also explains why these contaminants need to be controlled and how to control them by employing air purification technologies. Chapter 3 identifies and evaluates commercially available air purification technologies for the residential and commercial markets. This chapter specifically addresses those systems that use media filtration alone, or in combination with alternate pollutant control technologies. Chapter 4 identifies and evaluates new air purification technologies that are still in the research and development stage. This chapter discusses three new promising air purification technologies, namely electrostatically enhanced filtration with plasma sterilization, nanofibrous filtration, and nanoporous filtration. Chapter 5 discusses the main drivers and barriers to successful integration of air purification technologies in residential and commercial markets. Chapter 6 provides recommendations to energy companies interested in offering indoor air quality assistance to their residential and commercial customers. Finally, Appendix A contains a glossary of typical indoor air quality terms, and Appendix B presents six common test methods and standards that apply to residential and commercial air purification systems.

2
PERSPECTIVE

Why are advanced air purification technologies of interest to the residential and commercial sectors? This chapter begins to answer this key question. First, it describes the types of particulate and gaseous contaminants commonly found in residential and commercial buildings, and explains why they are hazardous and need to be controlled. It further discusses the unique threat of indoor air contamination by terrorist attacks with biological and/or chemical agents. Air purification is then highlighted as a critical stage in a three-part process to control contaminants.

2.1 Contaminants

Airborne contaminants are generally separated into two main categories of pollutants, namely particulates and gases. Particulates are commonly thought of as suspended solid particles or particle conglomerates, but they also include liquid mists. Gaseous contaminants consist of matter in the gaseous state. Sources and hazards associated with various common types of particulate and gaseous contaminants are summarized below.

2.1.1 Particulates

Particulates vary widely in shape, size, and type. Figure 2-1 shows typical size ranges for various common indoor air particulates. Of the scores of particulate contaminants, the most worrisome are those within the respirable range, which is considered to be greater than about 0.01 microns, and less than about 5 microns. Respirable particulates can penetrate deep into the lungs, and cause cancer or other respiratory complications. In contrast, smaller particles are typically exhaled, and larger particulates are usually removed by the upper respiratory system. Nevertheless, smaller particles can agglomerate to form larger particulates that can be trapped deep in the respiratory system. In addition, larger particulates that are removed by the upper respiratory systems can still cause health problems.[1]

Particulate contaminants enter indoor air from several origins, including animals and humans, plants, minerals, combustion sources, radon progeny, and consumer spray products.[2] The sources can be either indoor or outdoor. Particulates from indoor sources become airborne as a result of gentle breezes, dusting, vacuuming, walking on carpets and floors, shaking linens or clothing, fluffing pillows or cushions, air flow through central distribution systems, product spraying,

[1] Klein, M., "Indoor Air Quality, Filtration, and the Consumer Market," paper to be presented at NAFA 2002 Technical Seminar Presentation, September 2002, available on the website www.nafahq.org.
[2] *Residential Indoor Air Cleaners*, EPRI, Palo Alto, CA: 1992. CU.3042.3.92.

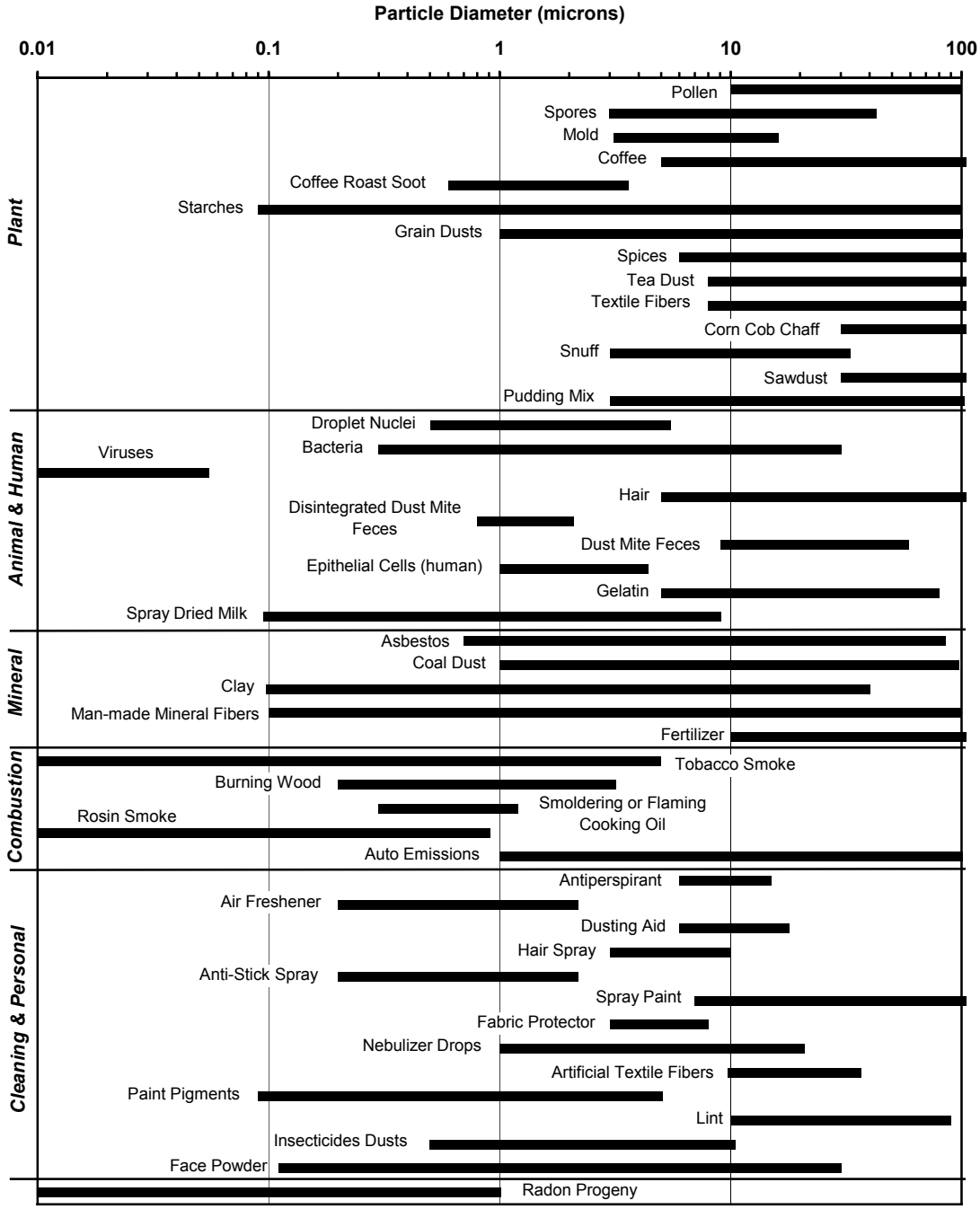


Figure 2-1
Size Distributions of Indoor Particulates

Source: Redrawn from *Residential Indoor Air Cleaners*, EPRI, Palo Alto, CA: 1992. CU.3042.3.92.

and so on. Particulates from outdoor sources may be introduced to the interior by open windows, doors, vents, ventilation or makeup air, or by being tracked in by people and pets.

Plants

Particulates of plant origin include fungi (specifically molds), fungal spores, pollen, and small particles from broken down plant fragments (e.g., pieces of leaves, stems, flowers, seeds, coffee grounds, cornstarch, clothing fibers, etc.). Fungi are potentially dangerous, as some are pathogenic. Inhalation of certain types of fungi can cause infection; however, once infected, the person is not contagious as he/she could be with a bacterial or viral infection. Fungi prefer humid and dark conditions, and are often found in rooms exposed to moisture originating either indoors (such as in bathrooms, kitchens, and laundry rooms) or outdoors (such as in basements, which are susceptible to moisture from the ground). Fungi can then proliferate if left unchecked in walls and floors. They can also grow in humidifiers or on air filters, and then be distributed throughout the room or building.

Spores, which are produced from fungi or bacteria, range in diameter from a few to tens of microns. Spores are more resistant to harsh conditions; therefore they can survive while they are dormant, or as they travel. Fungal spores can enter a building through human contact, and then be distributed throughout the building by the ventilation system. Sick building syndrome is often tied to the presence of mold spores.

One group of molds known for causing health effects in humans is Aspergillus. The genus Aspergillus consists of more than 185 species, about 20 of which have been determined to cause opportunistic infections in humans.[1] The pathogenic health effects from Aspergillus are referred to as Aspergillosis. Potential problems range from Aspergillus Sinusitis (which is a sinus infection caused by the fungus) to Allergic Bronchopulmonary Aspergillosis (which is an allergic reaction to Aspergillus mold spores that is common in asthmatics and cystic fibrosis patients) to Aspergilloma (which results in fungal growth in existing lung cavities that were caused by a previous illness) to Invasive Aspergillosis (which is often deadly, and can spread from the lungs to other areas of the body).

Pollens are larger in size, and vary from tens to hundreds of microns. While airborne they can enter the upper respiratory track and cause allergic reactions.

Broken down plant particulates are usually not too troublesome. However, inhalation of high concentrations of fine powders can be hazardous.

Animals and Humans

Particulates from animal and human origin range from hair particles to skin cells to bacteria to viruses to disintegrated insect feces. Of these, bacteria and viruses present some of the greatest concern because they are pathogens, and therefore are capable of causing disease. With the exception of Anthrax (which is spread via spores produced from the Anthrax bacterium), bacteria

[1] "Aspergillus," article on website, http://www.mold-help.org/aspergillus.htm.

and viruses are unable to survive the harsher conditions of outdoors.[1] Therefore they are carried and spread by animal or human hosts indoors. Buildings that house large numbers or large density of people, such as hospitals, prisons, and shelters, are especially susceptible to the spread of viruses and bacteria.

Bacteria are in the size range of roughly a few tenths of a micron to tens of microns. Viruses are much smaller, and range in size from a few thousandths to several hundredths of a micron. In fact, because of their very small size, viruses act somewhat like a gas and are hard to capture by filters. Viruses also can agglomerate to form larger particulates or attach themselves to other types of particulates. Viruses are often spread by sneezes or coughs. The droplets expelled in sneezes and coughs can contain viruses, which are then inhaled by nearby people. Keeping a reasonable distance from people carrying bacteria or viruses greatly reduces the chance of becoming infected.

Particulates from animals and disintegrated dust mite feces pose a different threat to humans. They are highly allergenic and can cause varying levels of discomfort for those with allergy sensitivities.

Minerals

One of the most notorious of mineral particulates is asbestos. Asbestos particulates, which are in the respirable range, can become airborne during remodeling and construction projects, and inhaled they can deposit in lungs, potentially causingasbestosis. Other mineral particulates include fragments of talc, clay, coal, and fiberglass. Mineral particulates vary significantly in size from one-tenth to hundreds of microns.

Combustion Sources

Combustion sources, such as cigarettes, fireplaces, ovens, water heaters, HVAC systems, and car exhaust from adjacent garages produce both gases and particulates that can contaminate indoor air. Many of the particulates produced during combustion are in the respirable range, making them a particular problem.

Consumer Spray Products

Consumer spray products include many different types of liquid substances associated with beauty (e.g., hair spray, fragrances, and deodorant), cleaning (e.g., glass cleaners, disinfectants), and other similar activities. Particulates from spray products usually are introduced in short bursts that dissipate quickly; however, these products are often used in close proximity to humans.

[1] *Fungi and Bacteria in Ventilation Systems*, Pennsylvania State University, Aerobiological Engineering. www.engr.psu.edu/ae/wjk/wjkfungi.html.

Radon Progeny

Radon progeny are very small radioactive particles (in the range of less than one hundredth of a micron up to about 1 micron) formed by the decay of radon gas. They can attach themselves to other larger particles and can be subsequently trapped deep into the respiratory system.

2.1.2 Gases

There are hundreds, if not thousands, of different gas molecules that are considered indoor air contaminants. Three main types include radon gas, various volatile organic compounds (VOCs), and combustion products (e.g., nitrogen dioxide and carbon monoxide).

Radon Gas

Radon gas is produced as radium disintegrates. It can be introduced to the indoors via contact with soil, rock, ground water, natural gas, and mineral building materials. Radon gas is potentially carcinogenic. It is particularly hazardous when it is in large concentrations, and when exposure to it is frequent and of long duration.[1] Figure 2-2 is a map developed by the U.S. Environmental Protection Agency (EPA) that shows the potential for elevated indoor radon levels in various U.S. counties. Each county is assigned to a zone based on its radon potential. The three zones correspond to the following predicted average radon screening levels:

- Zone 1: Predicted level is greater than 4 picocurries per liter (pCi/L)
- Zone 2: Predicted level is greater than 2 pCi/L and less than 4 pCi/L
- Zone 3: Predicted level is less than 2 pCi/L

VOCs and Combustion Products

VOCs originate from numerous sources in residential and commercial buildings. They can come from building materials, paints, solvents, adhesives, upholstery, cleaning products, process chemicals, and so on. As mentioned above, combustion products typically originate from the following combustion sources: cigarettes, fireplaces, ovens, water heaters, HVAC systems, and vehicles in adjacent garages. Gases can also enter the interior from exterior sources, such as wildfires, road repairs, crop spraying, etc. Health problems from VOCs and combustion products greatly depend on the type of gas, its concentration, and the level of exposure (both duration and frequency). Moreover, some individuals are more sensitive to particular contaminants than are other people. Problems can range from less severe (e.g., allergic reaction or irritation to eyes and/or respiratory tissue) to more severe (e.g., cancer or long term damage to the respiratory, liver, immune, cardiovascular, reproductive, or nervous systems).[2]

[1] *Residential Air Cleaning Devices: A Summary of Available Information*, EPA 400/1-90-002, EPA, Office of Air and Radiation (OAR), Washington, DC: 1990, www.epa.gov/iaq/pubs/residair.html#.
[2] Ibid.

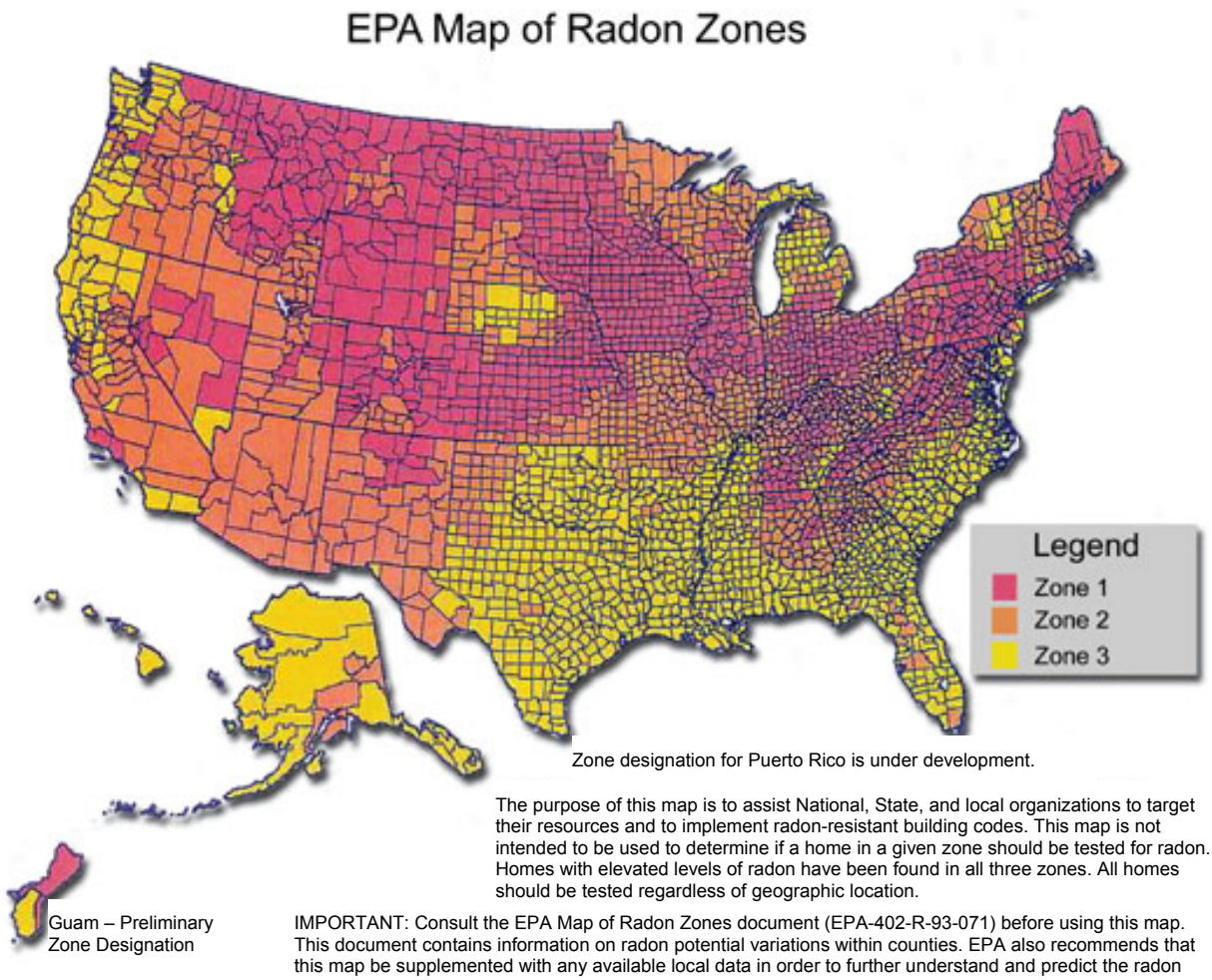


Figure 2-2
U.S. Map of Radon Zones

Source: EPA, www.epa.gov/iaq/radon/zonemap.html.

2.2 Biological and Chemical Attack Threat

The threat of a biological or chemical attack is by no means new; however, recent Anthrax contaminations, coupled with the events of "9-11" and continuing tensions with the Middle East, have sparked a new awareness of the potential for disaster by biological or chemical agents. Heavily occupied government or commercial buildings could be prime targets for this type of terrorist activity.

Biological agents of concern include spores, bacteria, viruses, endotoxins (which are toxins produced by bacteria), and mycotoxins (which are toxins produced by fungi). Exposure to these agents, and/or to infected hosts, can lead to serious disease. One common example of a type of

bacteria transmitted through spores is the Anthrax bacterium. Its spores can contaminate people through three main types of contact, namely inhalation, ingestion, and direct contact with open wounds. Once in a nutrient-rich environment, the spores can lead to bacteria growth and subsequent disease. Another example is the highly contagious Variola virus, which is transmitted by infected hosts. The Variola virus leads to Smallpox, which can cause death, scarring and blindness. In the event of an attack with biological agents, the primary focus is to minimize the number of people contaminated. This includes identifying and isolating those already exposed. Symptoms from exposure to biological agents are often slow to appear, making identification and isolation of victims challenging.

Chemical agents are numerous and can lead to very diverse symptoms. However, in contrast to biological agents, chemical agents result in more immediate symptoms. A few examples of chemicals used during war and terrorist actions include Nerve Gas, Mustard Gas, Cyanogen Chloride, Hydrogen Cyanide, and Dimethylacetamide. Chemical agents typically enter the body through inhalation of gases and vapors, or through the skin. Higher concentrations of hazardous gas molecules in the indoor air result in more serious symptoms. Exposure time and duration also play a role. Therefore, a chemical attack should be met with heavy dilution of the contaminated air with clean air to reduce concentration levels.

Biological or chemical agents can be introduced to the interior of buildings by sources such as mail, human carriers, air intakes that are easily accessible, or even through building exhausts under certain conditions. Direct introduction of contaminants to HVAC equipment is particularly hazardous. This can occur if equipment rooms are left unlocked, or if access to keys is not strictly controlled. It is also possible for indoor air to be contaminated from exterior air that is affected, although this scenario is less likely as much larger quantities of the agent would be required.

If the contamination exists in the interior of the building, it is important to evacuate through escape routes that are ventilated with 100 percent outside air. If contamination is outdoors, the building should be isolated from the exterior environment by closing windows and doors, and turning off the air intake or outdoor air opening.

2.3 How Advanced Air Purification Technologies Can Help

There are three basic steps to take to control indoor air contaminants. The first is to eliminate the source, or at least to reduce the level of contaminants entering the indoor air from the source. The second is to control ventilation. Ventilation control can enable dilution of contaminated air, making it less hazardous; or it can be used to isolate contaminated areas from safe areas. The third is to remove contaminants from the air by employing some sort of air purification device. This could consist of either contaminant removal alone, or removal combined with destruction of the captured contaminants. This report focuses on the third measure.

Air purification systems are defined herein as devices that remove airborne contaminants. They can be as simple as an air filter installed in a central HVAC system to remove larger particulates, or as complex as a stand-alone air cleaner with multiple stages designed to remove bacteria, viruses, allergens, and gaseous contaminants from a room. As shown in earlier sections of this chapter, there is a great need for air purification systems that control particulate and gaseous

contaminants. Many people suffer from allergies. In addition, diseases are easily transmitted in heavily populated buildings (particularly those in which people reside for extended periods of time). Moreover, biological and/or chemical agents distributed in a terrorist attack can yield high disease and illness rates if not systematically removed from the air sources of populated areas. Since allergens, spores, bacteria and viruses are particulates, effective particulate removal devices are demanded. Likewise, since odors, gaseous combustion products, and other chemical agents are inhaled in the form of gases and vapors, gas removal systems are needed.

Particulate removal systems come in two main categories: media filters and electrostatic devices. Media filters capture the particulates as they are drawn with a flow of air through the medium. Electrostatic devices use the principle of electrostatic precipitation to charge particles and then capture them on collection surfaces. The size range of particulates captured depends greatly on the specific technology. For example, only certain media filters with the true HEPA (high efficiency particulate arrestance) or ULPA (ultra low particulate air) distinction can capture particulates of sizes in the 0.1 to 0.3 micron range with high efficiency.

Gaseous removal systems rely on some type of sorption process (i.e., adsorption, absorption, or chemisorption) to remove the undesirable gas molecules from the air. In a sorption process a solid material is used in essence as a “filter” for the gases. Sorbent materials, as well as the substances they are treated with or impregnated with, are chosen based on their ability to remove specific gases. Activated carbon is a very common adsorbent for odorous molecules.

There are also several families of hybrid systems that combine particulate and gaseous removal technologies to control multiple contaminants. Some systems incorporate further strategies to ensure the captured biological contaminants are subsequently destroyed, and therefore not able to proliferate on filter surfaces. Some such strategies include the use of biocides on filters, ultraviolet (UV) destruction, and plasma sterilization.

Advanced purification technologies alone cannot guarantee the safety of indoor air; but, when combined with source control and well-designed ventilation systems and procedures, they have the potential to greatly improve indoor air quality. The remainder of this report assesses new and emerging air purification technologies for the residential and commercial sectors. Particular attention is placed on filtration and hybrid filtration systems, and their ability to control biological species, chemicals, and allergens. This assessment will highlight the most viable technologies, either commercially available or emerging, for residential and commercial markets.

3
ASSESSMENT OF COMMERCIALLY AVAILABLE TECHNOLOGIES

Several families of advanced air purification systems are currently on the market for residential and commercial end uses. This chapter evaluates those that entail air filtration, either alone or in conjunction with additional control strategies. In particular, Section 3.1 discusses media filtration with an emphasis on HEPA filtration technologies. Section 3.2 describes filters that are treated with anti-microbial agents for controlling the spread of microorganisms. Section 3.3 evaluates two families of products that employ electrostatic forces for enhancing particulate capture efficiencies, namely electrostatic filters and electrostatic precipitators. Section 3.4 focuses on ultraviolet germicidal irradiation (UVGI) combined with filtration. Lastly, Section 3.5 discusses technologies that augment particulate filtration with gas sorption. Each family of technologies has products for in-duct placement and for stand-alone use. Furthermore, the technologies are applicable for a wide variety of residential and commercial applications. Table 3-1 summarizes some of the main aspects of each general technology family. More detailed treatments follow in the subsequent sections.

3.1 Media Filtration: HEPA Filters

3.1.1 Description

Media filtration involves the use of a medium to filter out particulates from an airstream as the air is forced through the medium. Typical media are fibrous in nature and are made of materials such as glass, cellulose, wool felt, foam, textiles, ceramics, and so on. Some media filters are disposable, while others can be cleaned. The vast majority of air purification systems employ some sort of media filtration stage. Usually, at the very least a prefilter is used to capture the larger particulates before the air stream enters further cleaning stages. Subsequent subsections of this chapter will show how media filtration is combined with other cleaning strategies to enhance capture efficiency.

Media filters vary greatly in size, surface area, material, and geometry. Of particular interest for the present assessment are HEPA filters. Figure 3-1 shows a HEPA filter that is used in a portable air purification system. True HEPA filters are capable of efficiently capturing all sizes of particulates, including those with sizes between about 0.1 and 0.3 microns. This is the most difficult size range for media filters to collect. Particulates smaller than about 0.1 microns are captured by diffusive forces, while particulates larger than about 0.3 microns are captured by inertial forces (see Figure 3-2). Smaller particulates collide with air molecules and are sent into

Table 3-1
Summary of Commercially Available Technologies

Technology	Primary Function	Main Limitation	In-Duct System Considerations	Stand-alone System Considerations
HEPA filters	To filter particulates with efficiency of 99.97% and greater	Substantial air resistance through filter media	Often require HVAC system modifications Filters are costly	Well suited for stand-alone systems Systems and replacement filters are costly
Anti-microbial filters	To capture and control the proliferation of microorganisms	Total destruction of microorganisms is not likely	Can replace existing filters Do not increase pressure drop significantly	Less effective than HEPA filtration Can augment HEPA filtration
Electrostatic filters Filter/electrostatic precipitator units	To enhance capture efficiency (95% and greater) with electrostatic forces	Require frequent cleaning to stay effective	Filters can replace existing filters Electrostatic precipitators require electricity and are costly	Quieter than HEPA filtration Relatively high efficiencies
UVGI and filter systems	To capture and irradiate microorganisms	Some configurations present a health hazard	May necessitate HVAC system modifications Hybrid systems are costly	Well suited for augmenting HEPA filtration systems Expensive replacement lamps
Gas Sorption and filter systems	To capture gaseous and particulate contaminants	Ability to capture wide range of VOCs is limited	Adsorbent coated media filters can replace existing filters Effectiveness diminishes with loading	Well suited for additional stage in HEPA filtration systems Effectiveness depends on sorbent properties

random, diffusive, motion through the air. When this motion causes the small particulates to come into contact with the filter medium, they are captured. In contrast, larger particulates have more mass, and hence more inertia. This inhibits their ability to change directions once in motion. Therefore, as the direction of the airflow is forced to twist and turn around the fibers in the filter, the larger particulates are unable to change their direction; this can cause them to impact with the filter material. In the 0.1 to 0.5 micron range, particulate collection changes from

Figure 3-1
Honeywell HEPA Replacement Filter for 10500 and 17000 Portable Air Cleaners

Source: Honeywell. Used with permission.

predominantly diffusive to predominantly inertial in nature. Figure 3-3 shows schematically how there is a corresponding dip in the filter performance curve.

The true HEPA filter designation requires that the filter achieve a minimum efficiency of 99.97 percent for particulates of 0.3 microns in size during the clean-room standard Dioctylphthalate (DOP) test. In the DOP test, the capture efficiency is measured as Dioctylphthalate particulates are passed through the filter. The Dioctylphthalate particulates have a mean diameter of 0.3 microns, and are therefore well suited for determining the filter's efficiency for the most difficult particulate size. The results of the test will yield the lower bound of filter efficiency; the capture efficiencies for smaller and larger particulates will be even higher.

Ultra Low Penetration Air (ULPA) filters that achieve a minimum removal efficiency of 99.999 percent for 0.3 micron particulates are available. In addition, HEPA-like filters are marketed as HEPA filters, but they lack the distinction of 99.97 percent efficiency for 0.3 micron particulates. HEPA-like filters are made of the same type of materials as true HEPA filters; however, they can have capture efficiencies as low as 25 percent or as high as 95 percent. It is important to choose true HEPA or ULPA filters if maximum efficiency is desired. For the remainder of this report, the term "HEPA" is intended to include both true HEPA filters and ULPA filters, unless otherwise noted.

3.1.2 Applications

Media filters are widely used both in central HVAC systems and in stand-alone room cleaners. They represent a simple and fundamental stage in indoor air cleaning. The majority of residential and commercial air purification systems have some sort of a filtration stage, with the exception of filterless systems such as electrostatic-only or UV-only stand-alone room cleaners. Therefore, media filters are established. Nevertheless, continuing advances are improving the capture efficiency of media filters. HEPA filters (that is, true HEPA and ULPA filters) are the most efficient media-only technology commercially available. They are very commonly used in vacuum cleaners. In addition, their use for indoor air purification is already established in medical applications, such as in intensive care units and operating rooms, as well as in industrial

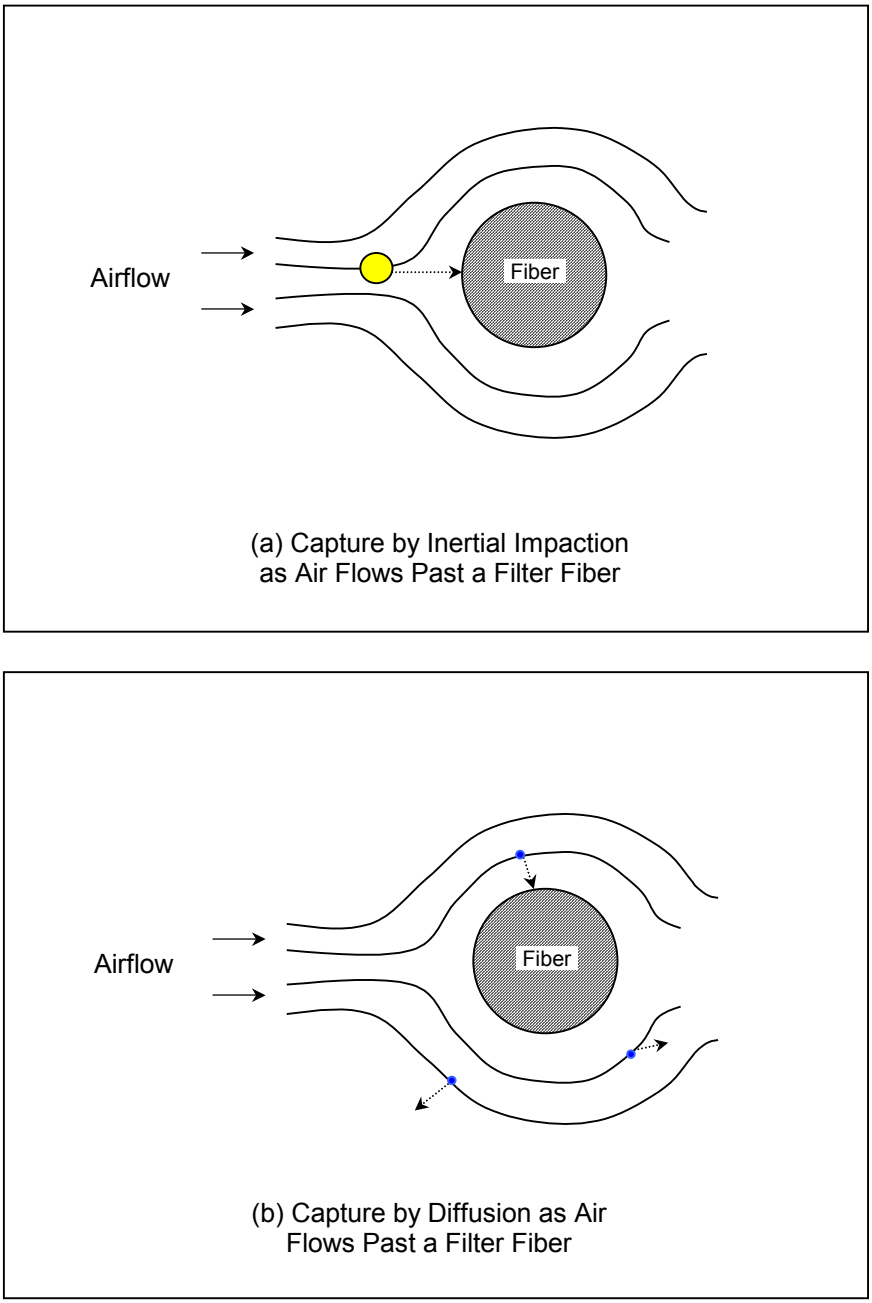


Figure 3-2
Schematic Diagram of Particulate Capture by (a) Inertial Impaction and (b) Brownian Diffusion

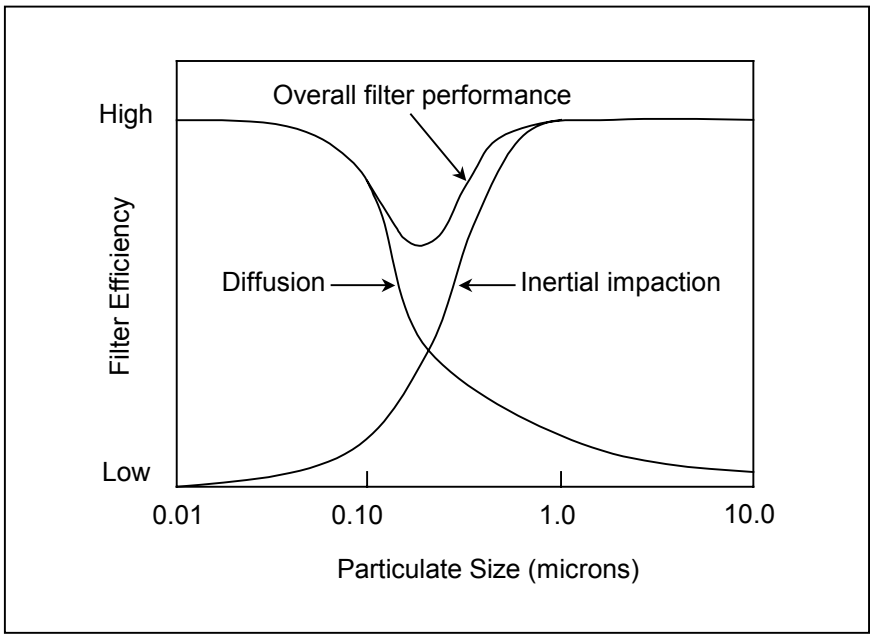


Figure 3-3
Schematic Representation of the Drop in Collection Performance of Typical Media Filters for Particulate Sizes Near 0.3 microns

Source: Redrawn from *Residential Indoor Air Cleaners*, EPRI, Palo Alto, CA: 1992. CU.3042.3.92.

cleanrooms and for radioactive waste processing. Moreover, as the awareness of indoor air quality has increased, HEPA filters have experienced greater application in a wide variety of seemingly less "sensitive" end-uses. For example, allergy sufferers benefit greatly from HEPA filters installed in their central HVAC systems or in stand-alone room cleaners. In addition, office buildings, schools, public buildings, prisons, museums, power plants, industry, and so on can all benefit from high efficiency filtration when it is economically viable. Table 3-2 summarizes the main current and potential end users of HEPA filters. HEPA filtration is particularly appropriate in applications that require the efficient removal of sub-micron particulates, including bacteria, viruses, and smaller allergens.

3.1.3 Developmental Status

Media filters, in general, are very well-established. HEPA filters are also commercially available to a large extent. Nevertheless, technological innovations will continue to increase the affordability, as well as reduce the pressure drop associated with HEPA filters. Specific research topics include the employment of novel filter materials, effective ways to increase the media

Table 3-2
Current and Potential End Users of HEPA Filters

Established End Users of HEPA Filters	End Users with Potential for Increased Application of HEPA Filters
Vacuum Cleaners	Schools and Public Buildings
Cleanrooms	Office Buildings
Hospitals & Healthcare Facilities	Prisons and Shelters
Asbestos Renovation Projects	Museums and Preservation
Radioactive Waste Processing	Miscellaneous Industrial Processes
Homes of Serious Allergy Sufferers	Personal Residences

surface area while maintaining a small cross-section to the flow and minimizing the thickness, the reduction of pressure drop across the filter, and the development of hybrid systems. Hybrid systems combine media filtration with one or more air purification strategies. Specific hybrid systems configurations are discussed in Sections 3.2 to 3.5.

3.1.4 Merits and Limitations

Merits

- **High Capture Efficiency:** Media filters come with a wide range of efficiencies, with the most efficient being true HEPA and ULPA filters. True HEPA filters and ULPA filters by definition are capable of capturing a minimum of 99.97 percent and 99.999 percent, respectively, of particulates at the most difficult particulate size of 0.3 microns.
- **Wide Applicability:** HEPA filters can capture a wide variety of air contaminants, ranging from general dust to allergens to bacteria to viruses to fungi.

Limitations

- **Limited by Capacity:** Media filters only capture particulates from the air that flows through them. The capacity of the particular system limits the amount of air they can handle in a given period of time. As a result, even if it is a HEPA filtration system, it may not sufficiently remove particulates from the space if the system is undersized.
- **Allow Some Particulates to Pass:** Even an efficiency of 99.999 percent will pass thousands of pathogens if the inlet concentration is millions, which it can be.
- **Do Not Specifically Destroy Microorganisms:** Though HEPA filters can capture bacteria, fungi, and viruses, in their basic form they do not destroy the microorganisms. Therefore, in the presence of moisture and other conditions beneficial for microorganism survival, HEPA filters can actually become a breeding ground for microorganisms.

- **Static Pressure Drop Can be Large:** As the quantity of filter material is increased to improve the capture efficiency, the air resistance across the filter increases, as does the corresponding static pressure drop. HEPA filters can have particularly high resistances to airflow. (For example, the initial resistance of a HEPA filter applied in a central HVAC system is on the order of 1 to 2 inches of water, compared with 0.3 to 0.7 inches of water for conventional final filters.)[1] Higher air resistances can necessitate a larger fan motor, and are louder to operate. Moreover, the air resistance increases as the filter becomes loaded with particulates. The use of a prefilter for capturing a large percentage of particulates before they enter the HEPA filter, and/or incorporating a backflow system to clean the HEPA filter, will increase the life of the filter and keep the air resistance at a minimum.
- **Can Necessitate Ductwork Modifications and Better Seals:** To keep the air resistance of HEPA filters as low as possible, the filters are often designed with a large surface area. This is usually accomplished by using deep pleats. The deep pleats tend to increase the filter's thickness, which may require changes to the ductwork in central systems to accommodate the larger size. In addition, better seals than are conventionally used in HVAC systems are required to prevent air from by-passing the filter.
- **Require Replacement:** Most media filtration systems require replacement anywhere from a few times a year to once every couple of years. Replacement is typically a simple procedure, but it depends upon the conscientiousness of the operator. HEPA filters are also relatively costly to replace. HEPA filters from healthcare facilities are usually treated as infectious waste, and require redbag disposal at a significant cost.

3.1.5 Manufacturers and Estimated Costs

Representative costs and manufacturers of HEPA filtration systems are separated into three main categories, namely portable units (i.e., units that can be moved from one area to another with relative ease), in-duct filters (i.e., high efficiency filters that replace conventional filters in central HVAC systems), and mounted stand-alone systems (i.e., units that are independent from the central HVAC system, but are ceiling, wall, or flush mounted).

Portable Units

Portable units for residential and commercial applications are becoming increasingly popular. However, to make an informed decision in choosing a portable system, consumers must weed through a relatively large amount of hype. The commercially available systems vary significantly in capacity, technology, and efficiency. Fortunately, a few organizations, such as AllergyBuyersClub.com, achooallergy.com, promolife.com, and ConsumerSearch.com, have posted cost and performance comparisons of the top rated systems. The costs for stand-alone portable filtration units vary greatly with system capacity. Table 3-3 includes estimates for representative HEPA systems with varying capacities. All of the systems listed include a prefilter and a true HEPA filter.

[1] *HEPA Filters in Commercial Buildings,* Airguard Research and Technical Center. www.airguard.com/downloads/HEPAin%20commercial%20buildings.pdf.

Table 3-3
Cost Estimates for Portable HEPA Filtration Systems

Product Name	Area Treated (sq ft)	Targeted Applications	Initial System Cost	Filter Replacement Costs
IQAir Cleanroom Series H13 HEPA Air Purifier	2400	• Residential • Commercial • Cleanrooms • Medical Environments • Microorganisms • Miscellaneous Particulates	$1500 (~$0.60 per sq ft of floor area)	• $290 for HEPA (every 3 to 4.5 years) • $130 for prefilter (every 1 to 2 years)
IQAir HealthPro HEPA Air Purifier	600	• Residential • Offices • Allergens • Microorganisms • Light tobacco smoke	$600 (~$1 per sq ft of floor area)	• $190 for HEPA (every 2 to 4 years), • $55 for prefilter (every 6 to 18 months)
Bemis HEPA Air Purifier	340	• Single room • Small office	$200 (~$0.60 per sq ft of floor area)	• $240 for 3 HEPA replacements
Honeywell Enviracaire® (Variety of Sizes)	80-370	• Single room • Small office	$70-300 (~$0.80 per sq ft of floor area)	• $35-100 for HEPA (every 1 to 3 years) • $13 for 2-pack of prefilters (every 6 months)

Most healthcare-grade air cleaners are more heavy-duty than residential or commercial portable units, and treat airflows from about 100 to 1200 cfm. These systems typically cost in the range of $2000-4000, with HEPA filter replacements on the order of $300.[1] Portable HEPA air cleaners specifically targeted for healthcare applications are supplied by companies such as the following:

- Abatement Technologies Inc. (www.hepacare.com)
- Air Quality Engineering Inc. (www.air-quality-eng.com/Medical.htm)
- Envirco Corp. (www.envirco.com)
- NQ Environmental Inc. (www.nqinc.com)

Many stand-alone systems are also sold as hybrid units that incorporate additional purification stages. These systems are often more expensive than systems consisting purely of media filtration. Hybrid technologies are discussed in Sections 3.2 through 3.5.

[1] "Air Cleaners, High-Efficiency-Filter, Mobile," *Healthcare Product Comparison System*, ECRI, Plymouth Meeting, PA: Nov. 1999.

In-Duct Filters

The costs for filters placed within central HVAC systems depend largely on the specific system size and configuration. HEPA filters can be retrofitted into existing ductwork, but their installation often requires alterations to accommodate the larger filter sizes and may require fan modifications to accomodate the higher pressure drop. Low and medium efficiency filters can also be upgraded easily to higher efficiency filters that do not carry the true HEPA designation, but that are still effective for removing many particulates. According to ConsumerSearch.com, two highly rated non-HEPA filters for use as replacement filters in residential central systems are:

- 3M Filtrete Ultra Allergen Reduction 1250 Filter (www.mmm.com)
- Precisionaire NaturalAire Microparticle Filter (www.flanderscorp.com)

Both filters range in price from about $8-15, depending on the filter size, and should be replaced about four times a year for optimum performance. These filters are good for removal of allergens and some microorganisms, but cannot be counted on for very high removal efficiencies for sub-micron particulates.

Residential and commercial grade true HEPA filters are also available for installation in central HVAC systems, but seem to have penetrated the market to a lesser extent. Currently, a small number of buildings use HEPA filtration for full building air treatment; however, some buildings (including a few hospitals) use HEPA filtration for an entire floor.

There are limited published cost data for HEPA replacement filters; however, many manufacturers claim to offer true HEPA filters. In general, manufacturers seem to be targeting cleanroom and medical applications. Of the numerous companies involved with manufacturing filters, a few of the most notable manufacturers with HEPA filter products for central systems include:

- Airguard (www.airguard.com)
- Camfil Farr (www.camfilfarr.com)
- Flanders Precisionaire (www.flanderscorp.com)
- Healthway Products Inc. (www.healthway.com)
- Koch (www.kochfilter.com)

Detailed cost and performance data and comparisons for various in-duct HEPA filters are in great demand. With more information readily available in the form of websites and other publications, residential and commercial consumers would be able to decide when they require a HEPA filter to replace their standard filter, and which type is best for their application.

Mounted Stand-Alone Systems

Mounted stand-alone HEPA systems are particularly desirable in commercial applications that necessitate high air purity in a specific area or areas. Though the systems are independent of the central HVAC system, they are semi-permanently mounted—that is, they can be removed, but

are not easily portable. These units are mounted on a ceiling, wall, or flush mounted in drop ceilings. They usually incorporate a prefilter, HEPA final filter, and blower; in many cases they also have a sorption stage for odors and other gaseous contaminants.

Natural Solutions, Inc. (www.naturalsolutions1.com) is one manufacturer of mounted HEPA systems that include a gas sorption stage. Their units are designed for room sizes ranging from about 500 to 1100 sq ft, and flowrates between 200 and 2000 cfm. Estimated costs vary with capacity from about $1400-2000. Airguard has similar modules.

3.2 Filters Containing Anti-microbial Agents

3.2.1 Description

Filters containing anti-microbial agents (or biocides) have the advantage over non-treated filters in that they control the captured microorganisms. Such filters are hybrid technologies, employing media filtration for particulate capture, and chemical agents for microorganism destruction. Media filters can also be treated occasionally with chemicals to kill captured bacteria and fungi; however, microorganisms can proliferate on the filters in between treatments. Ideally, filters that incorporate biocides destroy the microorganisms before they have a chance to multiply. In reality, some products can only be counted on for controlling microorganism levels, rather than on total destruction. Figure 3-4 is a simplified diagram showing how a captured microorganism can multiply into a widespread contamination site on an untreated filter. If microbial growth is left unchecked, microbes can then reenter the ventilation airflow. It should be mentioned that some filter media are more susceptible to microbial growth than others. In addition, environmental conditions (in particular, humidity) and system cleanliness are determining factors in whether or not microorganisms will proliferate.

Three of the predominant chemical agents applied to filters are SPOR-AX, INTERCEPT®, and AEGIS. Each of these agents bonds to the filter media, and causes no loss in filter capture efficiency. In addition, a study by the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) found that these chemical agents do not appear to off-gas and do not present special disposal problems.[1] SPOR-AX is used by Fiberbond Corporation, INTERCEPT® is licensed for use by American Air Filter International, and AEGIS is used widely by filter companies such as Koch Filter Corp., American Eco-Systems, Inc., The Air Sponge Filter Company, Air Kontrol, Environmental Products Group, J. Barba, Martin Color Fi, Mountville Mills, Purolator, and Tri-Dim Filter Corp.

[1] Fellman, G., "ASHRAE Study Shows Mixed Results for Antimicrobial Filters," *Indoor Environment Connections Online*, Volume 1, Issue 1, November 1999. www.ieconnections.com/archive/nov_99/1199_article2.htm.

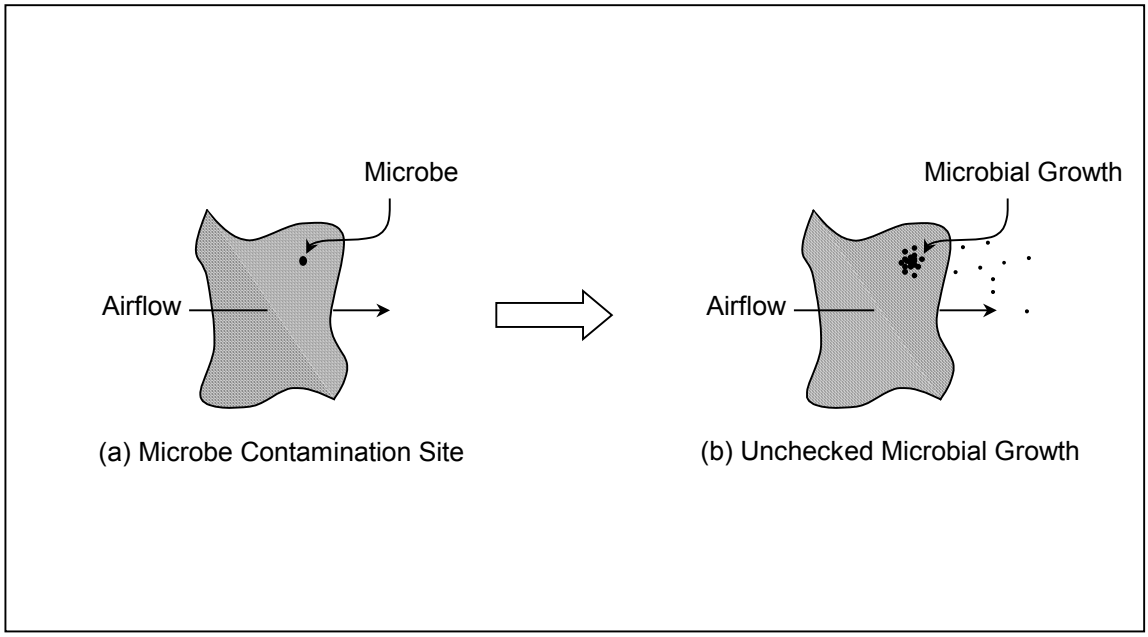


Figure 3-4
Simplistic Illustration of Microbial Growth on a Portion of an Untreated Filter

The majority of anti-microbial filters commercially available appear to have efficiencies ranging from low to medium to high, but they fall short of the true HEPA distinction. However, it is technically feasible to include biocides on HEPA filters as well.

3.2.2 Applications

Anti-microbial agents are capable of treating a wide range of microorganisms, including bacteria, mold, mildew, and yeast. The effectiveness of an anti-microbial filter in controlling these microorganisms depends on the specific chemical agents, as well as on the filter characteristics. Anti-microbial filters are applicable to many end uses, such as residential, commercial, medical, cleanroom, and group living environments.

3.2.3 Developmental Status

The use of anti-microbial agents on filters is fairly well-established; however, there has been controversy over the effectiveness of filters treated in this manner. Only one leading agent was determined by ASHRAE to be reasonably effective at controlling microorganisms on both clean and dusty filters.[1] More research is required to improve the performance of anti-microbial agents, including studies related to the potential for microorganisms to become resistant to biocides. At the same time, newly developed agents must maintain an EPA-approved status.

[1] Fellman, G., "ASHRAE Study Shows Mixed Results for Antimicrobial Filters," *Indoor Environment Connections Online*, Volume 1, Issue 1, November 1999. www.ieconnections.com/archive/nov_99/1199_article2.htm.

3.2.4 Merits and Limitations

Merits

- **Keep Captured Microorganisms Under Control:** While the effectiveness of anti-microbial filters varies with chemical agent, the leading competitors all control the proliferation of microorganisms on filter surfaces to some extent.
- **Long-Lasting:** The three primary chemical agents do not experience a significant loss in effectiveness over the life of the filter they are applied to.
- **Safe to Use:** The biocides are chemically bonded to the filters. The ASHRAE study determined that the chemicals do not appear to enter the airstream, and the treated filters do not require special disposal procedures.

Limitations

- **Do Not Solve Dirty System Problems:** Anti-microbial filters cannot eliminate all microorganisms for HVAC systems that are heavily contaminated. They should be used solely to control captured microorganisms from proliferating on the filter.
- **Controversy Over Effectiveness of Anti-Microbial Agents:** Some experimental results show that the effectiveness of filters treated with anti-microbial agents in preventing microbial growth is limited. More research is required to characterize and to improve the performance of these agents.
- **Limited by Filter Particulate Capture Efficiency:** Anti-microbial filters can only capture particulates as efficiently as the filter design allows. Filters with less than the true HEPA designation may permit the transfer of considerable quantities of microorganisms. If the microorganisms are not captured, the anti-microbial agent cannot destroy them.

3.2.5 Manufacturers and Estimated Costs

As discussed previously, three of the predominant anti-microbial agents are SPOR-AX, INTERCEPT®, and AEGIS. Fiberbond appears to be the exclusive manufacturer of filters treated with SPOR-AX. American Air Filter International licenses the INTERCEPT® agent for use on some of its filter products. The AEGIS agent, though apparently less effective, is the most widely implemented. Filter manufacturers, such as Koch Filter Corp., American Eco-Systems, Inc., The Air Sponge Filter Company, Air Kontrol, Environmental Products Group, J. Barba, Martin Color Fi, Mountville Mills, Purolator, and Tri-Dim Filter Corp. all have used AEGIS on anti-microbial filters.

Standard-sized residential in-duct filters treated with anti-microbial agents are available in sizes varying from 4” by 8” to 4” by 14” for approximately $8 from American Eco-Systems, Inc. (showcase.netins.net/web/ecosys/eco.html). Homeowners can readily install these standard filter replacements by themselves.

Commercial anti-microbial filters from Airguard (referred to as the “Bio-Pure” line) are available in a wide range of sizes—from 10-24” by 20-25” and with thickness from 1-4”. They are pleated panel filters with efficiencies of only 25-30 percent. Costs vary from $4 to $12.

Filter systems that incorporate a prefilter, final filter, and/or gas sorption material are more costly. In addition, the cost of the filter increases with an increase in filter efficiency.

3.3 Electrostatically Enhanced Filtration

3.3.1 Description

There are two basic types of electrostatically enhanced filtration systems. Both families of technologies use electrostatic charges to improve particulate capture. The electrostatic augmentation allows for a higher capture efficiency with a smaller air resistance. The first, most simple, type of system consists of a filter that contains charged, or chargeable, media. The second, which is often referred to as an electronic air cleaner, uses electrostatic precipitation technology to charge and capture particulates. Electronic air cleaners are used either in conjunction with a media filtration stage, or they are used as an alternative to media filtration. The present assessment focuses on charged media filters and electronic air cleaners that incorporate a media filtration element.

Both types of electrostatically enhanced filter technologies are available as in-duct or stand-alone systems. Figure 3-5 shows typical in-duct charged filters (or, electrostatic filters). The difficulty of installation in the ducts of a central HVAC system ranges from straightforward for charged media filters to moderate for electronic devices. Stand-alone units employing charged filters or electronic stages are available in a variety of sizes. In addition, they are either portable or mountable on ceilings and walls. Some electronic cleaners use ductwork much like central systems, but they remain independent of the primary HVAC system.

Charged Media Filters

There are a few types of charged media filters (or, electrostatic filters) on the market. One of the most effective types contains charged electret materials as the filter media. Electrets are polypropylene, propylene, polyethylene, or similar polymer materials that are given both positive and negative charges during manufacture. The charges are very long-lasting, and are often considered to be “permanent.” As air flows past electret filters, oppositely charged particles are attracted to the electret filters.

Other electrostatic filters become charged as air flows through them. These filters are made of materials that are highly prone to becoming statically charged. In some cases, a conventional filter medium is placed adjacent to, and just after, grids of statically-prone material; in others, layers of self-charging media with alternating polarity make up the entire filter. The efficiency of charged filters ranges from low to high, and is also a function of dust load.

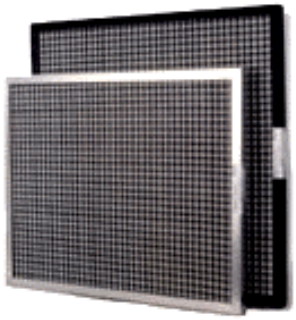


Figure 3-5
BoAir Permanent Electrostatic Furnace Filters with Layers of Polypropylene and Polyurethane

Source: BoAir. Used with permission.

Electrostatic media filters are often sold as permanent filters; but some lesser quality electrostatic filters are disposable. Permanent filters must be cleaned regularly (and disposable filters must be replaced often) to guarantee the effectiveness of the electrostatic charge.

Electronic Air Cleaners

One common configuration for electronic air cleaners for residential and commercial applications consists of two stages: one for charging particulates and one for collecting them. First, the particulates are charged as they pass charging electrodes. The charging electrodes are typically a series of wires to which a voltage has been applied. Then, as the particulates flow through the second stage, they become attracted to a series of grounded collection electrodes. The collection electrodes are metal plates that are oriented parallel to each other, and parallel to the airflow. Figure 3-6 illustrates how charged particles precipitate from the airflow and collect on the grounded plates of electronic air cleaners. The collection efficiency depends on the flowrate, plate surface area, dust-load, and particulate size. The use of media filters in conjunction with the electronic stage improves collection efficiency and slows down the rate of dust accumulation on plate surfaces.

A less efficient configuration that is designed to replace a conventional in-duct filter easily consists of a row of wire electrodes sandwiched between two sheets of fabric mesh material; these inner three layers are then placed between two grounded metal grilles.[1] In this type of cleaner, air flows perpendicular to the collection grid surface, and through the multi-layer system. In a similar manner as discussed previously, electrostatic forces cause charged particulates to collect on the grounded surfaces. Particulates are also captured on the inner media filters.

[1] *Residential Indoor Air Cleaners*, EPRI, Palo Alto, CA: 1992. CU.3042.3.92.

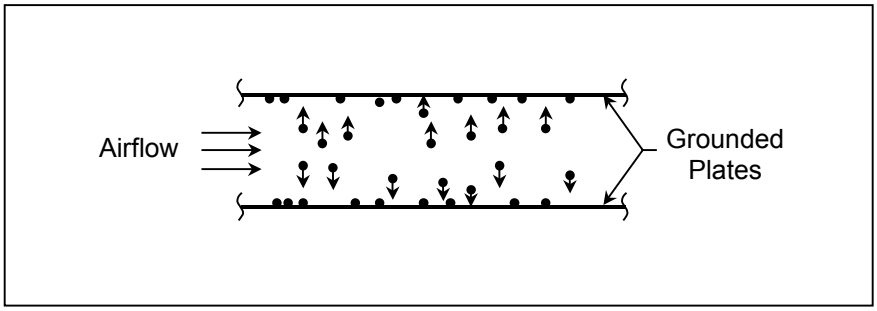


Figure 3-6
Illustration of Particulate Movement During the Collection Stage of a Two-Stage Electronic Air Cleaner

3.3.2 Applications

Electrostatically enhanced filtration technologies are experiencing increased implementation in residential and commercial applications. They have an advantage over HEPA filtration systems in that they do not necessarily require significant HVAC modifications to achieve higher than conventional capture efficiencies. Specifically, they do not increase the pressure drop appreciably; as a result the corresponding fan power (and, hence, energy use) increase is much smaller than for media filters. In addition, if electrostatic systems are combined with HEPA filters, and/or with other air cleaning technologies, overall capture efficiencies are further enhanced.

Electrostatic filters and electronic air cleaners are commercially available as in-duct and stand-alone systems. Depending on the system, they are capable of capturing anywhere from a moderate to a high percentage of microorganisms, allergens, and everyday dust. They are applicable for improving indoor air quality and lowering particulate levels in homes, commercial buildings, medical facilities, nursing homes, prisons, and so on.

3.3.3 Developmental Status

The use of electrostatic forces to capture particulates is well established for indoor air quality and process emission control. Nevertheless, advancements continue to improve the longevity and charging potential of electrostatic filter materials. Furthermore, as the principles of electrostatics are combined in unique combinations with other advanced purification strategies (e.g., HEPA filtration and gas sorption) to produce hybrid systems, the potential for ultra high collection efficiencies increases.

3.3.4 Merits and Limitations

Merits

- **Increase Capture Efficiency:** Electrostatic forces enhance particulate capture. Capture efficiencies of up to 95 percent are common for electrostatic filters. In addition, electronic air cleaners can achieve efficiencies of 95 percent and greater.

- **Low Pressure Drop:** The use of electrostatics to supplement particulate collection enables the use of filters with lower air resistances than would otherwise be required to achieve comparable efficiencies.
- **Simple Installation:** Many electrostatic filters are available in sizes equivalent to standard in-duct filters. These filters can then slide right into the space previously occupied by a standard filter. Furthermore, portable stand-alone systems just require an AC power source. In-duct and mounted systems may require installation by qualified personnel.
- **Long-Lasting:** Pre-charged filters maintain their charge for long periods of time, if not permanently, as long as they are properly cleaned and maintained. Self-charging filters are less effective.
- **Electronic Air Cleaners Produce Ozone:** Ozone is produced during the ionization process used in electronic air cleaners. Although ozone is hazardous at high levels, it may be an advantage for disinfection. Molds and fungus are routinely controlled in refrigerated warehouses in the food industry with ozone at just below the maximum 24 hour exposure limit.

Limitations

- **Require Frequent Cleaning:** Permanent electrostatic filters and the collection surfaces of electronic air cleaners require cleaning about every month. If not properly maintained, the capture efficiency suffers. Maintenance is relatively simple, but depends on the diligence of the operator.
- **Electronic Air Cleaners Produce Ozone:** At high levels, the ozone produced by electronic air cleaners can cause adverse health effects. Fortunately, the levels produced by the types of electrostatic precipitation technologies applied to indoor air quality are typically very low.
- **Electronic Air Cleaners Require AC Power:** Some degree of electrical work may be required to install in-duct electronic air cleaners. However, the power required by these systems is very low.
- **Capture Efficiency Greatly Varies:** Though capture efficiencies for electrostatic systems are often as much as 95 percent or greater, there are many products on the market with low or moderate efficiencies. Consumers must be careful to choose quality products. It is also important to make sure the system is effective for both gram negative and gram positive bacteria, as certain bacteria types are less prone to removal by electrostatic forces.
- **Can Allow Air to Bypass:** Some in-duct electrostatic filters are slightly smaller than optimal for a well-sealed fit. This quality helps with installation ease, but can enable the by-pass of polluted air.

3.3.5 Manufacturers and Estimated Costs

Charged Media Filters

There are numerous manufacturers of electrostatic filters for residential and commercial applications. A few include:

- 3M (www.mmm.com)
- Air Cleaners Inc. (www.airclean.com)
- Airguard (www.airguard.com)
- Air Quality Engineering Inc. (www.air-quality-eng.com)
- Blueair (www.blueair.info)
- BoAir (www.boair.com).
- Cimatec Environmental Engineering Inc. (www.cimatec.com)
- Dust Free (www.dustfree.com)
- Good Filter Company (www.goodfiltercompany.com)
- LakeAir (www.lakeair.com)
- Newtron Products Company (www.newtronproducts.com)
- Pliotron (www.pliotron.com)
- Peak Pure Air (www.peakpureair.com)
- WJS Products (www.acfilters.com)

The cost of electrostatic filters varies greatly depending on many factors, such as efficiency, whether or not the medium is pre-charged or self-charging, filter size, whether it is permanent or disposable, and so on. Disposable, less efficient filters can be purchased for under $10 for a variety of sizes used in residential and commercial applications, while permanent filters can cost in excess of several hundred dollars.

Electronic Air Cleaners

Some of the primary manufacturers of residential and commercial electronic air cleaners are:

- Emerson
- Friedrich
- Honeywell (www.honeywell.com)
- Powrmatic Inc.
- Sharper Image (www.sharperimage.com)
- Smokeeter
- Trion (www.trioninc.com)

Both in-duct and stand-alone electronic air cleaners are significantly more expensive than electrostatically charged filters. Prices begin at about $350 and go to upwards of $800 depending on the size and application. In addition, in-duct systems typically require professional installation. One particular electronic air cleaner called the Ionic Breeze Quadra Silent Air Purifier from Sharper Image sells for about $350. This product is unique in that it uses

electrostatic forces not only to attract particulates to the collection plates, but also to slowly circulate the air. The fan-less electronic linear propulsion technology is proprietary and patented.[1] However, the effectiveness of this product in removing pollutants is questionable.[2,3]

3.4 Media Filtration and Ultraviolet Germicidal Irradiation (UVGI)

3.4.1 Description

UVGI has been used for several decades to destroy contaminants in air, water, and solid waste streams by a process called photolysis. In photolysis reactions, matter decomposes as a result of absorbing incident light.

The entire UV band of wavelengths covers the span of 100 to 400 nm. UVGI is associated with the UV-C range of wavelengths, which is from 100 to 290 nm. Most UVGI systems emit radiation predominantly at 253.7 nm.[4] Wavelengths between about 254 and 265 nm are the most effective for damaging the DNA of microorganisms. UV-B includes mid-range wavelengths of 290 to 320 nm and is responsible for causing sunburn and sometimes cataracts. UV-A, which can cause skin cancer, consists of the longer wavelengths of 320 to 400 nm.

For air purification, UVGI systems are available either as lamps or emitters that are placed in the area to be irradiated, or they are packaged with other air purification strategies (e.g., HEPA filtration, gaseous sorption, etc.) as a multi-stage system. Moreover, systems simply containing lamps and emitters are used for in-duct irradiation to control microbial growth in the HVAC system and distributed air, as well as for direct contamination control in the indoor space. Figure 3-7 shows a UV system designed for in-duct mounting in a residential HVAC system. When used directly in the contaminated room, UV lamps and emitters are usually mounted on the ceiling or walls. Most commercially available multi-stage packaged systems are designed as portable units, but they can also be designed for in-duct placement.

The focus of the current report is on UVGI combined with filtration systems. One common stand-alone system configuration consists of prefiltration to remove larger particulates, HEPA

[1] U.S. Patent # 4,789,801 *Zenion effect technology*.
2 Epinions.com, January 15, 2002, Review of Ionic Breeze Quadra Silent Air Purifier, www.epinions.com/content_52429164164?sp=ink.
[3] Consumer Reports, Feb 2002 issue, Review of Ionic Breeze Quadra Silent Air Purifier.
[4] "Lights, Ultraviolet, Germicidal," *Healthcare Product Comparison System*, ECRI, Plymouth Meeting, PA: May 1999.

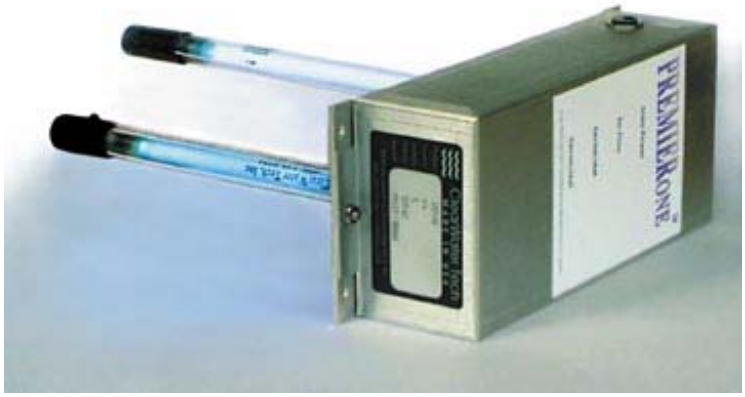


Figure 3-7
PremierOne© Germicidal UV System 300 for In-duct Mounting

Source: Air-Life Environmental.

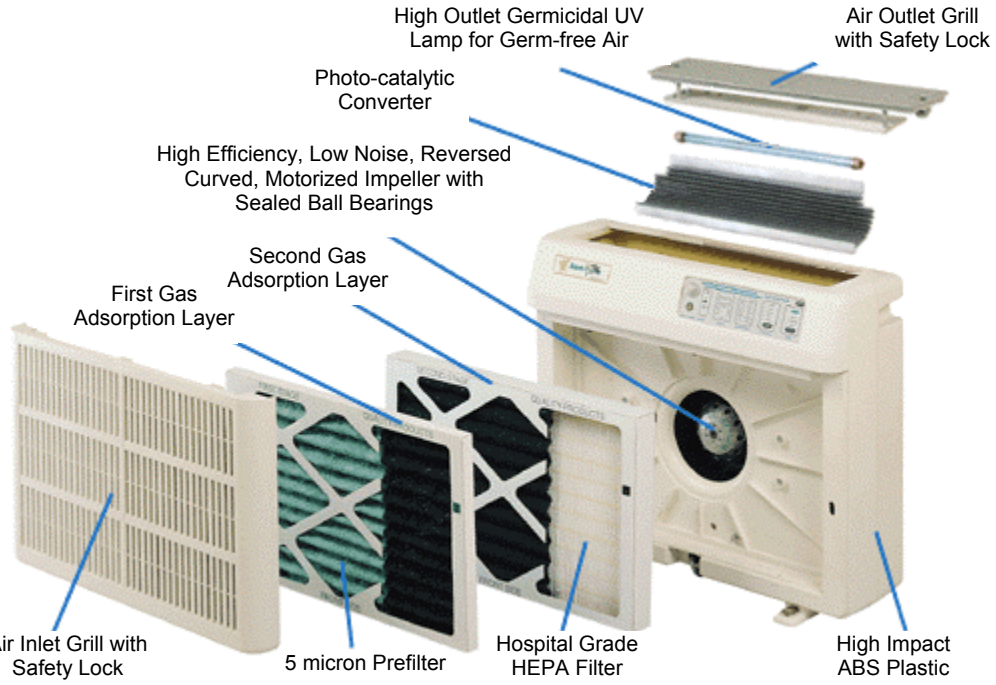


Figure 3-8
Diagram of a Hybrid Air Purification System Employing HEPA Filtration, Gas Adsorption, Photocatalytic Oxidation, and UVGI: Sun Pure Catalytic Air Purification System

Source: Ultra-Sun Technologies Inc. Used with permission.

filtration for fine particulate capture, gaseous sorption for odor and VOC removal, and UVGI for microbial destruction. One system on the market also incorporates a photo-catalytic oxidation stage, as shown in Figure 3-8. Photo-catalytic oxidation is an advanced oxidation process that employs catalytic surfaces to enhance the generation of powerful hydroxyl radicals that in turn oxidize pollutants. Photo-catalytic systems typically use UV radiation to produce hydroxyl radicals from water and/or oxygen, on the catalyst surface at active sites, and the free radicals initiate the oxidation of contaminants. The reactions are more productive in the presence of the catalyst. UV radiation can also be used to generate ozone, which in turn destroys pollutants via oxidative reactions. However, only systems that combine filtration with direct decomposition of contaminants by UVGI are included herein.

3.4.2 Applications

UVGI is not a new technology. UV lamps and emitters have been used extensively for industrial pollution control, as well as in specialized applications such as healthcare and laboratories. However, packaged systems containing filtration and UVGI stages are relatively new. In the last twenty years or so there has been a resurgence in the use of UVGI to control contaminants in the healthcare field. Of particular interest is its use for the destruction of Mycobacterium Tuberculosis (TB) organisms. Because of this increased interest, more hybrid UVGI systems have become available for the healthcare field. These hybrid systems are also widely applicable for controlling the spread of any type of disease in places such as personal residences, offices, commercial buildings, prisons, daycares, nursing homes, and shelters.

3.4.3 Developmental Status

As mentioned earlier, the use of UVGI lamps and emitters for air purification is well established for the healthcare industry and many industrial and commercial applications. However, hybrid systems employing filtration and UVGI have only become popular in the last decade. In addition, most of their application has been in hospitals, TB wards, and laboratories. A few systems designed for residential and commercial buildings are now on the market, but there is still a large potential for both technological refinement and market growth. Greater concern over biological warfare should act as an impetus for further development.

3.4.4 Merits and Limitations

Merits

- **UVGI Destroys Microorganisms:** The principal advantage of UVGI is that it can destroy microorganisms by causing DNA damage.
- **Hybrid UVGI and HEPA Filtration Systems Are More Reliable:** When combined with HEPA filtration, the reliability, and hence, the effectiveness of each individual technology is enhanced. HEPA filtration captures at least 99.97 percent of the microorganisms, while UVGI kills additional microorganisms and helps control microbial growth within the system.
- **Hybrid Systems Tend to be Safer Than Direct Irradiation:** Direct irradiation of a space by UV lamps can have health implications to room occupants and maintenance personnel

(see "limitations" below). Hybrid stand-alone systems that re-circulate the air and irradiate it within the system tend to shield occupants from the irradiation.

- **UVGI Helps Keep HVAC Systems Clean:** UV lamps and emitters placed within HVAC ducts help prevent microbial growth on coils, duct surfaces, and filtration equipment in addition to irradiating the air that is distributed by the system.

Limitations

- **UVGI Can Have Health Effects:** There is evidence that long-term exposure to high-intensity UVGI can result in health effects, such as conjunctivitis and erythema (which is painful skin reddening). If long-term high-intensity exposure is unavoidable, protective clothing must be worn. Exposure is reduced by the use of shielded stand-alone units, in-duct systems, or properly baffled upper room UVGI installations.
- **Stand-alone Units Can Cause Noise and Discomfort:** In the case of TB, a stand-alone HEPA filter or UVGI system depends on circulating air through the device using a fan. As mentioned previously for HEPA filters, noise is a problem because of the fan. Comfort is also a limitation. In a room with a patient with active TB, the concentration of droplet nuclei is so high that the device would have to achieve many air changes or turnovers per hour, and the draft thus engendered would make the room seem like a wind tunnel.
- **UVGI Can Damage Interior Items:** UVGI can cause fading to fabrics and paints. It can also harm plant cells.[1]
- **The Effectiveness of UVGI Depends on Several Factors:** The level of microbe destruction is dependent on a variety of factors, such as room configuration, airflow patterns, irradiation intensity, and dust accumulation. Care must be taken to properly orient a hybrid UVGI and filtration system within the room to yield effective air circulation through the unit. The level of irradiation required for the contaminant level of the space must also be determined. Further, as with all air purification systems, the system must be well maintained, including cleaning of the lamps and filter cleaning or replacement at appropriate intervals.

3.4.5 Manufacturers and Estimated Costs

Portable Units

Several manufacturers have portable hybrid filtration and UVGI systems on the market. The products from five manufacturers are discussed here and summarized in Table 3-4. Cost estimates are based on the list prices from various distributors and/or from manufacturers. In general, initial costs vary from about $0.40 to $4 per square foot of floor area, depending on the room size in which the systems are used, the number of air changes per unit time desired, and on the level of contamination.

[1] Hitchings, D. T.,"Preventing Transmission of Tuberculosis in Health Care Facilities: An Engineering Approach," ASHRAE Hospital Design and Operations Conference Proceedings, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc., Triangle Chapter, Durham, NC: 1995, www.safelab.com.

Table 3-4
Cost Estimates for Hybrid Filtration and UVGI Systems

Manufacturer Product Name	Technologies Incorporated	Targeted Applications	Initial System Cost	Replacement Costs
Natural Solutions AllerAir 5000 AllerAir 6000 AllerAir 8000	• Prefiltration • True HEPA filtration • Gas removal with coconut shell carbon and zeolite media • UVGI	• Residential • Commercial • Medical environments • Microorganisms control • Miscellaneous particulates	$600-1400	• $100-200 for HEPA (every 3 to 5 years) • $100-200 for UV lamps (every 10,000 hr) • $100-200 for sorption media (every 1 to 3 years) • $20-50 for four-pack of prefilters
C.A.R.E. 2000 C.A.R.E. 2000 PC C.A.R.E. 2000 BC C.A.R.E. 2000 ADS	• Pre- and Post-filtration • True HEPA filtration • Carbon adsorption • UVGI	• Residential • Commercial • Medical environments • Microorganisms control • Miscellaneous particulates	$600-1200	• $120 for HEPA (every 3 to 5 years) • $90-180 for UV lamps (yearly) • $120 for sorption media (every 1 to 2 years) • $30 for set of pre- and post-filters (every 1/2 to 1 year)
NQ Environmental NQ200 NQ320 NQ400 NQ500 NQ720 NQ1000 NQ2000	• Prefiltration • True HEPA filtration • Carbon adsorption • UVGI	• Commercial • Medical environments • Microorganisms control • Miscellaneous particulates	Healthcare grade systems start at about $3000	Not specified
Ultra-Sun Technologies Sun Pure SP-20C	• Prefiltration • True HEPA filtration • Carbon adsorption • UVGI • Photo-catalytic oxidation	• Medical clean rooms • Portable classrooms • Assisted living facilities • Residential	$1000	• $100 per year for filter and UV lamp
Hamilton Beach 4160 4161 4162	• Carbon prefilter • HEPA filtration • UVGI	• Residential • Small offices	$160-200	• $50 for HEPA (yearly) • $8 for UV lamps • $8 for carbon prefilter

				prefilter

Natural Solutions, Inc. (www.naturalsolutions1.com) has three UV products referred to as the AllerAir 5000, AllerAir 6000, and AllerAir 8000. These portable units include prefiltration, true HEPA filtration, gas removal with coconut shell carbon and zeolite media, and UV radiation at 254 nm. The AllerAir 5000 system is for residential applications and covers areas between about 150 and 1500 sq ft. The AllerAir 6000 and 8000 are for more heavy-duty commercial applications. Prices for the AllerAir systems range from about $600 to $1400, depending on the model. In addition, 10,000 hr UV lamps range from about $100 for standard UV lamps to $200 for medical grade UV-C lamps. HEPA filter replacements cost between $100 and $200, and last 3 to 5 years. The gas adsorption medium also costs between $100 and $200, and must be replaced every 1 to 3 years. A four-pack of prefilters ranges from $20 to $50.

C.A.R.E. 2000 has three portable systems that incorporate UVGI. Each system includes pre- and post-filtration, HEPA filtration, carbon adsorption, and UVGI. The smallest system is suitable for residential and small commercial applications, and the larger two systems are for hospitals and other applications requiring greater microbial control. Costs range from about $600 to $1200. In addition, HEPA filter replacements cost roughly $120 and are needed every 3 to 5 years. A two-pack of UV lamps is about $90, and the lamps usually need to be replaced yearly. The small and mid-size systems use two pairs of UV lamps, and the large system uses four pairs for extra germicidal protection. The carbon filter, which lasts between 1 and 2 years, costs about $120. Lastly, a set of pre- and post-filters costs on the order of $30 every 6 months to 1 year.

NQ Environmental Inc. (www.nqinc.com) offers several portable systems that use HEPA filtration, carbon adsorption, and UVGI. The NQ Commercial Clarifier is for offices and commercial applications. The NQ-200, -320, -400, -500, -720, -1000, and -2000 are specifically designed for healthcare and similar applications. Depending on the system, they use between two and eight 22” long UVGI lamps. Prices for the healthcare grade systems start at roughly $3000.

Ultra-Sun Technologies Inc. (www.ultrasun.com) has a portable system called the Sun Pure SP-20C that combines prefiltration, HEPA filtration, gas sorption, UV, and photo-catalytic oxidation (see Figure 3-8). It is designed for medical isolation rooms, portable classrooms, assisted living facilities, and residential applications. The list price for this system is about $1000, and it requires an average of about $100 per year for replacement of the UV lamp and filter. The SP-20C also contains infrared and chemical sensors for regulating the equipment and for giving a visible indication when VOC and carbon monoxide levels are abnormally high. Moreover, the on-board computer lets the operator know when the system is in need of service.

Hamilton Beach has three small hybrid systems consisting of true HEPA filtration, carbon impregnated prefilters, and UV irradiation. They are applicable for small rooms and offices. The systems cost between about $160 and $200. The main filter requires yearly replacement at a cost of about $50. Additional carbon filters and UV lamps are each around $8.

In-Duct Systems

Pureatech Inc. (www.pureatech.com) has a product for in-duct use called the Pureatech™ Air Treatment System (PATS), which is placed on the return air plenum of an HVAC system. The PATS system combines three pollutant control strategies. In the first stage, a media filter with

MERV rating of 8 at three microns (see Table B-1) captures larger particulates. In the second stage, 254 nm UV light destroys microorganisms and oxidizes gases. In the third stage, an activated carbon filter adsorbs gases. As of this writing, the company is only 2 ½ years old and has primarily focused on residential applications. However, Pureatech recently installed the PATS system in a hospital in New York.[1] The costs for the systems are very application dependent, and Pureatech was reluctant to provide detailed cost information. In general, installation of a single system in a typical home ranges from $3500 to $4500. Larger homes and commercial buildings require more units and perhaps customized solutions. Therefore, the costs would increase accordingly.

Ultra-Sun Technologies Inc. (www.ultrasun.com) also has an in-duct system (SP-200) with electrostatic filtration, UVGI, and photo-catalytic oxidation on the market for $1350. This system is designed for whole-home purification.

UVGI Without Filtration

There are also a wide variety of UVGI systems that do not directly incorporate a filtration stage. These systems cost on the order of $100 to $200 for ceiling mounted systems, $500-$800 for wall mounted units, $300 to $700 for duct-mounted units, and upwards of several thousands of dollars for stand-alone floor systems.[2] The following is a list of a few representative manufacturers of UV-only systems:

- Air-Life Environmental (www.airlife.com)
- American Ultraviolet Co. (www.americanultraviolet.com)
- Atlantic Ultraviolet Corp. (www.atlanticuv.com)
- Honeywell (www.honeywell.com)
- Lumalier (www.lumalier.com)
- Peak Pure Air (www.peakpureair.com)
- Spectronics Corp. (www.spectroline.com)
- Steril-Aire Inc. (www.steril-aire-usa.com)
- UltraVation (www.ultravation.com)

3.5 Media Filtration and Gas Sorption

3.5.1 Description

Gas sorption materials can be used to remove odors, VOCs, and other gaseous contaminants from the indoor air. In many cases, they are combined with media filtration to allow for both gas phase and particulate capture. Three basic processes are employed for gas sorption, namely

[1] Personal communication with Dwayne Bassett, Director of Marketing, Pureatech, Inc.
[2] "Lights, Ultraviolet, Germicidal," *Healthcare Product Comparison System*, ECRI, Plymouth Meeting, PA: May 1999.

adsorption, chemisorption, and absorption. The most widely used process is adsorption. In adsorption, gas molecules adhere to the surface of a solid sorbent. Generally, the sorbents are designed to have very large surface areas so that they can capture a large quantity of gaseous pollutants. One of the most common adsorbent materials is activated carbon. Activated carbon is made by the destructive distillation of the non-carbon materials in wood, coconut shells, etc. This leaves a carbon material with very small pores and large surface area available for adsorption. Other adsorption materials include activated alumina, zeolite, clay, and silica gel.

Chemisorption is another type of adsorption process; however, with chemisorption, a chemical bond forms between the gas molecules and solid sorbent surface. It can be thought of as adsorption by chemical rather than physical forces. Chemisorption can occur either with the main sorbent material, or with a sorbent material that has been treated or impregnated with other reactive reagents. Multi-sorbent materials are designed in such a way as to capture specific targeted pollutants by chemisorption and physical adsorption.

Absorption occurs when gas molecules penetrate, or dissolve, into a liquid or solid material. In contrast to adsorption, absorption is considered a bulk material process, rather than a surface process. Generally absorption is not used in indoor air quality applications. However, its use is quite prevalent in industrial emission control.[1]

The effectiveness of gas sorption is less quantified than that of particulate capture technologies. However, it is clear that the collection efficiency of gases depends greatly on their length of exposure to the sorbent material, which is a function of both airflow rate and the amount of sorbent. Other aspects influencing capture efficiency include sorbent characteristics (e.g., type, quantity, configuration, depth, and available surface area), environmental conditions (e.g., temperature and humidity), and gaseous contaminant characteristics (e.g., types and concentrations).

Two of the most prevalent forms of sorbent material are powders and granular pellets. Both forms enable easy mixing of various sorbent types. The granular pellets are usually used in beds with depths on the order of inches. Often multiple beds of this type are installed for optimum exposure to the sorbent. Powdered forms are directly incorporated into fibrous media filters. The resulting hybrid filters capture particulates and gaseous constituents. Figure 3-9 shows a typical carbon impregnated media filter designed for hospitals, industrial plants, and residential use from Bon-Aire Filters, Inc. (www.bon-airefilters.com). The current work focuses on hybrid filters and on hybrid systems that incorporate both particulate filtration and gaseous sorption. Hybrid filters and hybrid systems are available both as in-duct units and as stand-alone systems.

3.5.2 Applications

Technologies that combine particulate filtration and gas sorption are applicable to the industrial, commercial, and residential sectors. They are particularly well suited for end uses that have

[1] *Air Pollution Control Systems for Stack and Process Emissions*, EPRI, Palo Alto, CA: 2001. 1001438.

Figure 3-9
Bon-Aire Activated Carbon Impregnated Non-Woven Polyester Filter

Source: Bon-Aire Filters, Inc. Used with permission.

odorous indoor air or hazardous gaseous contaminants. Sorption has long been used in industry to control gaseous emissions, and has experienced a considerable amount of use in commercial applications that yield high concentrations of vapors and gases, such as hair and nail salons, and dry cleaners. Their application to residences and office buildings is newer, but will likely increase. Gas sorption can also help mitigate vapors and gases that arise from construction and renovation processes. For example, adhesives, building materials, carpeting, paints, and upholstery all produce gas phase emissions that contaminate indoor living environments.

3.5.3 Developmental Status

The effectiveness of gas sorption technologies in controlling indoor gaseous contaminants is less well known than that of other indoor air cleaning technologies. The physical and chemical interactions between sorbents and gas molecules are complex. Therefore, a greater understanding is required before the performance of sorbents for capturing a wide range of gaseous contaminants is well quantified. Nevertheless, there are many commercially available products that employ the combination of media filtration and gas sorption.

3.5.4 Merits and Limitations

Merits

- **Capture Gas Phase Contaminants:** The addition of gas sorbents to air filters and/or air purification systems enables the collection of gaseous contaminants, such as odors and VOCs.
- **Form Factor Allows for Control of Multiple Gas Types:** The granular and powdered forms allow more than one type of sorbent to be combined with relative ease. Moreover, sorbents can be impregnated with reactive reagents to target specific contaminants, such as formaldehyde.

- **Simple In-Duct Hybrid Filters Require No Modifications:** Hybrid filters containing sorbent material bonded to media fibers can replace conventional filters with no HVAC modifications. Such systems usually perform best for odor removal, rather than for VOC control.
- **Well Suited for Hybrid Stand-alone Systems:** There is an obvious fit between gas sorption materials and stand-alone filtration systems. By implementing sorbent-impregnated media filters as a prefilter or final filter stage, or sorbent beds as an additional cleaning stage, hybrid systems can control both particulates and gaseous contaminants without much design complexity in a stand-alone system. In fact, many hybrid filtration systems incorporate some degree of sorption.

Limitations

- **Sorption Processes are Not Well Characterized:** For indoor air purification applications, there are relatively little data to quantify the effectiveness of particular systems. Moreover, a greater understanding of the physical and chemical processes affecting gas collection is required for optimum system design.
- **Systems Vary Considerably:** Some products claiming to control gaseous contaminants really only work well for large odorous molecules. Others are capable of collecting a wide variety of hazardous gas molecules.
- **Sorption Rate Reduces with Loading:** As the sorbent becomes loaded with gas molecules, the effective surface for sorption is diminished. Therefore, sorbents require replenishment on an on-going basis to be effective.

3.5.5 Manufacturers and Estimated Costs

Many manufacturers of hybrid air purification systems incorporate a gas sorption stage. Some systems employ a hybrid sorption/media filter, while others use beds of granular adsorbent. The level of sorbent capacity varies greatly from product to product. Table 3-5 compares the approximate cost ranges and quantities of sorbent material used by manufacturers in several commercial portable air cleaners. Cost estimates are from manufacturers and/or distributors.

Other manufacturers of stand-alone systems with filtration and gas sorption include:

- Amaircare (www.amaircare.com)
- Austin Air Systems Limited (www.austinaircleaners.com)
- Hamilton Beach
- Healthway Products Inc. (www.healthway.com)

Table 3-5
Cost Estimates and Sorbent Quantities for Portable Hybrid Filtration and Gas Sorption Systems

Manufacturer	Technologies Incorporated	Quantity of Sorbent[a]	Initial System Cost	Replacement Costs

	Incorporated	Sorbent[a]	Cost	
Austin Air Systems (www.austinaircleaners.com)	• Prefiltration • True HEPA filtration • Activated carbon/zeolite	~8-15 lbs, depending on model	$250-500 (~$0.30 to $3 per sq ft of floor area)	• $100-250 for HEPA/sorption filter (every 5 years) • $20-25 for prefilters
Blueair Inc. (www.blueair.info)	• HEPA (not true) particle filter • Electrostatic filter • Carbon	• ~3.7 lbs for particle • ~5.7 lbs for smokestop	$380-500 (~$1 per sq ft of floor area)	• $50-80 every 6 months for particle filter • Sorbent cost not specified
C.A.R.E. 2000	• Pre- and Post-filtration • True HEPA filtration • Carbon • UVGI	~15 lbs	$600-1200 (>$0.50 per sq ft of floor area)	• $120 for HEPA (every 3 to 5 years) • $90-180 for UV lamps (yearly) • $120 for sorption media (every 1 to 2 years) • $30 for set of pre- and post-filters (every 1/2 to 1 year)
Friedrich	• Prefiltration • Electrostatic Precipitator • Carbon	~6 oz of mesh carbon	$450 (~$1 per sq ft of floor area)	Not specified
IQAir (www.iqair.com)	• Prefiltration • True HEPA filtration • Carbon	~5 lbs for HealthPro Plus	$600-1500, depending on system (~$0.60 to $1 per sq ft of floor area)	• $190-290 for HEPA (every 2 to 5 years) • $55-130 for prefilter (every 6 months to 2 years) • Sorbent cost not specified
Ultra-Sun Technologies, Inc. (www.ultrasun.com) Sun Pure SP-20C	• Prefiltration • True HEPA filtration • Carbon • UVGI • Photo-catalytic oxidation	~7 oz of carbon	$1000 (Cost per sq ft of floor area is not available)	• $100 per year for filter and UV lamp • Sorbent cost not specified

[a] Carbon quantities compiled from www.promolife.com/products/air1.htm.

- Natural Solutions, Inc. (www.naturalsolutions1.com)
- Newtron Products Company (www.newtronproducts.com)
- NQ Environmental Inc. (www.nqinc.com)

- Peak Pure Air (www.peakpureair.com)
- Purafil Inc. (www.purafil.com)

Specifically, Purafil Inc. has a new product called the Shelter in Place (SIP) system that is designed for mitigation of biological and chemical agents in the event of an attack. The system has been featured on CNN Headline News and in USA Today. It is intended to prevent external contaminants from entering a protective space. Although more complex, it also has the potential to be designed in such a way as to shelter an entire floor or series of floors if an internal attack takes place on another floor. It is a portable system that uses five stages of air purification, namely prefiltration, true HEPA filtration, sorption by blended media, sorption by impregnated carbon, and post-filtration. According to Purafil's website, BlueCross BlueShield (BCBS) recently purchased two SIP systems for use in the BCBS facility's data center.[1] The systems will be used for protecting staff and their main computer room from terrorist attacks.

[1] "Purafil sells two Shelter In Place units to BlueCross BlueShield," statement on their website, www.purafil.com/public/buildingprotection.htm.

4
ASSESSMENT OF TECHNOLOGIES IN RESEARCH AND DEVELOPMENT STAGE

This chapter assesses air purification technologies in the research and development stage. The focus is on new types of purification technologies that combine media filtration with another purification technology or where the filtration media have been vastly improved. Thus, this chapter excludes technologies that use new designs of existing types of filtration media. The following four sources of information were instrumental in determining what air purification technologies to include:

1. The Environmental Protection Agency (EPA) Small Business Innovation Research (SBIR) Awards for air filtration technologies;

2. Air filtration patents awarded by the United States Patent and Trademark Office (USPTO) between January 1, 2000 and September 23, 2002;

3. Air filtration patent applications submitted to USPTO between January 1, 2000 and September 23, 2002;

4. Guidance on new and emerging air purification technologies from the industry experts that participated in this report.[1]

The first source is the EPA's SBIR Awards. The SBIR Program provides financial support to help small science- and technology-based firms develop new environmental technologies and ready them for commercialization.[2] On its website, the EPA provides a listing of companies awarded contracts between 1989 and 2002. From this listing, three types of air purification technologies for residential and commercial applications were identified: electrostatically enhanced filter with plasma sterilization, nanoporous filter, and nanofibrous filter. These three technologies were added to the initial list of new and emerging air purification technologies in the research and development stage.

The second source is the USPTO patent database.[3] A search in this database for new air filtration patents awarded between January 1, 2000 and September 23, 2002 resulted in a return of approximately 100 patents. However, many of these patents were for filters in vehicle, power plant, and industrial applications. Many patents also were for new designs of existing types of media filters. Based on the selection criteria, two new patents were selected for the initial list of

[1] Myron Jones, John Kesselring, and Mukesh Khattar, formerly project managers at EPRI.
[2] EPA's Small Business Innovation Research (SBIR) Program, http://www.epa.gov/ncerqa/sbir
[3] U.S. Patent and Trademark Office, Patent Full-Text and Image Database, http://patft.uspto.gov/netahtml/search-adv.htm

new and emerging air purification technologies: an anti-microbial filter containing iodine and a biomagnetic filter.

The third source is the USPTO patent application database.[1] A search in this database for new air filtration patent applications submitted between January 1, 2000 and September 23, 2002 resulted in a return of approximately 50 new patent applications. However, none of these fit the selection criteria, and were therefore not selected.

The fourth source is a group of industry experts that worked closely with the project team. This group provided on-going guidance, including input on what emerging air purification systems to select. Based on their experiences with air purification technologies, the biomagnetic filter was removed from the initial list because it showed a rather low capture efficiency (about 96 percent) compared to other filters currently on the market.[2] The iodine filter was also removed from the initial list because this filter is already commercially available and therefore did not fit the selection criteria for filters in the research and development stage.[3] In addition, the iodine filter shows only modest capture and kill efficiencies compared to other anti-microbial filters currently on the market.[4] Table 4-1 summarizes some of the main characteristics of the three new and emerging air purification technologies selected.

4.1 Electrostatically Enhanced Filter with Plasma Sterilization

4.1.1 Description

Atmospheric Glow Technologies (AGT) is developing the Enhanced Plasma Sterilized (EPS™) filtration system. The company has two patents on the technology and has one patent pending.[5,6,7] AGT has also exclusively licensed six patents on the "One Atmosphere Uniform Glow Discharge Plasma" technology from the University of Tennessee Research Corporation.

Chapter 3 discussed how an electrostatic field improves the filter capture efficiency, especially for small particles. The EPS filtration system first uses a continuous, positive DC field—applied across the filter—to increase the particulate capture ability of the filter. Thereafter, the EPS filtration system uses plasma to kill the microorganisms captured by the filter.

[1] U.S. Patent and Trademark Office, Patent Application Full-Text and Image Database, http://appft1.uspto.gov/netahtml/PTO/search-adv.html.
[2] U.S. Patent # 6,383,264 *Biomagnetic filter*.
[3] The iodinated air filter is developed and sold by Aria Pureair Ltd. of Canada under the name ARIA 300, www.ariaair.com.
[4] U.S. Patent # 6,190,437 *Iodinated air filter*.
[5] U.S. Patent #6,245,132 *Air filter with combined enhanced collection efficiency and surface sterilization.*
[6] U.S. Patent #6,245,126 *Method for enhancing collection efficiency and providing surface sterilization of an air filter.*
[7] U.S. Patent Application #60/326,189 *Rapid sterilization of an air filter downstream by exposure to reactive oxidative species generated from an atmospheric plasma mechanism located upstream.*

Table 4-1
Main Characteristics of Air Purification Technologies in Research and Development Stage

Technology	Primary Function	Main Merits	Main Limitations	Developmental Status
Electrostatically enhanced filter with plasma sterilization (EPS™)	To increase filter capture efficiency with electrostatic forces and kill microorganisms captured with a plasma	• Allows non-HEPA, low-pressure drop filter to be used while still capturing a high percentage of microorganisms, which results in less energy consumption • High kill efficiency • Sterilizes filter for easy and safe disposal	• Capture efficiency is not as high as the capture efficiency of HEPA filters • Potentially high cost may prohibit integration in residential and commercial buildings • System generates 4 ppm of NOx which is slightly higher than acceptable limits	Filter system recently installed in first real-life demonstration
Nanofibrous filter	To increase filter capture efficiency without any increase in filter pressure drop	• Higher filter capture efficiency than HEPA filter but with only a modest (or no) pressure drop increase • Estimated to cost about the same as a HEPA filter	• Does not kill microorganisms • No test results available to confirm the capture efficiency and pressure drop claims	• Filters for industrial applications are available (Donaldson) • Filters for commercial applications are still under development (Donaldson, eSpin, Inframat)
Nanoporous filter	To increase filter capture efficiency without any increase in filter pressure drop	• High filter capture efficiency • Low pressure drop	• Does not kill microorganisms • No test results available to confirm the capture efficiency and pressure drop claims • No cost data available	Under development

Two specially formulated metallic electrodes and high-voltage, high frequency electrical currents generate a controlled electric field. This field disrupts exposed atmospheric molecules to create plasma and highly reactive oxygen species. The EPS system generates the plasma in air under standard pressure and at ambient temperature. Thus, the sterilization process requires neither a vacuum nor a non-atmospheric gas, such as compressed helium or argon. Exposing the filter to plasma sterilizes the filter, which makes it easy and safe to dispose of later and more importantly it prevents microbial buildup and dissemination. In general, the filter needs to be replaced every two to three months. The EPS filtration system is a modular system that can be inserted into any indoor HVAC system, as illustrated in Figure 4-1.

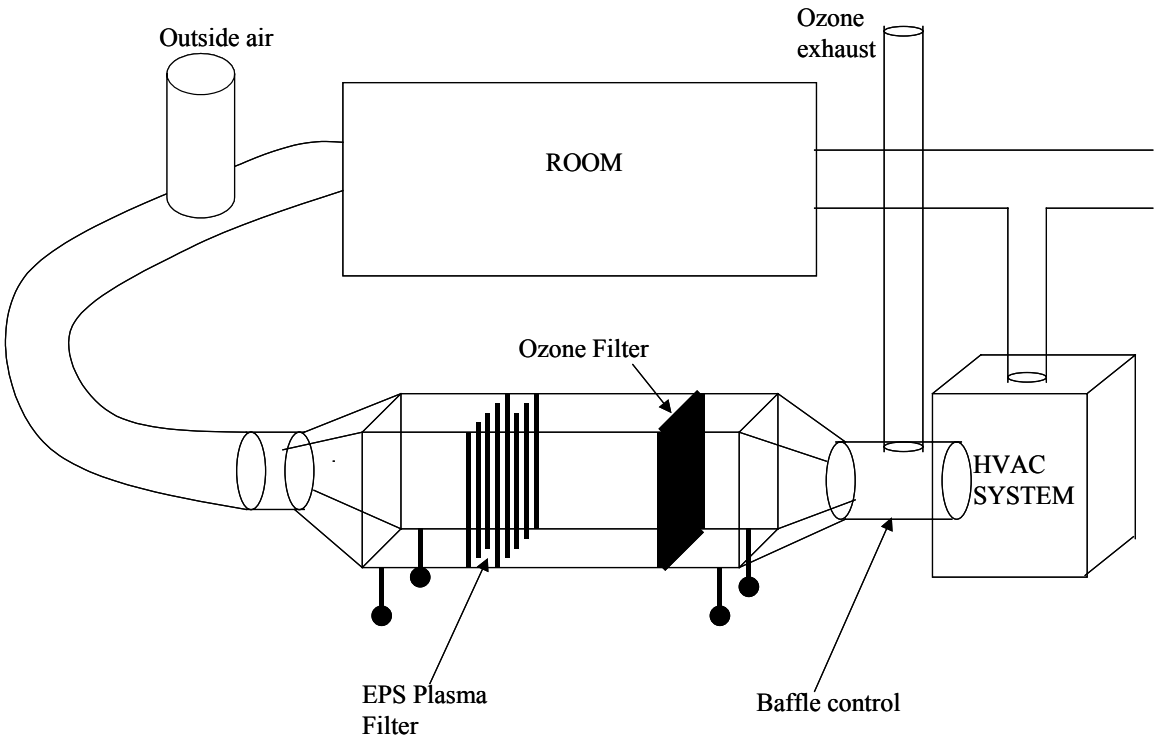


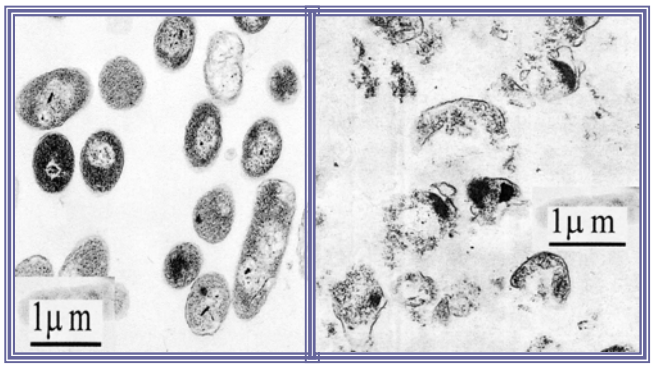
Figure 4-1
Concept of the Electrostatically Enhanced Filter with Plasma Sterilization (EPS System)

Source: Atmospheric Glow Technologies. Used with permission.

Ozone, the highly reactive oxygen, which is six orders of magnitude more reactive than oxygen, deactivates bacteria, viruses, and biological and chemical warfare agents, such as Sarin, Smallpox, Mustard Gas, and Anthrax. Figure 4-2 shows how E. coli bacteria are deactivated after 30 seconds of exposure to the plasma. The highly reactive oxygen disrupts the membrane of the bacteria, which renders them harmless. AGT has conducted several tests, in-house, of the EPS systems' kill efficiency. These experiments show that the kill efficiency of the EPS system is 99.9999 percent.[1] In general, the plasma is generated intermittently; one to two times a day and for one to five minutes. The periodic application of the plasma is primarily for biocontaminants.

[1] Atmospheric Glow Technologies' submittal to a 100R&D award.

Test data from AGT indicate that to deactivate biocontaminants, it is sufficient if the EPS system generates plasma about 5 minutes per day. For chemical agents, however, the plasma must run continuously. Such a system would likely dictate the necessity of a sensor.



(a) (b)

Figure 4-2
(a) E.coli Before and (b) After 30 seconds of Exposure to the Atmospheric Plasma

Source: Atmospheric Glow Technologies. Used with permission.

The Oak Ridge National Laboratory has safety-tested the EPS system.[1] This safety test included testing for the presence of nitrogen- and oxygen-based gaseous by-products. The testing was also intended to evaluate the compliance of this system relative to OSHA and EPA regulations. The test showed that the EPS filter system generates 4 ppm of NO_2 for the entire filter, which is slightly higher than acceptable limits. AGT, however, states that the current design of the EPS system does not place plasma on such a large area of the filter at once, and therefore the new filter is within acceptable emission level limits for NO_2. The Oak Ridge National Laboratory did not have the necessary equipment to test for the ozone (O_3) concentrations.

4.1.2 Applications

The EPS filtration system is a modular system that can be placed into an indoor HVAC system if a section of the duct is cut away. Initially, AGT will target facilities sensitive to indoor air quality, such as government and military buildings, hospitals, and assisted living centers, with a premium-priced, highly featured system with automated controls and extra-potent killing ability. Thereafter, AGT will address the more cost-sensitive markets, such as office buildings, schools, daycare centers, museums, and libraries, with a low-featured economical system.

4.1.3 Developmental Status

The EPS filtration system is in its demonstration phase. So far, the ESP filtration system has been installed in one building, which consists of research laboratories and office space (EPRI-PEAC in Knoxville, Tennessee). This demonstration unit has a two-by-two-foot filter and a five-

[1] Oak Ridge National Laboratory Safety Test Report, Testing Performed for Atmospheric Glow Technologies, January 3, 2002.

ton HVAC system, which is approximately equivalent to a capacity of purifying the air in a 2,000 square-foot space. The duct of the conventional HVAC system was modified to incorporate the EPS filter. The system is set up in such a manner that heating and cooling is fully functional without the filter operating. The purpose of this unit is to be in a full-scale operating mode and to take the environment as it is. The intent is to test each day for room indoor air quality, collection on the EPS filter, and the quality of the processed air being discharged into the space. It is not expected, however, that the selected building will have any unique air quality problems. Test data collection will start in early November 2002.

AGT is also negotiating with several federal agencies for placements of more demonstration units in real-life settings. The company expects to have a few more demonstration units installed in various building types by the second quarter of 2003.

After successful demonstration and testing, the next step will be commercialization of the technology. AGT is currently developing marketing and sales plans. Their first customer target will be government buildings, followed next by commercial buildings, and then by residential buildings.

AGT is currently developing a floor air purifier for homes. The floor air purifier uses the same technology as the EPS filtration system but will be simpler and cheaper.

4.1.4 Merits and Limitations

Merits

- **Increase Filter Capture Efficiency:** Electrostatic forces enhance the particulate capture of the filter. The capture efficiency of the EPS filtration system is 99.9 percent, which has been validated by an independent third party.
- **Allows Inexpensive Non-HEPA, Low-Pressure Drop Filter to be Used:** The increased capture capabilities due to the electrostatic field allow the use of inexpensive non-HEPA, low-pressure drop filters.
- **High Kill Efficiency:** The kill efficiency of the EPS filtration system is very high at 99.9999 percent. It is important to remember that this is the kill efficiency for those particles that have been captured by the filter. Some microorganisms, however, will pass through the filter.
- **Sterilizes the Filter for Safe and Simple Filter Replacement:** The EPS filtration system destroys all microorganisms throughout the filter media. Since the plasma sterilizes the filter, the filter requires no special handling when replaced. Moreover, sterilization of the filter prevents microbial growth and dissemination.
- **Fast Sterilization Process:** The sterilization takes place once or twice a day, and lasts only a few minutes.
- **Low Energy Consumption:** The use of a non-HEPA, low-pressure drop filter results in less energy consumption. The plasma generation process consumes roughly the same amount of energy as a hand-held blow dryer.

- **Modular and Simple Installation:** The housing for the filter and electrodes can be manipulated so as to retrofit any HVAC system. The housing slides right into the space previously occupied by a standard filter.

Limitations

- Lower Capture Efficiency than HEPA and ULPA Filters: The capture efficiency of the EPS filtration system is 99.9 percent, which is lower than HEPA (99.97 percent) and ULPA filters (99.999 percent)
- Quarterly Filter Replacement: The filter needs to be replaced every two to three months. The filter media, however, is inexpensive (approximately 10 percent of the cost associated with HEPA and ULPA filters.
- Few Site Installations: As of October 2002, the EPS filtration system has only been installed in one building.
- High Equipment Cost: The cost for the EPS filtration system is estimated to be approximately $10,000 for a system installed in a medium-sized office building (fewer than 100,000 square feet.)

4.1.5 Current Manufacturers and Estimated Costs

AGT estimates the EPS filtration system for a medium-sized office building will cost less than $10,000.

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4.2 Nanofibrous Filter

4.2.1 Description

Nanotechnology is defined as the creation of functional materials, devices, and systems through control of matter at the scale of 1 to 100 nanometers, and the exploitation of novel properties and phenomena at the same scale.[1] In general, however, most nanofibers manufactured for air filter applications have diameters between 2 and 500 nanometers. The small diameter of nanofibers makes them well suited for use in filtration applications to adsorb gaseous pollutants and to filter particulates smaller than 3 microns. The nanofibers have a very high surface area to mass ratio and can be formed into sheet structures with very low porosity.

[1] EPA Small Business Innovation Research Phase I FY02 Program Solicitation No. PR-NC-01-11782.

Nanofibers improve the filter efficiency at relatively small decreases in permeability. While a smaller fiber size leads to an increased pressure drop, interception and inertial impaction increase faster, thus compensating for the pressure drop increase. Therefore, small fibers in the submicron range provide better filter efficiency at the same pressure drop. Or conversely, the same filter efficiency at a lower pressure drop can be achieved by smaller fiber sizes.[1] In laboratory tests and actual industrial operating environments, nanofibrous filters also demonstrate improved filter life and more particle-loading capacity.

Recently, the focus has been on producing non-woven webs of electrospun nanofibers at a commercial scale for specific environmental applications, such as filtration media for air purification. Several companies, including eSpin Technologies, Donaldson, and Inframat, are developing nanofibrous filters from the electrospinning process. Electrospinning uses an electric field to draw a jet of a polymer solution from the tip of a capillary to a collector. The fine jets dry to form polymeric fibers, which can be collected on a web—a nanoweb. These non-woven nanowebs consist of entangled fibers or filaments that are bonded together mechanically, thermally, or chemically. They are flat, porous sheets that are made directly from separate fibers or from molten plastic or plastic film. Thus, they are not made using the conventional fiber-making processes, such as weaving or knitting, and they do not require converting the fibers to yarn. Listed below are some of the more familiar products made with non-woven webs:

- Filters
- Disposable diapers
- Sanitary napkins and tampons
- Household and personal wipes
- Sanitary wraps, caps, gowns, masks, and drapings used in the medical field
- Envelopes
- Carpeting and upholstery fabrics

eSpin Technologies is developing a high-throughput electrospinning process to enable large-scale and economical production of nanofibers. eSpin's nanofibers are extremely small fibers at 2 to 200 nanometers in diameter. This is 10 to 100 times smaller in diameter than what is possible with conventional textile technology, and it is about 1000 times smaller than a human hair. Figure 4-3 shows eSpin's nanofibers compared to a single human hair, while Figure 4-4 shows the nanofibers compared to a pollen spore. The nanofibers can be made from a variety of organic (such as nylon, polyester, and acrylic) or biological polymers (such as protein and collagen).

[1] Graham et. al, *Polymeric Nanofibers in Air Filtration Applications*, paper presented at the Fifteenth Annual Technical Conference & Expo of the American Filtration & Separations Society, Galveston, Texas, April 9-12, 2002.

Figure 4-3
eSpin Technologies' Nanofibers (in background) Compared to a Single Human Hair (in foreground)

Source: eSpin Technologies. Used with permission.

Figure 4-4
eSpin Technologies' Nanofibers (in background) Compared to a Pollen Particle (in foreground)

Source: eSpin Technologies. Used with permission.

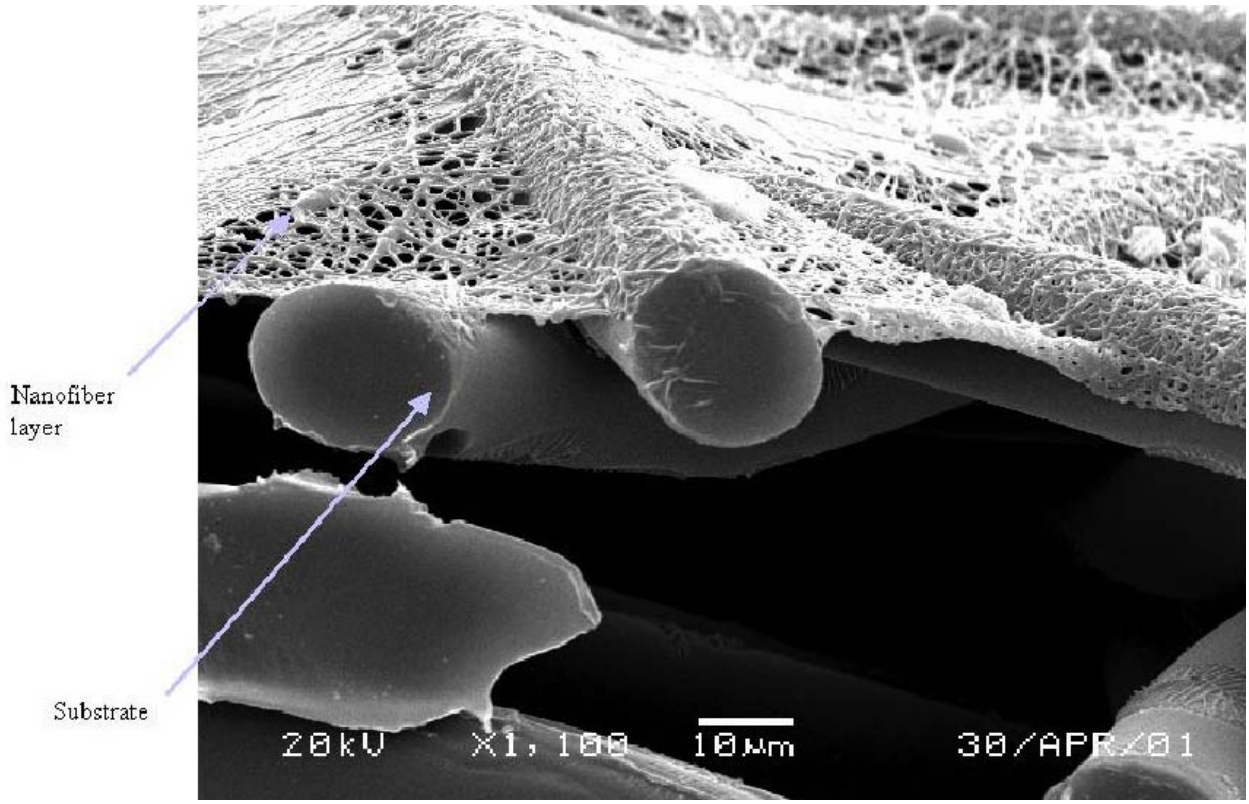


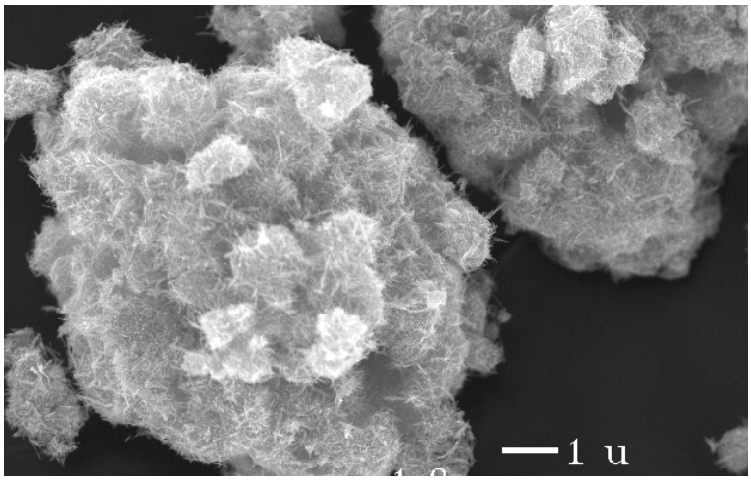
Figure 4-5
Electrospun Nanofibers on a Polyester Substrate

Source: Donaldson. Used with permission.

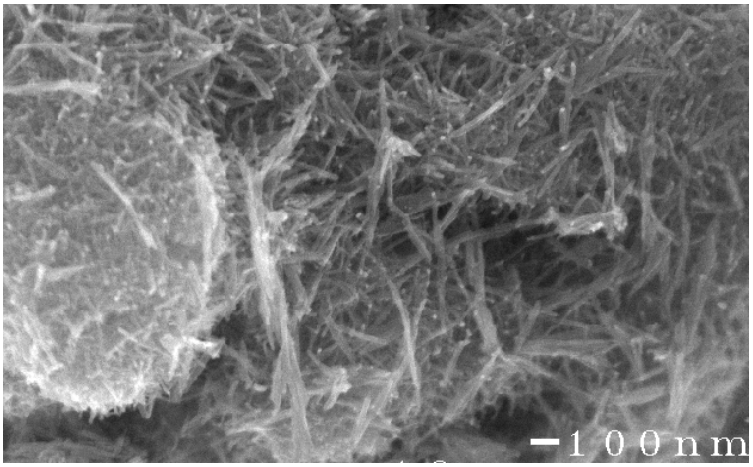
Nanofibers can be electrospun onto a variety of substrates, including polyester, nylon, glass, and cellulose. Figure 4-5 shows a cross-section of nanofibers electrospun onto a polyester substrate. The substrate provides mechanical properties, while the filtration performance is dominated by the microweb. The specific nanofibers in Figure 4-5 are made of nylon material and have a diameter of 250 nanometers. The nanofibers are developed by Donaldson, and are commercially available.

In cooperation with the Environment Research Institute at the University of Connecticut, Inframat is developing nanofibers of manganese dioxide. These fibers are approximately 20 nanometers in diameter and 300 nanometers long. They loosely agglomerate to form a "bird's nest" as shown in Figure 4-6. The manganese dioxide is used as a catalyst for converting toxic VOCs. The open-weave structure provides a host where catalysis can occur efficiently while permitting relatively easy flow of the gas stream through the structure. Treatment of VOCs is a complicated issue however. Although some chlorinated hydrocarbons can be destroyed, toxic decomposition by-products worse than the original compounds may be produced. Data from conversion experiments performed at two VOC concentration levels show promising conversion rates. At low VOC concentration (less than 100 ppb), all compounds except for three (Dichlorodifluoromethane, 1,2-Dichlorotetrafluoroethane, and 112-Trichloro-122-

Trifluoroethane) reach 90 percent and higher conversion rates at 400 degrees Celsius. At high VOC concentration (1000 ppb), all compounds except for the three mentioned above had conversion rates over 99 percent at 350 degrees Celsius.[1]



(a)



(b)

Figure 4-6
(a) As-synthesized MnO_2 Powder has Bird's Nest Morphology, (b) The Bird's Nest Structure is Formed through the Networking of Nanofibrous MnO_2

Source: Inframat. Used with permission.

4.2.2 Applications

Nanofiber-based media filtration is expected to show up in many types of industrial, commercial, and residential applications in the future. Donaldson already uses nanofibers in air purification systems in industrial applications, such as dust collection systems and cabin air filtration of

[1] Data from Nanofibrous MnO_2-catalyzed VOCs conversion experiments performed by Dr. Liu Shili of Environment Research Institute at the University of Connecticut.

mining vehicles.[1] Donaldson also sells nanofiber media to other companies that incorporate the material into their own filtration systems. The company is currently developing, in collaboration with HVAC equipment and filter manufacturers, new air purification applications for residential and commercial buildings. eSpin Technologies is currently supplying nanofibers for filtration, clean room applications, surgical gowns, biomedical devices, nanocomposites, and specialty fabrics. Other applications of eSpin's nanofibers are: use in ultracapacitors for energy storage; filtering of blood, viruses and biomolecules; and creation of strong, lightweight materials. Inframat plans to incorporate its nanofibers in air purification systems for VOC emission control in homes, offices, airplanes, and submarines. The targeted applications for the three companies are summarized in Table 4-2 below.

Table 4-2
Material and Application Characteristics of Nanofibrous Filters

Company	Material and Fiber Size	Targeted Applications
Donaldson	Nylon material with fiber diameters of about 250 nanometers	• Selling complete filtration systems for industrial applications • Supplying nanofiber-based filter media to other companies' systems • Developing new HVAC filtration applications for residential and commercial markets
eSpin Technologies	Activated carbon, nylon, and polyester with fiber diameters of 20-200 nanometers	• Selling nanofibrous filter media to automotive industry • Developing new filtration applications for removal of gaseous pollutants and filtering of particulates from air in commercial buildings.
Inframat	Manganese dioxide with fiber diameters of 20 nanometers The manganese dioxide fibers are structured in a "bird's nest"	Catalytic removal of VOCs from indoor air in homes, offices, airplanes, and submarines.

4.2.3 Developmental Status

Donaldson is currently manufacturing nanofibers for industrial air purification systems using its in-house electrospinning capabilities. The company is forming technical and commercial relationships with HVAC and filter manufacturers to develop new filtration applications based on nanofibers for residential and commercial markets. Because of non-disclosure agreements,

[1] Graham et. al, *Polymeric Nanofibers in Air Filtration Applications*, paper presented at the Fifteenth Annual Technical Conference & Expo of the American Filtration & Separations Society, Galveston, Texas, April 9-12, 2002.

however, Donaldson could not name their co-developers.[1] The company works mostly with nylon but is also investigating other materials. Donaldson also conducts research and development in the area of media configurations, such as adding nanofibers to filter paper and fiberglass substrates.

eSpin Technologies has developed a series of nanofibrous filters for both the automotive and the chemical industries. The company is currently developing and manufacturing new nanofibrous filter media for a large, global air filter manufacturer (due to non-disclosure agreement, the company name is not available). This filter manufacturer will assemble the media filter into a filter box that then will be sold commercially. eSpin works with various media filters, such as nylon and polyester, and substrates, such as paper and fiberglass. The company has completed work on an EPA SBIR Phase I award and is currently working on its SBIR Phase II award. Recently, eSpin Technologies was awarded $2 million from the U.S. Department of Commerce's Advanced Technology Program to advance its electrospinning process.[2]

Inframat Corporation has completed the first phase of an EPA SBIR Award and is currently working on its EPA SBIR Phase II proposal. Most likely, the Phase II proposal will address:[3]

- How the nanofibrous MnO_2 will be integrated into the air purification device. Should it be integrated in the format of filter paper or as a coating on a porous ceramic substrate?
- How to heat MnO_2 and control temperature with low cost
- How to increase the airflow rate with low cost

The developmental status of the three companies is summarized in Table 4-3.

4.2.4 Merits and Limitations

Merits

- **High Capture Efficiency:** Although the exact capture efficiency for various types of particulates is not available, preliminary results indicate that nanofibrous filters can capture submicron particles with a capture efficiency that is about 400 to 500 times better than a HEPA filter.[4]
- **Wide Applicability:** Nanofibrous filters can capture a wide variety of contaminants, including dust, allergens, bacteria, viruses, and fungi.
- **Cheaper than HEPA Filters:** It is expected that nanofibrous filters for indoor air applications will be somewhat cheaper than HEPA filters.

[1] Phone conversation with Kristine Graham, Senior R&D Engineer, Nanofiber Media Products, Donaldson Company.
[2] Press Release, *eSpin Technologies Receives $2 Million Award for Nanofiber Technology Development form Advanced Technology Program (ATP)*, October 8, 2002, http://www.nanospin.com/news.htm.
[3] Email correspondence with Amy Chen, Principal Investigator, USNanocorp, achen@nanocorp.com.
[4] Phone conversation with Dr. Jayesh Doshi, founder and CEO of eSpin Technologies.

Table 4-3
Developmental Status of Nanofibrous Filters

Company	Developmental Status	Co-developers/Commercial Partners
Donaldson	• Currently manufacturing 10,000 square meters of nanofiber material per day for industrial applications • Has installed nanofiber filters in factory dust collecting systems and air filtering systems in army tanks • Moving outside of their traditional markets to develop new nanofilter-based filtration applications for commercial buildings	Currently forming technical and commercial relationships with HVAC and filter manufacturers
eSpin Technologies	• Currently manufacturing nanofibrous filters for the automotive and chemical industries • Developing nanofibrous media filter for large, global filter manufacturer • In collaboration with TVA, developing air filter for coal fired power plants • Has completed a Phase I SBIR for EPA and currently working on Phase II SBIR • Awarded $2 million Advanced Technology Program from the U.S. Department of Commerce	• Currently forming technical and commercial relationships with filter manufacturers • Interested in establishing a collaborative research project with EPRI and a few energy companies
Inframat	• Has completed a Phase I SBIR for EPA and currently working on a Phase II SBIR proposal for EPA that will include engineering issues in fabricating an indoor air purification device • Demonstration likely if awarded Phase II SBIR	• Working with Prof. Shili Liu of the Environmental Research Institute, University of Connecticut • Looking for commercial partners

- **Improved Capture Efficiency without a Substantial Increase in Filter Pressure Drop:** In comparison to HEPA filters, the nanofibrous filters will have only a modest, if any, increase in pressure drop but a much higher capture efficiency.

- **Modular and Easy to Use in Existing HVAC Systems:** The nanofibrous filters can generally be made very thin—only a few millimeters thick—which makes it easy to assemble them into filter boxes and install them in existing HVAC systems.
- **Enhanced Life of Filter:** Although no exact figures are available, it is believed nanofibers increase the life of the filter. For example, nanofiber-based filter media used in automotive applications have an increased filter life of 50,000 to 60,000 miles.[1]
- **Can Catalytically Destroy VOCs and Odor-Causing Vapors:** Nanofibrous filters can be manufactured of materials that can also act as catalysts for removal of VOCs and other odor causing vapors.

Limitations

- **Do Not Specifically Destroy Microorganisms:** Although nanofibrous filters can capture bacteria, viruses, and fungi, they do not destroy and kill these microorganisms. The nanofibrous filters can become a breeding ground for microorganisms.
- **High Temperature Requirements for VOC Conversion:** Experimental results show temperatures of above 350 degrees Celsius is required to obtain high VOC conversion rates.
- **No Test Data Available:** There are no test data available on the capture efficiency of nanofibrous filters.
- **Not Yet Tested in Real Life Settings:** As of October 2002, no results were available from real-life demonstration of nanofiber-based media filtration in residential or commercial buildings.
- **Not Fully Developed Yet:** Nanofiber-based media filters for residential and commercial applications are still under development.

4.2.5 Current Manufacturers and Estimated Costs

Only one of the three nanofibrous filter manufacturers was willing to estimate the future cost of the nanofibrous filter. A spokesperson for eSpin Technologies expects the nanofibrous filter for indoor air filtration applications to be somewhat cheaper than HEPA filters once production is ramped up.[2]

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[1] Phone conversation with Dr. Jayesh Doshi, founder and CEO of eSpin Technologies.
[2] Ibid.

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4.3 Nanoporous Filters

4.3.1 Description

Conventional filter processing technologies cannot produce filters that have the ability to filter particles less than 3 microns in diameter. This processing constraint is due to the fact that the precursor powders and fibers that are used to produce packed bed filters are highly polydisperse and have a mean size that is in the few microns range (often above 3 microns). The polydispersity of the initial powder results in loose packing and a very non-uniform pore size distribution. This is illustrated in Figure 4-7.

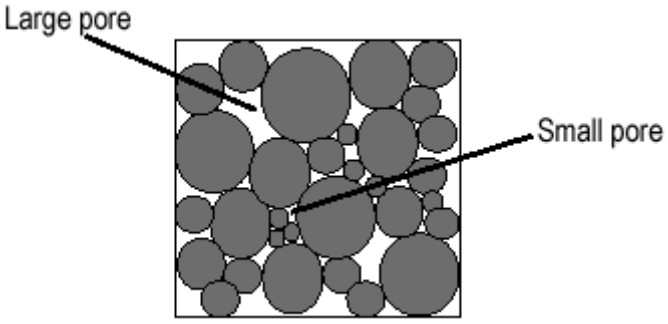

Figure 4-7
Effect of Precursor Powder Polydispersity on Pore Distribution

Source: NanoProducts Corporation. Used with permission.

The non-uniform pore size distribution makes the smaller pores ineffective since the polluted air preferentially passes through the path of least resistance—the larger pores. This significantly lowers the filtration efficiency of the filter. If the precursor powder can be packed in an ideal cubic close pack structure as illustrated in Figure 4-8, the minimum pore size is a function of the size of the precursor powder, as shown in Equation 4-1:

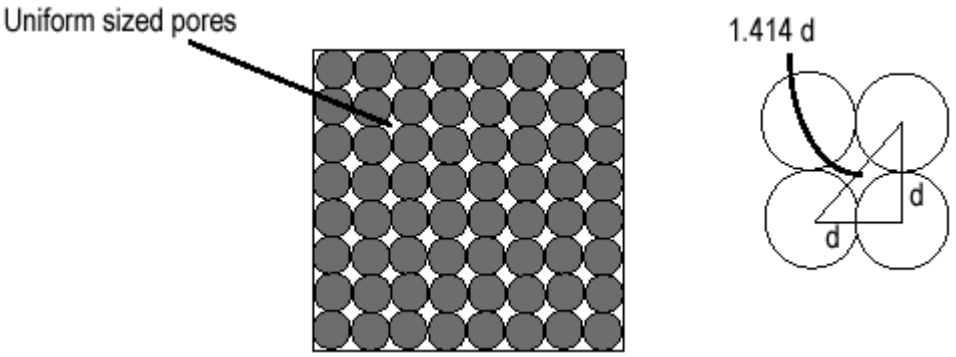

Figure 4-8
Effect of Precursor Powder Monodispersity on Pore Size Distribution

Source: NanoProducts Corporation. Used with permission.

$$\text{Minimum pore size} = 0.414 \times d_{powder} \quad (4\text{-}1)$$

If the packing produces a triangular pore, then the pore size is as stated in Equation 4-2:

$$\text{Minimum pore size} = 0.155 \times d_{powder} \quad (4\text{-}2)$$

Thus, if the precursor powder size exceeds 10 microns, the minimum pore size under ideal packing conditions will be greater than 1.5 microns. Such a media filter would have poor filtration efficiencies for submicron particles. Another drawback of micron-sized precursor powders is the natural limit they place on the thickness of the filters. For mechanical stability and strength, these filters need to be at least a few layers thick. This often translates into a few millimeters thick for indoor air applications. Such a thickness increases the resistance, and lowers the air throughput of the filter per unit filtration area.

Nanomaterials Research LLC, which is a subsidiary of NanoProducts Corporation, has developed a nanoporous filter using nanomaterials and precision pore-size engineering. The company focuses on three-dimensional multiscale—nanometer through millimeter—materials engineering and device integration. Nanoporous filters are fabricated using the so-called "templated nanofabrication" method, which is based on self-organized nanostructured anodic aluminum oxide material. This material contains regular and aligned nano-sized pores that form a template. The dimensions and morphology of the nanopores are engineered with high precision. According to the company, the nanoporous filter has the ability to filter submicron particulates, such as fine particles, pollens, and bacteria, and it has a low pressure drop. Neither test data on filter efficiency nor on filter pressure drop are available, however. Figure 4-9 shows the filter produced with aligned nanopores.

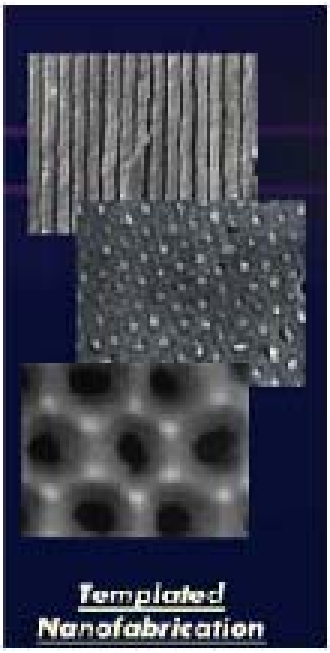

Figure 4-9
A Structured, Nanoporous Filter Produced using Nanomaterials and Precision Pore-size Engineering

Source: NanoProducts Corporation. Used with permission.

4.3.2 Applications

NanoProducts plans to use the nanoporous filter in indoor air purification systems in homes, offices, recreational buildings, and automobiles. As of October 2002, the filter had not yet been demonstrated in any buildings.

4.3.3 Developmental Status

NanoProducts has completed work for an EPA SBIR Phase I Award that included the development of nanoporous filters for simultaneous removal of VOCs and particulates from air. Most particulates are smaller than 1 micron. These small particulates are carriers of chemicals such as VOC. Thus, if the small particulates are filtered by the nanoporous filter then the VOCs are also removed. The company is currently developing and optimizing these filters. The company is also developing integrated technologies that can filter and catalytically destroy organics and odor causing vapors.

4.3.4 Merits and Limitations

Merits

- **High Capture Efficiency:** Although the exact capture efficiency of nanoporous filters is unknown, these filters are believed to be able to capture submicron particulates, such as fine particles, pollens, and bacteria, because of the low filter porosity.
- **Lower Pressure Drop:** Nanoporous filters have lower pressure drops because they can be manufactured much thinner than conventional filters. A lower pressure drop through the filter leads to lower energy consumption for the filtration system.
- **Catalytically Destroys VOCs and Odor Causing Vapors:** Nanoporous filters can be manufactured of materials that are also catalysts for removal of VOCs and other odor causing vapors.

Limitations

- **Does Not Specifically Destroy Microorganisms:** Although nanoporous filters can capture microorganisms, they do not destroy and kill these microorganisms. Therefore, the nanofibrous filters can become breeding grounds for microorganisms.
- **No Independent Test Data Available:** No test results are available to back up the filter-efficiency and pressure-drop claims.
- **Not Yet Tested in Real-Life Settings:** The nanoporous filter has yet to be demonstrated in a real-life setting, such as an office or home.
- **Still too Costly:** No cost information is available, but it is expected these filters will be costly as long as the production capacity is low.

4.3.5 Current Manufacturers and Estimated Costs

NanoProducts Corporation was not willing to provide any cost for the nanoporous filter. It is estimated, however, that the nanoporous filters will be costly as long as the production capacity is low.

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5
MARKET DRIVERS AND BARRIERS

The importance of the indoor environment to human health has been highlighted in numerous EPA reports.[1,2,3] The first two EPA reports ranked indoor air pollution among the top five environmental risks to public health. The latter EPA report presents a vision for indoor environmental quality, and is a blueprint for channeling available resources to improve human health indoors. This EPA report also presents the risks to human health caused by poor indoor air, with a particular emphasis on children's health. For example, indoor air pollutants are estimated to cause thousands of cancer deaths and hundreds of thousands of respiratory health problems each year in the United States. Most Americans, however, are not aware of the significant health risks of indoor pollutants. They also do not know how to mitigate the risk for cancer, asthma, and other health-related problems.

Chapter 2 set the stage for this report by describing the various types of particulate and gaseous pollutants found in indoor air, and the potential problems these pollutants pose. It further discussed the unique threat to indoor air caused by acts of biological and chemical warfare, and introduced some of the ways advanced air purification systems can help. Next, Chapters 3 and 4 assessed various types of air filtration and hybrid technologies for residential and commercial buildings, with emphases on their potential applications, developmental status, merits and limitations, and estimated costs. The current chapter details the most important drivers and barriers to successful integration of air purification technologies. In particular, this chapter elaborates on the driving factors introduced in Chapter 2, and highlights the main barriers identified for filtration and hybrid systems during the technology assessments of Chapters 3 and 4. The main barriers for filtration and hybrid systems are also generally applicable to all types of advanced air purification technologies. Market drivers and barriers pertaining to the residential sector are presented first, followed by those pertaining to the commercial sector.

5.1 Residential Sector

People spend a large percentage of their time in their homes. Therefore, it is essential that residential indoor air is of high quality. Many types of pollutants can potentially contaminate indoor air, including bacteria, viruses, fungi, spores, pollen, asbestos, tobacco smoke, radon gas and progeny, and a wide assortment of other particulates, gases, and vapors. Health effects, as well as diminished well-being and comfort, resulting from poor indoor air in homes constitute drivers for the air purification market. However, several important barriers must be addressed for air purification equipment to achieve the greatest market penetration. The primary barriers include high cost, lack of information for making informed decisions on products, very limited

[1] *Unfinished Business: A Comparative Assessment of Environmental Protection*, EPA, Washington, DC: 1987.
[2] *Reducing Risk: Setting Priorities and Strategies for Environmental Protection*, EPA, Washington, DC: 1990.
[3] *Healthy Buildings, Healthy People: A Vision for the 21st Century*, EPA, Washington, DC: 2001.

performance data in real-life settings, increased maintenance over conventional HVAC systems, higher noise levels for some technologies, aesthetic issues for those wishing to conceal equipment, and a lack of standards for both indoor air quality and air purification systems. Table 5-1 is a summary of the drivers and barriers discussed herein.

Table 5-1
Drivers and Barriers to Successful Integration of Air Purification Technologies in the Residential Sector

Residential Sector	
Drivers	**Barriers**
• Asthma • Allergies • Cancer • Other health effects • Comfort & well-being	• Lack of information • Limited performance data and no industry-wide standards • High cost • Maintenance issues • Noise and aesthetics

5.1.1 Drivers

The single most important factor driving the residential air purification market is health. As reiterated throughout this report, contaminated indoor air can pose a multitude of health effects to people. Of major concern are asthma, cancer, and allergic rhinitis. The discussion below addresses each of these illnesses. However, other health effects not specifically addressed include headaches, watery eyes, nasal congestion, runny nose, coughing, bronchitis, dizziness, confusion, shortness of breath, nausea, vomiting, skin rashes, and irritation to the eyes, ears, and throat. Other important driving factors are related to the greater sense of comfort and well-being that results from high indoor air quality.

Asthma

An estimated 17 million Americans suffer from asthma.[1] About 5,000 people die every year from asthma attacks. Children are particularly prone to having asthma because their respiratory systems are extra sensitive to asthma triggers, such as allergens, microorganisms, and chemicals. It is estimated that about 1 in 13 school children in the United States have asthma. Among chronic diseases, asthma is the number one cause of absenteeism from school. There is sufficient evidence to link the development of asthma to exposure to environmental tobacco smoke and dust mites at the preschool age.

Environmental tobacco smoke is also known as secondhand smoke. Secondhand smoke includes both exhaled mainstream smoke from smokers and side-stream smoke from the end of a cigarette, cigar, or pipe. Secondhand smoke contains more than 4,000 substances, including over

[1] *Healthy Buildings, Healthy People: A Vision For The 21st Century*, EPA-402-K-01-003, EPA, Washington, DC: October 2001.

40 that are linked to cancer. Many of the compounds in tobacco smoke are released at higher rates in side-stream smoke than in mainstream smoke.

The means by which secondhand smoke triggers asthma is believed to be through its irritancy effects. That is, smoke irritates the chronically inflamed bronchial passages of asthmatics. This is a different pathway from most of the other environmental triggers of asthma, like dust mites and pet dander, which trigger asthma episodes through allergenic effects. In addition to triggering asthma, the presence of secondhand smoke also increases the severity of an asthma attack. It is believed that secondhand smoke may be responsible for causing thousands of healthy children to develop asthma each year.

Secondhand smoke also causes a variety of other effects, many of which are most clearly manifested in children because of their particular vulnerability to secondhand smoke. Children who breathe secondhand smoke are more likely to suffer from pneumonia, bronchitis, worsened asthma, and more frequent ear infections. Secondhand smoke may even cause sudden infant death syndrome. The vulnerability of children to secondhand smoke is likely due to several factors, including the fact that children are still developing physically, they have higher breathing rates than adults, and they have little control over their indoor environments. Children receiving high doses of secondhand smoke, such as those with smoking mothers, run the greatest relative risk of experiencing damaging health effects. About 27 percent of homes in the United States with children aged six and younger currently allow smoking. Thus smoking affects approximately 9 to 12 million children in their homes each year.

Allergies

According to estimates from the American Academy of Allergy, Asthma, and Immunology, roughly 35 million people in the United States suffer from seasonal allergic rhinitis.[1] The propensity toward allergies is often inherited. If both parents have allergic diseases, the risk of their child developing allergies is as high as 70 percent. If one parent has an allergic disease, the risk is 48 percent, which is still high. The major allergy sources are pollen, molds, dust mites and dander.

The most common source of nasal allergies is pollen. During most seasons, trees, weeds, and grasses release pollen, which affect the throats, eyes, and noses of people allergic to pollen. Pollen can hitch rides on air currents and travel long distances; so, eliminating plants in the proximity will not necessarily take care of the allergy problems. Another trigger of nasal allergies is molds. There are thousands of molds and yeast types, but fortunately only a few dozen types of molds trigger nasal allergy symptoms. Molds normally grow outdoors in soil, compost piles, rotten logs, fallen leaves, or on grains, but they can also grow indoors where they flourish in damp rooms, such as bathrooms, closets, and basements. Molds can also be found in refrigerators, fresh food storage areas, garbage cans, air conditioners, humidifiers, mattresses, and upholstered furniture. Dust mites are microorganisms that live in carpets and upholstered furniture, and they thrive all year long. Dust mites bother most people, even if they do not have allergies. Some people, however, develop nasal allergies when exposed to dust mites. Another source of allergies is animals. It is a common belief that people are allergic to the animal hair and fur, but it is the animal dander, saliva, and urine that trigger an allergic reaction. Since animal

[1] American Academy of Allergy, Asthma, and Immunology website, http://www.aaaai.org/

dander can settle on carpets and furniture, it can trigger an allergic reaction in a susceptible person for months after the animal is gone.

The early symptoms of nasal allergies are itchy eyes, itchy nose, and sneezing, followed by a runny nose. The latter symptoms, which are usually more severe, begin four to five hours following exposure to the allergen and can last for weeks. In the second phase, the stuffiness intensifies and the person also becomes sensitive to other irritants like perfume and cigarette smoke.

Cancer

Tobacco smoke, radon, asbestos, and benzene are all known human carcinogens found in indoor air. The devastating health effects of tobacco smoke are perhaps best known. However, after tobacco smoke, radon is the second leading cause of lung cancer in the United States. Radon is of special interest because studies have shown that radon, unlike tobacco smoke, is universally present in residential indoor air environments.[1] Therefore, radon poses a risk for lung cancer to the general population. About 12 percent of all lung cancer deaths are linked to radon, which equates to about 20,000 deaths annually. Radon is a gaseous radioactive element. It is an extremely toxic and colorless gas, which is derived from the radioactive decay of radium. Typical sources of radon are earth and rock beneath homes, well water, and building materials. Houses that are not connected to the ground e.g. have a crawl space or multiple floors have less radon problems. Also, the radon level depends on the soil type. Exposure to radon does not give any immediate symptoms, but radon exposure has been definitively linked with lung cancer. All major national and international organizations that have examined the health risks of radon agree that it is a lung carcinogen. Lung cancer usually occurs 5 to 25 years after exposure. There is no evidence that other respiratory diseases, such as asthma, are caused by radon exposure. Moreover, there is no evidence that children are at any greater risk of radon induced lung cancer than adults. However, smoking does increase one's risk of developing radon-induced lung cancer.

Asbestos and benzene also cause cancer. Asbestos is a generic term for a group of naturally occurring mineral silicates. Asbestos, as with many minerals, may be present in fibrous or crystalline forms. Asbestos fibers are used in building materials for insulation, roofing, fire prevention, and as reinforcements in cement. Their large length to width ratio and small diameter characterizes asbestos fibers.[2] They are extremely aerodynamic. If asbestos fibers are inhaled at high concentrations over an extended period of time, they accumulate in the lungs, potentially causing several types of diseases. One such disease is asbestosis. Asbestosis is a slowly progressive disease involving scarring of the lung tissue. This scarring impairs the lung and restricts breathing, which leads to inadequate oxygen intake to the blood.[3] Another disease caused by asbestos is mesothelioma, which is a diffuse cancer of the lining of the chest or abdominal cavity. It is nearly 100 percent fatal within a year. Regular cigarette smokers that have been exposed to asbestos have elevated lung cancer rates. (The risk is elevated by about 50 times.) Asbestos and cigarette smoking is an example of interaction between two separate

[1] "The Health Effects of Exposure to Indoor Radon," *Biological Effects of Ionizing Radiation (BEIR) VI Report*, released to EPA by permission of The National Academy of Sciences, February 19, 1998. http://www.epa.gov/iaq/radon/beirvi1.html.
[2] *Indoor Air Quality Health Effects Primer*, EPRI, Palo Alto: CA: 1996. CR-106639.
[3] Environmental Health and Safety, http://www.dehs.umn.edu/ihsd/asbestos/healtheffect.html.

exposures that work together in a fashion that is more than additive. It remains controversial whether asbestos can cause lung cancer in non-smokers.[1]

Although it can be harmful to humans, benzene is a volatile chemical in liquid-form that is used widely in industry as a solvent. Benzene usually enters the body either through skin contact, consumption of tainted water or food, or inhalation. Once inside the body, benzene enters the bloodstream where it is carried into the bone marrow and fatty tissues. The liver brakes down the benzene eventually. However, harmful metabolites are formed. Short-term exposure to benzene may result in confusion, sleepiness, rapid pulse, loss of consciousness, anemia, damage to the nervous system, suppression of the immune system, and ultimately death.[2] Possible health effects from long-term exposure to benzene are leukemia, severe anemia, and damage to the reproductive system.

Comfort and Well-being

As discussed in Chapter 2, several types of contaminants are common in residential buildings. The most common gaseous contaminants are radon gas, various VOCs, and combustion products (e.g., nitrogen dioxide and carbon monoxide); the most common particulate contaminants come from animal and human origins, plants, minerals, combustion sources, radon progeny, and consumer spray products. Some of the more dangerous particulate contaminants that come from animals and humans are bacteria and viruses, which are capable of causing bacterial and viral infections. Viruses are often spread by sneezes or coughs.

Many studies have shown that fresh, clean air and natural light benefit people by improving their general sense of well-being, increasing their productivity levels, and making them less prone to becoming infected with bacteria and viruses. Most people therefore strive to have a comfortable, clean, odor-free, and healthy home environment. During the last couple of years, much focus has been on how to improve the indoor air quality in residences, either by eliminating or reducing the sources of contaminants or purifying the air using a residential air cleaner technology.

5.1.2 Barriers

The most important barrier to installation of air purification systems in homes is related to the lack of trust-worthy information on typical indoor air quality problems and how air purification technologies can address these problems. Today, manufacturers bombard the potential buyers with statements and claims about air purification technologies that are hard to weed through. Often a third party has not independently verified their claims, and very limited performance data are available. Other important barriers are related to cost, maintenance, and noise and aesthetics.

Lack of Information

There is a significant need for more information addressing residential indoor air quality concerns. Specifically, descriptions of common contaminants, health effects of contaminated air,

[1] *Indoor Air Quality Health Effects Primer*, EPRI, Palo Alto: CA: 1996. CR-106639.
[2] BenzeneFYI.com, http://www.benzenefyi.com/benzene_health_effects_and_treatment.html.

and air quality control measures (in particular, air purification) are greatly in demand. Currently, potential purchasers of air purification technologies often struggle with confusing comparisons and false claims (e.g., HEPA vs. True HEPA) when weeding through hyped information provided by manufacturers and distributors of such systems. Also, most consumers are not aware of how the capture efficiency relates to a specific size of particulate and how the effectiveness of a system depends on the airflow as well. A misinformed consumer therefore may end up purchasing a system that does not address his or her air purification needs.

Limited Performance Data and No Industry-wide Standards

A major barrier to air purification technologies in residential buildings is the lack of performance data showing their impact on exposure in real life settings. Because of the small number of studies and small sample sizes examined, there is not yet enough scientific evidence that the use of air purification systems actually can avoid or limit the adverse effects of indoor air pollution. Therefore, more clinical trials to measure the impact of air purification technologies on health benefits are needed. Also, in order to ensure consistent equipment testing, more standardized test procedures need to be developed. Today, no industry-wide set of performance standards exists to help consumers compare air purification systems. There are, however, several test methods and standards that have been developed for different types of filters and also several organizations that test and rate air purification systems. Some of these test methods and standards are discussed in Appendix B.

Due to the limited performance data available, the American Lung Association recommends that consumers become as informed as possible about air purification systems, research their options thoroughly, and keep in mind that these systems are not intended to be the primary solution to health problems related to indoor air quality. If consumers do choose to use them, the air purification products should be used along with appropriate source control, ventilation, and medical treatment.

High Cost

The high costs of air purification systems are a deterrent to many people, particularly if the health benefits cannot easily be quantified. Depending on the system capacity and type of purification technology, the initial purchase cost of a system is normally somewhere between $100 and $1,500. However, there are additional costs that must be considered. Filters and parts need to be replaced. Disposable, less efficient filters cost under $10, while permanent filters can cost in excess of $300. It may also be necessary to service the unit at some point, which may be costly if it is no longer under warranty. In addition, there is an increase in the household's energy consumption due to the operation of the air purification system.

Maintenance Issues

An air purification system requires maintenance to ensure that the system continuously removes pollutants in an effective manner. Specific maintenance measures depend on the type of purification system. Systems employing media prefilters and/or final filters require frequent replacement of disposable filters or cleaning of permanent filters. Electronic air purification units require washing of the electrostatic precipitator surfaces. Systems that incorporate UVGI require

periodic dusting and eventual replacement of UV lamps. Sorption systems require replacement of sorbent materials. Though these maintenance measures are generally simple and straightforward, they demand that consumers are attentive, handy, and willing to use some of their time to tend to the equipment. However, it is important to note that conventional filters in central systems also require maintenance for optimum performance. Therefore, the level of maintenance is not necessarily increased with the application of an advanced in-duct filtration system. A stand-alone system may add more maintenance to a building that used to get by with only a central system; nevertheless, since the stand-alone system works to clean at least part of the indoor air, the central system will be distributing cleaner air, and thus its filters should last longer.

A less frequent maintenance measure for in-duct systems is duct cleaning. If done correctly, duct cleaning will help reduce indoor air contaminant levels by eliminating one of their sources—the ducts. However, some feel that duct cleaning stirs up otherwise stationary contaminants, and can actually cause more harm than good. It is important that ducts be cleaned by professionals.

For disposable components, another barrier is related to availability. It is sometimes difficult to find places that supply the correct types of replacement parts, such as filters, lamps, and sorbent materials. Such items often have to be special ordered. This may frustrate homeowners and maintenance personnel.

Noise and Aesthetics

Some people may be very sensitive to noise levels, especially when they are trying to sleep. Certain types of air purification systems, particularly systems containing HEPA filters, tend to be quite noisy. The noise levels generated by such a system may be a deterrent when a potential buyer is looking for an air purification system. Another barrier relates to the aesthetics. For some people it is important that the system blends in well with the room. If it does not, it must be concealed somehow.

5.2 Commercial Sector

Some estimates indicate that up to 24 percent of office workers in the United States are affected by air quality problems in their workplaces.[1] In addition, children in schools and daycare facilities are often exposed to poor quality indoor air during a significant portion of their day. Patients, residents, inmates, visitors, and/or employees of healthcare facilities, prisons, and long-term care facilities are at especially high risk of exposure to contaminated indoor air. In recent years the symptoms of illness caused by poor indoor air quality are getting increased attention from the media, health professionals, insurance companies, and state and federal regulatory agencies. Moreover, heightened international tensions have promulgated the need for measures to mitigate the effects of chemical and biological terrorist attacks on indoor air quality.

[1] Blase et. al, "More people suing over indoor air quality problems," *The Business Journal*, July 1999, http://www.bizjournals.com/sanjose/stories/1999/07/05/focus5.html.

The following subsections summarize important market drivers and barriers for implementation of indoor air purification systems in the commercial sector. These drivers and barriers are also listed in Table 5-2.

Table 5-2
Drivers and Barriers to Successful Integration of Air Purification Technologies in the Commercial Sector

Commercial Sector	
Drivers	**Barriers**
• Building-related illnesses • Sick building syndrome • Well-being of children • Hospital-acquired illnesses • Liability concerns • Productivity • Chemical and biological terrorism	• Lack of information • Limited performance data and no industry-wide standards • High cost • HVAC modification requirements for retrofits • Absence of indoor air quality regulations

5.2.1 Drivers

As shown in Table 5-2, the primary factors driving the market for air purification systems in the commercial sector include building-related illnesses, sick building syndrome, the well-being of children in schools and daycare centers, hospital-acquired illnesses, liability concerns, productivity, and acts of chemical and biological terrorism. As in the residential sector, the main impetus for insuring high quality indoor air in the commercial sector is to prevent adverse health effects. However, employee productivity and employer liability are also important concerns.

Building-Related Illness

Building-related illnesses include hypersensitivity diseases and infectious diseases.[1] These illnesses are defined as specific recognized diseases that are related to chemical, infectious, or allergic agents in the building. Contrary to sick building syndrome, building-related illnesses have a known origin.

Several types of hypersensitivity diseases and their causes are listed in the following:

- **Humidifier Fever:** Humidifier feveris characterized by fever, chills, and muscle aches. Organic dust is believed to trigger this disease.
- **Allergic Rhinitis:** Allergic rhinitis is caused by an immunological sensitization to antigens found in house dust, mold spores, animal sources, insect extreta and pollen. The symptoms of this disease include sinus inflammation, runny nose, eye irritation, and sneezing. As mentioned previously, allergy triggers are also commonly found in residential indoor air.

[1] *Indoor Air Quality Health Effects Primer*, EPRI, Palo Alto, CA: 1996. CR-106639.

- **Building-related Asthma:** Building-related asthma is characterized by symptoms such as wheezing, cough, dyspnea, and complaints of chest tightness. This disease may be caused by biocides in water sprays, contamination of humidifiers, or microbial contamination of ventilating systems.
- **Hypersensistivity Pneumonitis:** Hypersensistivity pneumonitis is a very rare interstitial lung disease caused by fungi and bacteria. It is usually associated with fungi and bacteria that have proliferated in the presence of unwanted water. Proliferation sites include contaminated filters and poorly maintained cooling coils.

Infectious diseases and their causes include:

- **Legionnaire's Disease:** Legionnaire's disease is a bacterial infectious disease that can be fatal. The early symptoms are headache and malaise followed by high fever. The disease then progresses, if untreated, to colsoidation of lung tissue, respiratory failure, and death. The disease has been associated with aerosol drift from shower-heads, whirlpools, evaporative condensers, humidifiers, and particularly cooling towers. Cooling towers are prevalent in hotels, hospitals, and large office buildings to dissipate heat from air-conditioning systems. Cooling towers must be treated regularly to avoid risk of Legionnaire's disease.
- **Pontiac fever:** Pontiac fever is a short-lived non-pneumatic disease without known fatalities. The symptoms are fever, chills, headache, and muscle pain. The disease has been associated with contaminated air conditioning systems, cooling towers, whirlpool spas, and hot water systems.
- **Aspergillosis:** Aspergillosis is a family of fungal illnesses caused by Aspergillus fungi and spores (see Chapter 2). Aspergillosis is marked by inflammatory lesions in the tissues or on any mucous surface. The disease may develop in the bronchi, lungs, skin, or the membranes of the eye, nose, or urethea. The Aspergillus fungi is common on outdoor surfaces and in outdoor air. The fungi can grow on cooling-coil drip pans found in HVAC systems, in evaporative condensers, and on water-damaged materials.

Sick Building Syndrome

Sick building syndrome is a general name for a number of ailments, allergies, and complaints due to some physical aspect of a building. Usually, the occupants only complain about discomfort while present in the building. The existence of low levels of pollutants, synthetic irritants, fungi, other microorganisms, or simply a lack of adequate fresh air, are sufficient factors to cause reactions in a percentage of building occupants. Formaldehyde and other VOCs are suspect in producing sick building syndrome. In some new buildings the problem can be the use of synthetic materials, such as carpeting or insulation, which release hydrocarbons or other vapors into the air at a very low rate. Most often an improperly designed and maintained HVAC system within the building is responsible. The World Health Organization has classified the symptoms of sick building syndrome into the following categories:

- Sensory irritation in the eyes, nose, or throat
- Skin irritation
- Neurotoxic symptoms, such as headaches, dizziness, fatigue, and difficulty concentrating

- Odor and taste complaints

Well-being of Children in Schools and Daycare Centers

Recently, much focus has been on improving indoor air quality in buildings housing children. Today's children spend most of their days in schools, daycare centers, and in other buildings for after-school activities. Due to tight budgets and limited staff, these buildings are often under-maintained, and consequently have poor indoor air quality. Unfortunately, as explained previously, children are much more sensitive to air pollutants than adults. The EPA has developed an indoor air tool kit for schools.[1] This toolkit includes checklists for all school employees, a coordinator's guide, an "Indoor Air Quality Problem Solving Wheel," a fact-sheet on indoor air pollution issues, sample policies and memos, and a video on ventilation. Other organizations, such as the American Lung Association, have also developed tool kits for schools.[2]

Hospital-Acquired Infections

High indoor air quality is particularly critical in healthcare facilities, such as hospitals and nursing homes, due to two main factors: 1) many dangerous microbial and chemical agents are inherently present and they can become airborne readily, and 2) patients with existing illnesses have an increased susceptibility to health effects from inhalation of contaminants. However, not only patients need to be protected, but also hospital personnel and visitors. Patients with infectious diseases, such as tuberculosis, chicken pox, measles, and German measles, must be contained in special ventilated care areas because these diseases spread easily via air. Unfortunately, great strides are still required to insure that indoor air quality in hospitals is sufficiently high throughout the country. Until then, infections due to contaminated air will continue to cause unnecessary cost and suffering. Because indoor air quality problems are hard to quantify, poor indoor air quality is often not recognized as a problem until a crisis occurs.

In recent years, the overall hospital-acquired infection rate has been 5 to 10 percent in Europe and North America, but the rates vary widely and can be as high as 30 percent in intensive care units.[3] The most dangerous bacteria that may be transmitted are Staphylococcus Aureus and Mycobacterium Tuberculosis. The rapid increase of TB in the United States and simultaneous development of multiple drug resistant strains of Mycobacterium tuberculosis have caused a lot of concern among healthcare personnel. Bacterial and viral infections still account for most of the fatal infections in patients with compromised immune systems, but the rate of fungal infections is increasing. Candidiasis and Aspergillosis are the most common fungal infections.

Liability Concerns

Indoor air quality litigation is growing rapidly and the focus is shifting from residential to commercial facilities. Two examples are: 1) the $12.5 million claim against the Social Security

[1] *Indoor Air Quality (IAQ) Tools for Schools Kit*, EPA, http://www.epa.gov/iaq/schools/tools4s2.html.
[2] *Tools for Schools*, American Lung Association of California, http://www.californialung.org/support/toolsforschools.html.
[3] "Indoor Air Quality in Hospitals and Other Health Care Facilities," Healthy Buildings 2000 Workshop, August 6-10, 2000, Espoo, Finland, http://www.hb2000.org/workshop22.html#part1.

Administration for the Legionnaire's disease outbreak in Richmond, California, which killed several people, and 2) the Call versus Prudential case in Florida in which building defendants settled in one of the first jury trials in sick building litigation.[1] Even the EPA suffered a $950,000 settlement due to poor indoor air quality in its headquarters.[2]

In the early 1980s, litigation alleging harmful exposure to indoor air started with initial lawsuits concerning occupational exposure to single contaminants, such as pesticides, solvents and asbestos. By the late 1980s, a new type of indoor air quality claim began to appear by homeowners and commercial building occupants claiming they had been damaged by non-industrial contaminants, such as formaldehyde, radon, carbon monoxide, and tobacco smoke. In the last ten years, a new and more far-reaching type of indoor air pollution claim has emerged: the sick building syndrome.

Consequently, the insurance industry has seen an increase in claims related to indoor air because of an increasing number of lawsuits related to health effects to building occupants from poor indoor air quality. Most general insurers, however, deny indoor air quality claims based on "the absolute pollution exclusion" in most general liability policies. The exclusion protects insurance carriers from the potential losses associated with long-term or gradual pollution exposures, and was the insurance industry's response to controlling future environmental claims. The pollution exclusion, therefore, leaves many businesses vulnerable to lawsuits. All too frequently, when businesses request insurance coverage, they learn for the first time of their insurer's "pollution exclusion" clause. To fill the hole in their insurance coverage, and to meet their environmental compliance and risk management requirements, many businesses purchase specific pollution insurance policies to cover exposures to indoor air quality claims.

Productivity

According to one study, acute upper respiratory diseases, such as influenza and the common cold, cause about 160 million lost workdays, and 300 million workdays of restricted activity annually.[3] This results in an estimated annual loss of $60 billion due to lost time and reduced productivity as a result poor indoor air quality.[4] Though many studies indicate that poor indoor air quality leads to decreased productivity, productivity effects are generally difficult to directly quantify.[5,6] One study estimates worker productivity can be improved by 0.5 to 5 percent if the indoor environment is improved (due to improved lighting and indoor air quality), which translates to between $12 and $125 billion from direct improvements in worker performance that

[1] *Indoor Air Quality - 59:15968-16039*, Department of Labor, OSHA, Federal Register, 1994, http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=FEDERAL_REGISTER&p_id=13369&p_text_version=FALSE.

[2] Richard Humphreys, "Liability Issues, Air Quality and Your Liability," Pollution Engineering, April 1999, http://www.pollutionengineering.com/beyondcompliance/liability/lia1999/lia0499.htm.

[3] Blase et. al, "More people suing over indoor air quality problems," The Business Journal, July 1999, http://www.bizjournals.com/sanjose/stories/1999/07/05/focus5.html

[4] William J. Fisk, "How IEQ Affects Health, Productivity," *ASHRAE Journal*, May 2002.

[5] *Report to Congress on Indoor Air Quality, Volume II: Assessment and Control of Indoor Air Pollution*, EPA-400-1-89-001C, EPA, Office of Air and Radiation, Washington, DC: 1989.

[6] Sten Olaf Hanssen, "Evaluation of association between indoor air climate wellbeing and productivity," Healthy Buildings 2000 Workshop, August 6-10, 2000, Espo, Finland, www.hb2000.org/download/WS9_Economics_Paper.pdf.

are unrelated to health.[1] Because worker salaries exceed building energy, maintenance and construction costs, it is cost-effective to improve the indoor environment even when the percentage improvements in health and productivity are relatively small. Indeed, this study found that benefit-to-cost ratios of indoor air quality improvements were approximately 50:1 and 20:1 for increased ventilation and improved filtration, respectively.

Chemical and Biological Terrorism

Chapter 2 described how the increased threat of chemical and biological acts of terror has led to a greater demand for systems that are capable of indoor air purification. As mentioned earlier, biological and chemical agents can be introduced into a building's indoor air environment in a variety of ways, causing a wide range of health effects, and potentially leading to mass fatality. Once in the building, the HVAC system can then act to spread the agent inadvertently.

Chemical agents of concern are numerous and include Nerve Gas, Mustard Gas, Cyanogen Chloride, Hydrogen Cyanide, and Dimethylacetamide. These agents are generally introduced to the body by inhalation of gas and vapor phase molecules.

Although more difficult to create, biological weapons have an order of magnitude more destructive potential on a per mass basis than chemical weapons. Most microorganisms that cause disease or produce toxins may be used as biological weapons in a bioterrorist attack on a building. These microorganisms include viruses, bacteria, fungal spores, and toxins. Toxins are biological poisons. There are two types of toxins: endotoxins produced by bacteria and mycotoxins produced by fungi. The biological weapons most often discussed today are the Anthrax bacterium and the Variola virus (which leads to Smallpox). There are many others of concern as well, including the very lethal Ebola virus.

Agents can be introduced in many ways, including the use of an aerosolizer, human carriers, or an explosion. An aerosolizer is a spraying device that can be used to spray a liquid or powder into the air. This could be done either into the ventilation systems or into general areas of the building. Human carriers in the form of unsuspecting mail carriers were used in recent Anthrax scares. An explosive dispersion inside a building is a possibility too, but such an explosion would cause immediate alarm and mitigate the effects.

5.2.2 Barriers

Table 5-2 lists some of the main market barriers to implementation of air purification systems in commercial buildings. These barriers include lack of information pertaining to indoor air quality problems and solutions, limited performance data in real-life environments, high initial and operating costs, HVAC modification requirements, and absence of indoor air quality regulations. Each barrier is described in more detail in the following paragraphs.

[1] "Improved Productivity and Health from Better Indoor Environments," Center for Building Science News, Lawrence National Laboratory, Summer 1997, http://eetd.lbl.gov/newsletter/cbs_nl/nl15/productivity.html.

Lack of Information

As mentioned previously in the discussion of barriers for the residential sector, there is a significant need for more information addressing indoor air quality concerns. Indoor air quality has been the subject of many studies in recent years, but there is still a need for greater understanding about how air purification systems can mitigate indoor air contaminants. Of particular interest to the commercial sector is information pertaining to biological and chemical pollutants and strategies to control them. Also of great concern is the control of TB and other infectious diseases in hospitals, prisons, and long-term care facilities. More resources are required to inform building personnel on the types of air purification systems available for controlling infectious contaminants, and on the potential problems and benefits associated with air cleaning strategies.

Limited Performance Data and No Industry-wide Standards

As with systems designed for residential applications, there are limited performance data available for commercial air purification systems. More studies in real-life settings are required to demonstrate the effectiveness of both commercially available and emerging systems in reducing indoor contaminants. Moreover, more clinical trials are needed to prove whether or not the addition of an air purification system actually substantially reduces adverse health effects. Misleading claims may give false hope to those responsible for indoor air quality in commercial spaces. For example, although a system may remove a very large percentage of pollutants, the pollutants not removed may result in an unacceptable quantity of illnesses. In addition, standardized tests for air purification equipment are necessary to enable comparisons among the various systems available. Currently no industry-wide performance standards exist. However, several test methods and standards have been developed for different filter types and there are a few organizations that test and rate air purification systems (see Appendix B).

High Cost

Stand-alone purification systems for commercial applications are costly. Prices of $1000 to upwards of $3000 are common for clean room and healthcare grade systems. In-duct components are generally less expensive since they use the existing fan and infrastructure of the central HVAC unit; however, some in-duct systems may result in costly duct and ventilation equipment modifications. Replacement filters, UV lamps, and/or sorbent materials are also relatively expensive and are on the order of $10 to $20 for prefilters, $200 to $300+ for HEPA filters, $100 to $200 for UV lamps, and $100 to $200 for sorption media. Air purification systems also increase building energy costs, predominantly in the form of greater fan power requirements.

HVAC Modification Requirements

The installation of an in-duct HEPA filter can result in substantial increases in static pressure drop and air resistance across the filter. According to some estimates, the initial resistance of a HEPA filter applied in a central HVAC system is on the order of 1 to 2 inches of water, compared with 0.3 to 0.7 inches of water for conventional final filters.[1] This resistance further

[1] *HEPA Filters in Commercial Buildings,* Airguard Research and Technical Center. www.airguard.com/downloads/HEPAin%20commercial%20buildings.pdf.

increases as the filter becomes loaded with particulates. A larger fan may be required to overcome the higher pressure drop.

In order to minimize the air resistance across HEPA filters, they are typically designed to have deep pleats that act to increase the surface area for particulate capture, while keeping the pressure drop as low as possible. However, the deep pleated design increases the filter thickness. The larger thickness, in turn, may necessitate ductwork modifications to accommodate the increased filter size. HEPA filters may also require better seals than are used in conventional systems in order to prevent the air from taking the path of least resistance and by-passing the filter.

Multi-stage hybrid systems placed in ducts may also require duct modifications to accommodate the larger equipment sizes. In addition, some hybrid systems, such as those incorporating electrostatic precipitators and/or UV lamps will require access to electricity.

Absence of Indoor Air Quality Regulations

Compared with other environmental and health concerns, indoor air quality has so far not been extensively regulated. The Occupational Safety & Health Administration (OSHA) believes that there are no non-regulatory alternatives that adequately protect workers from exposure to indoor air pollution. Tort liability laws and Worker's Compensation provide some protection, but they are not sufficient. Therefore, OSHA has proposed regulations of indoor air quality. However, presently, no federal statute is specifically directed at indoor air quality, and no federal agency is directly authorized to regulate it. Various bills concerning regulation of indoor air are pending in Congress. Most indoor air regulation activities are currently taking place at the state and local government levels. For example, in California smoking indoors in public places was forbidden in 1995.[1]

Appendix B presents standards for indoor air that have been developed by various organizations, such as ASHRAE, AMI, and ARI. However, these standards are all voluntary.

[1] *California Workplace Smoking Restrictions*, AB-13 Fact Sheet, Cal/OSHA Consultation Service, http://www.dir.ca.gov/dosh/dosh%5Fpublications/smoking.html

6
RECOMMENDATIONS

The goal of this chapter is to recommend a variety of actions energy companies can take to help their residential and commercial customers make choices that will ultimately lead to better indoor air quality. The recommendations provided here are based on findings from previous chapters of the report. Specifically, in Chapter 5 the project team identified two great barriers that must be removed: 1) lack of informational and educational material that discusses the importance of indoor air quality and that identifies measures for improving indoor air, and 2) limited and hyped performance data on air purification systems from manufacturers and distributors. Today, potential purchasers of air purification systems often struggle with little information and confusing comparisons and false claims. Consequently, consumers either purchase systems that do not sufficiently address their indoor air needs or they abstain entirely from investing in such systems. Thus, the lack of information and the limited quantity of independently verified performance data on air purification systems are major barriers influencing successful market penetration in residential and commercial markets. This chapter identifies actions that energy companies can pursue to address these barriers.

In general, residential and commercial customers view their energy companies as trustworthy and knowledgeable, and they therefore will more readily accept information and data provided by energy companies than manufacturers. The project team recommends that energy companies get involved in the development of a set of fact sheets and educational seminars for residential and commercial customers to address the lack of information on indoor air and air purification systems. The project team also recommends that independent testing and evaluation of air purification systems be carried out by an independent third party, in collaboration with energy companies and ASHRAE, to validate the manufacturers' claims in regards to system performance (particularly capture efficiency and kill efficiency).

Some of the recommendations included in this chapter, such as fact sheets and educational seminars, can be developed and implemented in less than one year. Other recommendations, however, are more long-term actions, such as developing test procedures, and evaluating and demonstrating air purification systems. Typically, the latter types of activities require two to three years to implement. Table 6-1 summarizes all of the recommended activities. This table also indicates whether the activity is short-term (less than half a year), medium-term (about one year), or long-term (in excess of two years) in nature. The recommended activities are discussed in greater detail in subsequent sections.

Table 6-1
Summary of Recommended Activities

Recommended Activity	What and How to Implement	Estimated Time to Implement
General Indoor Air Quality Fact Sheets	Develop two-to-four page fact sheets to create an indoor air quality packet for energy company staff, customers and/or contractors. 1) Develop a fact sheet for residential market that discusses common indoor air quality pollutants and problems, health effects, methods of mitigating the problems, and how to monitor indoor air quality. 2) Develop a fact sheet for commercial market that discusses common indoor air quality pollutants and problems, health effects, methods of mitigating the problems, and how to monitor indoor air quality. This fact sheet also discusses in general terms the threat of chemical and biological attacks.	Short-term: 3-4 months per fact sheet
Technology Fact Sheets	Develop two-to-four page fact sheets to create an indoor air purification technology packet for energy company staff, customers and/or contractors. 1) Develop a fact sheet for residential market on residential air purification technologies intended for single room applications, including descriptions of each technology type, merits and limitations, and typical manufacturers and costs. 2) Develop a fact sheet for residential market on residential air purification technologies intended for whole house applications, including descriptions of each technology type, merits and limitations, and typical manufacturers and costs. 3) Develop a fact sheet for commercial market on commercial air purification technologies, including description of each technology type, merits and limitations, and typical manufacturers and costs.	Short-term: 3-4 months per fact sheet

Table 6-1
Summary of Recommended Activities (cont.)

Recommended Activity	What and How to Implement	Estimated Time to Implement
Building-and-Application Specific Fact Sheets	Develop two-to-four page fact sheets to create indoor air quality and indoor air purification packets for energy company staff and facility managers of educational buildings, health care facilities and long-term living facilities. 1) Develop a fact sheet addressing the typical indoor air quality concerns of schools and daycare centers. 2) Develop a fact sheet addressing the typical indoor air quality concerns of health care facilities and long-term living facilities. 3) Develop a fact sheet addressing chemical and biological attack threats on commercial buildings.	Short-term: 3-4 months per fact sheet
Educational Seminars	Develop seminars addressing indoor air quality in homes, educational buildings, and healthcare facilities. To meet the renewed interest in chemical and biological attack threats, one seminar addressing this topic will also be developed. These seminars will first be presented to energy company staff, and can subsequently be presented to homeowners and facility managers. 1) Develop and conduct a seminar on the importance of good indoor air quality in homes. 2) Develop and conduct a seminar on the importance of good indoor air quality in schools and daycare centers. 3) Develop and conduct a seminar on the importance of good indoor air quality in health care and long-term living facilities. 4) Develop and conduct a seminar on chemical and biological attack threats on commercial buildings.	Medium-term: 6-12 months per seminar

Table 6-1
Summary of Recommended Activities (cont.)

Recommended Activity	What and How to Implement	Estimated Time to Implement
Website Information & Tools	Make all written information that is developed, such as fact sheets and write-ups on demonstration projects, available over the Internet to energy company staff, customers and/or contractors.	Short-term: 3-4 months
Electrotechnology Assessment	Conduct an assessment of electrotechnologies used in air purification system applications. The assessment will include ultraviolet germicidal irradiation, catalytic photolysis, photocatalytic oxidation, X-rays, electron beams, microwave radiation, pulsed light, activated sorbents, and cold plasmas.	Medium-term: 6-12 months
Demonstration Project & Case Study Development	Initiate and participate in a field demonstration of the electrostatically enhanced filter with plasma sterilization in a hospital, which has an indoor air environment that is much more demanding than most commercial buildings. Once the demonstration phase is completed, develop a case study outlining the findings.	Long-term: 2-3 years
Collaborative Research & Development Project	Initiate and develop a collaborative research project for energy companies. 1) In collaboration with manufacturers of air purification systems, ASHRAE, and other organizations develop testing procedures for determining system effectiveness in capturing particulates *and* killing microorganisms, and thereafter have an independent test facility evaluate the various systems to validate the manufacturers' claims. 2) In collaboration with nanofibrous media filter manufacturers investigate new, emerging applications of nanofibrous filter media.	Long-term: 2-3 years

6.1 Fact Sheets

Fact sheets are an extremely convenient and valuable way to convey information. Consider developing families of 2-to-4 page fact sheets covering the following three subjects:

- General fact sheets on indoor air quality
- Technology fact sheets presenting commercially available and emerging air purification technologies
- Fact sheets addressing building-specific air quality needs

6.1.1 General Fact Sheets

Consider developing two general fact sheets on indoor air quality:

1. **Fact Sheet: Indoor Air Quality in Homes.** This fact sheet includes common indoor air pollutants found in a home, typical health effects caused by poor indoor air quality, the sensitivity of children, how to monitor indoor air quality, and how to mitigate indoor air pollutants.
2. **Fact Sheet: Indoor Air Quality in Commercial Buildings.** This fact sheet includes common indoor air pollutants found in commercial buildings, typical health effects caused by poor indoor air quality, how to monitor indoor air quality, how to mitigate indoor air pollutants, liability issues, cost-benefit analysis of improvement in indoor air quality and improved productivity. This fact sheet also discusses, in general terms, the threat of chemical and biological attacks, and how to protect building occupants from such threats.

The project team estimates it would take about 3 to 4 months to develop and publish each fact sheet.

6.1.2 Technical Fact Sheets

Consider developing three technical fact sheets:

1. **Fact Sheet: Air Purification Technologies for a Single Room in a House.** This fact sheet presents what features to look for when shopping for an air purification system for a room. It helps homeowners weed through a lot of hype currently used by manufacturers and distributors. This fact sheet also compares residential air purification technologies for residential rooms and discusses their merits and limitations.
2. **Fact Sheet: Air Purification Technologies for a Whole House.** This fact sheet presents what features to look for when shopping for an air purification system for a whole house. It helps homeowners weed through a lot of hype currently used by manufacturers and distributors. This fact sheet also compares residential air purification technologies for a whole house and discusses their merits and limitations.

3. **Fact Sheet: Air Purification Technologies for Commercial Buildings.** This fact sheet presents what features to look for when shopping for an air purification system for a commercial building. It helps building owners and/or facility managers weed through a lot of hype currently used by manufacturers and distributors. This fact sheet also compares air purification technologies for the commercial sector and discusses their merits and limitations.

The project team estimates it would take about 3 to 4 months to develop and publish each fact sheet.

6.1.3 Building-and-Application-Specific Fact Sheets

Consider developing three building-and-application-specific fact sheets:

1. **Fact Sheet: Indoor Air Quality in Schools and Daycare Centers.** This fact sheet addresses the importance of good indoor air quality in buildings housing a large number of children, such as schools and daycare centers. It discusses typical indoor air quality problems, health effects caused by indoor air pollutants, and how to mitigate them. It also addresses maintenance and operation of HVAC systems, monitoring of indoor air quality, air purification technologies, and liability.
2. **Fact Sheet: Indoor Air Quality in Healthcare Facilities and Long-Term Living Facilities.** This fact sheet addresses the importance of good indoor air quality in buildings housing a large number of people with communicable diseases and suppressed health systems, such as hospitals, clinics, assisted living centers, shelters, and prisons. It discusses typical indoor air quality problems, health effects caused by indoor air contaminants, and how to mitigate them. It also addresses maintenance and operation of HVAC systems, monitoring of indoor air quality, commercially available and emerging air purification technologies, and liability.
3. **Fact Sheet: The Threat of Chemical and Biological Attacks and How to Protect Your Employees.** This fact sheet addresses the increased concern of chemical and biological attacks on commercial buildings. It discusses types of chemical and biological agents, health problems and symptoms caused by these agents, how to prevent attacks, how to monitor air quality, the importance of isolating affected rooms or areas, mitigation strategies, and emergency plans.

The project team estimates it would take approximately 3 to 4 months to develop and publish each fact sheet.

6.2 Educational Seminars

Consider offering four types of educational seminars:

1. **Educational Seminar: The Importance of Good Indoor Air Quality in Homes.** This seminar presents typical residential indoor air pollutants and how to mitigate them. Specifically, this seminar discusses typical health effects caused by poor indoor air quality, and the sensitivity of children and people with asthma and allergies. It also

addresses how to monitor indoor air quality, and what features to look for when shopping for an air purification system, either for a single room or the whole house.

2. **Educational Seminar: The Importance of Good Indoor Air Quality in Schools and Daycare Centers**. The topics covered in this seminar are the well being of children, the sensitivity of children to indoor air pollutants, and ways to mitigate air pollution. This seminar could leverage on EPA's work on indoor air quality in schools and previous EPRI work in the educational building area.
3. **Educational Seminar: The Importance of Good Indoor Air Quality in Healthcare Facilities and Long-Term Living Facilities.** This seminar addresses the need for good indoor air quality in hospitals, clinics, assisted living centers, shelters, prisons, and other buildings housing a high number of people with communicable diseases and suppressed immune systems. The topics covered are typical indoor air quality problems, health effects, and mitigation strategies, such as maintenance and operation of HVAC systems, monitoring, and air purification technologies. This seminar could leverage on previous EPRI work in the healthcare area.
4. **Educational Seminar: Chemical and Biological Attack Threats on Commercial Buildings, and How to Protect Your Employees.** This seminar presents types of chemical and biological agents, symptoms caused by these agents, how to monitor indoor air quality, and how to prevent or mitigate a potential attack on heavily occupied government or commercial buildings. Specifically, the seminar discusses the importance of making air intakes and HVAC equipment inaccessible to unauthorized personnel, isolating affected rooms or areas, diluting the contaminated air with clean air to reduce concentration levels, and developing evacuation and emergency plans.

For each seminar, the project team estimates it would take about 6 to 12 months to develop the seminar material, conduct the seminar, and publish the seminar proceedings.

6.3 Website Information and Tools

Consider making all material that is developed, such as fact sheets and seminar proceedings, also available on the Internet. For example, EPRI could place information on www.epri.indoorair.com. The website would provide general information on indoor air quality and typical indoor air contaminants, as well as specific technical information on air purification technologies (e.g., test results, case studies, collaborative research efforts, and demonstration projects).

The project team estimates it would take about 3 to 4 months to load a website with already developed material, such as fact sheets, seminar proceedings and case studies, and then bring the website live.

6.4 Technology and Market Assessment

Consider conducting an assessment of electrotechnologies employed in residential and commercial air purification applications. This assessment would include electrostatic precipitation, ultraviolet irradiation, ozonation, catalytic photolysis, photocatalytic oxidation,

pulsed corona discharge, silent discharge, electron beams, ion jets, activated sorbents, and any other electrotechnologies. The findings would be presented in a report. This second report would be a complementary report to the present report, which primarily focuses on media filtration.

The project team estimates it would take about 6 to 12 months to conduct a technology and market assessment and have the findings published in a report.

6.5 Collaborative Research

Consider pursuing two collaborative research projects:

1. **Collaborative Research on Test Procedures and Evaluation of Residential and Commercial Air Purification Technologies.** Initiate and develop a collaborative research project addressing the need for consistent testing and evaluation of air purification system efficiencies in capturing contaminants and killing captured microorganisms. A major barrier to successful integration of air purification technologies is the potential buyers' wariness about the effectiveness of these technologies and whether the test results have been independently verified. Thus, this collaborative research addresses the need for validating manufacturers' claims.

   Energy companies/EPRI in collaboration with other organizations and independent test facilities could play a major role in testing and evaluating these technologies. For example, consider developing test protocols (one protocol for a room and one protocol for a complete house) in collaboration with ASHRAE and manufacturers. Other organizations that may be interested in participating in testing of air purification technologies are EPA, Centers for Disease Control and Prevention (CDC)1, OSHA2, the National Institute for Occupational Safety and Health (NIOSH)3, The Building Owners and Managers Association (BOMA)4, American Society of Home Inspectors (ASHI)5, and the Department of Homeland Security6. In fact, EPRI should consider making this collaborative project a cornerstone project of an Indoor Air Initiative as it is expected federal funding will be available shortly for such initiatives.

   Moreover, consider using existing test facilities rather than developing one in order to leverage funding. Some modifications to existing test facilities may be necessary, but such modifications generally are less expensive to implement than building a new test facility. One such existing, independent test facility that could be used is the Conventional Research House in Chicago. This facility currently is used to conduct indoor air quality research and to test advanced prototype heating and cooling systems for characterizing efficiency and comfort. The Gas Technology Institute (GTI) owns this test facility; however, GARD Analytics manages it.[7] The Conventional Research House consists of a single story, 3-bedroom house, with a full basement. It was specifically developed to study the performance

[1] U.S. Department of Health and Human Services, Center for Disease Control and Prevention, http://www.cdc.gov/
[2] U.S. Department of Labor, Occupational Safety and Health Administration, http://www.osha.gov/
[3] National Institute for Occupational Safety and Health, http://www.cdc.gov/niosh/homepage.html
[4] The Building Owners and Managers Association, http://www.boma.org/
[5] American Society of Home Inspectors, http://www.ashi.org/
[6] The Department of Homeland Security, http://www.whitehouse.gov/deptofhomeland/
[7] GARD Analytics, www.gard.com.

of heating and cooling systems in an actual house, including the critical interactions between the equipment and the house itself. The research setup currently can monitor combustion products, such as carbon monoxide, carbon dioxide, nitrogen dioxide, nitric oxide, total oxides of nitrogen, total hydrocarbons, and sulfur hexafluoride (tracer gas). However, the setup could be changed to allow for testing the performance efficiencies of air purification systems.

2. **Collaborative Research on Nanofibrous Filtration Media.** Initiate and develop a collaborative research project on nanofibrous filtration media. This type of filter media is currently being developed by several companies, such as eSpin Technologies, Donaldson Company and Inframat. Nanofiber-based filters is an emerging filtration technology that shows great promise for indoor air purification application in commercial buildings that require a high particulate capture efficiency (see Chapter 4). This research project primarily focuses on applications of nanofibrous media filters in new indoor air purification applications, but could also investigate other applications, such as filtration applications in power plants.

The project team estimates it would take about 2 to 3 years to initiate and develop a collaborative research project, conduct the research, and thereafter have the results published in a report.

6.6 Demonstration Projects

Consider conducting a demonstration of the electrostatically enhanced filter with plasma sterilization system, developed by Atmospheric Glow Technologies (presented in Chapter 4). This air purification system has shown promising results when tested for a variety of microorganisms (both conventional as well as exotic like Anthrax and spores) in laboratory test configurations. A first demonstration unit was recently installed in a commercial building consisting of office space and laboratories. Consider installing a second demonstration unit in a building with unique indoor air quality problems, such as a hospital.

The project team estimates it would take about 2 to 3 years to initiate and develop a demonstration project, conduct the demonstration, analyze the results, and publish the findings in a report.

A
GLOSSARY

Absorption:	A bulk process in which matter permeates or dissolves in another substance
Adsorption:	A process in which gas, liquid, or even solid molecules move from a bulk phase and accumulate on the surface of a solid or liquid
Aerodynamic Particle Size:	A classification of particle sizes as spheres of unit density based on terminal velocities
Aerosol:	Atmospheric dust suspended in a gas
Air Filtration:	Removal of particulate contaminants from an air-particulate suspension by the passage of the suspension through a filter medium that retains the particulates
Air Purification:	Removal and/or destruction of particulate and/or gaseous air contaminants by any number of control strategies (e.g., media filtration, electrostatic forces, oxidation, gaseous sorption, etc.)
Atmospheric Dust:	A complex mixture of smokes, mists, fumes, dry granular particles, bioaerosols, and natural and synthetic fibers
Chemisorption:	A type of adsorption process in which weak chemical bonds are formed between gas or liquid molecules and a solid surface
Clean Air Delivery Rate (CADR):	The rate of contaminant reduction in the test chamber when the unit is turned on, minus the rate of natural decay when the unit is not running, times the volume of the test chamber as measured in cubic feet
High Efficiency Particulate Arrestance (HEPA)	An air filter with removal efficiency

Filter:	of greater than or equal to 99.97 percent for dioctylphthalate (DOP) particles at 0.3 μm
Hybrid Technology	Combines two or more technologies
Natural Decay:	The reduction of particulate matter due to natural phenomena in the test chamber, principally sedimentation, agglomeration, and surface deposition
Photolysis:	The decomposition of matter that results from the absorption of incident light
Ultra Low Penetration Air (ULPA) Filter:	An air filter with removal efficiency of greater than or equal to 99.999 percent for dioctylphthalate (DOP) particles at 0.3 μm
Ultraviolet Germicidal Irradiation (UVGI):	Radiation associated with the UV-C range of wavelengths, which is from 100 to 290 nm; most UVGI systems emit radiation predominantly at 253.7 nm

B
AIR CLEANER TEST METHODS AND STANDARDS

The heating and air conditioning industry, the automotive industry, the atomic energy industry, and government and military agencies, have developed air cleaner test methods. Several test methods have become standard in general ventilation applications. This Appendix presents the air cleaner test methods and standards that apply to residential and commercial air cleaners. The test methods and standards specifically discussed include:

- Arrestance Test, ASHRAE Standard 52.1
- Atmospheric Dust-Spot Efficiency Test, ASHRAE Standard 52.1
- Dust-Holding Capacity Test, ASHRAE Standard 52.1
- Particle Size Removal Efficiency Test, ASHRAE Standard 52.2
- DOP Penetration Test, U.S. Military Standard MIL-STD-282
- Test Method for Portable Household Air Cleaners, AHAM/ANSI Standard AC-1-2002
- Test Methods for Commercial and Residential Air Filter Equipment, ARI Standards 680 and 850

B.1 Arrestance Test, Atmospheric Dust-Spot Efficiency Test and Dust-Holding Capacity Test

ASHRAE Standard 52.1-1992, which is a voluntary standard, covers all three tests.

B.1.1 Arrestance Test

In the ASHRAE arrestance test, a given amount of a prepared test dust is fed into the test unit at a known and controlled rate. A high-efficiency after-filter determines the concentration of dust in the air leaving the filter that is tested. The arrestance is calculated using the weight of the dust passing the tested filter and the total dust fed. The dust is artificially generated, and is considerably coarser than typical atmospheric dust. This means the arrestance test can only determine the ability of a filter to remove the largest atmospheric dust particles, but provides no information on the filter's ability to remove smaller particles. The arrestance test cannot differentiate between filters when extremely small particles are involved.

B.1.2 Atmospheric Dust-Spot Efficiency Test

Finer airborne dust particles soil walls and other interior surfaces. The efficiency of a filter in reducing the soiling of surfaces can be computed by measuring the change in light transmitted from white, filter paper targets discolored by the dust particles. This is the method used in ASHRAE's atmospheric dust-spot efficiency test.

B.1.3 Atmospheric Dust-Holding Efficiency Test

Not all filters of the same type retain collected dust equally well. The dust-holding capacity defines the amount of particular type of dust that an air cleaner can hold when it operates at a specific airflow rate to some maximum resistance value. The ASHRAE Standard 52.2 specifies that arrestance of the filter must be measured at least four times during the dust-loading process and that the test be terminated when two consecutive arrestance values of less than 85 percent, or one equal to or less than 75 percent of the maximum arrestance, have been measured. Thus, the ASHRAE dust-holding capacity is the integrated amount of dust held by the filter up to the time the dust-loading test is terminated.

B.2 Particle Size Removal Efficiency Test

ASHRAE Standard 52.2 is a method of testing air cleaning devices for removal efficiency by particle size. Two specific air cleaner performance characteristics are important: the ability of the air cleaner to remove particles from the air stream and the air cleaner's resistance to the airflow. From the test, a set of curves describing the particle size removal efficiency is developed. These curves, together with initial clean performance curves, are used to develop a composite curve representing performance in the range of particle sizes. Points on the composite curve are used to determine the Minimum Efficiency Reporting Value (MERV) of the air cleaner. Table B-1 shows the MERV parameters.

Table B-2 provides an approximate cross-reference of ASHRAE Standard 52.2 to ASHRAE Standard 52.1. This table also shows filter media guidelines.

B.3 DOP Penetration Test

For high-efficiency filters (HEPA filters), the normal test in the United States is the thermal dioctylphthalate (DOP) method. This test method is described in U.S. Military Standard MIL-STD-282. In this method, a smoke cloud of DOP droplets condenses from DOP vapor. (DOP is an oily liquid with a high boiling point.) The DOP smoke cloud is fed to the filter. The air leaving the filter contains the average concentration of penetrating smoke. Penetration, not efficiency, is usually specified in the test procedure because HEPA filters have efficiencies so near 100 percent. The two terms are related by the equation: Efficiency = 1 – Penetration. The DOP test results are commonly referred to as efficiency for 0.3 μm particles.

Table B-1
Minimum Efficiency Reporting Value (MERV) Parameters

MERV	Composite Average Particle Size Efficiency, % in Size Range 0.30-1.0 µm	Composite Average Particle Size Efficiency, % in Size Range 1.0-3.0 µm	Composite Average Particle Size Efficiency, % in Size Range 3.0-10.0 µm	Average Arrestance, % by Standard 52.1 Method	Minimum Final Resistance,[a] Pascal
1	N/A	N/A	$E_3 < 20$	$A_{avg} < 65$	75
2	N/A	N/A	$E_3 < 20$	$65 \le A_{avg} < 70$	75
3	N/A	N/A	$E_3 < 20$	$70 \le A_{avg} < 75$	75
4	N/A	N/A	$E_3 < 20$	$75 \le A_{avg}$	75
5	N/A	N/A	$20 \le E_3 < 35$	N/A	150
6	N/A	N/A	$35 \le E_3 < 50$	N/A	150
7	N/A	N/A	$70 \le E_3$	N/A	150
8	N/A	N/A	$85 \le E_3$	N/A	150
9	N/A	$E_2 < 50$	$85 \le E_3$	N/A	250
10	N/A	$50 \le E_2 < 65$	$85 \le E_3$	N/A	250
11	N/A	$65 \le E_2 < 80$	$85 \le E_3$	N/A	250
12	N/A	$80 \le E_2$	$90 \le E_3$	N/A	250
13	$E_1 < 75$	$90 \le E_2$	$90 \le E_3$	N/A	350
14	$75 \le E_1 < 85$	$90 \le E_2$	$90 \le E_3$	N/A	350
15	$85 \le E_1 < 95$	$90 \le E_2$	$90 \le E_3$	N/A	350
16	$95 \le E_1$	$95 \le E_2$	$95 \le E_3$	N/A	350

[a] The minimum final resistance shall be at least twice the initial resistance, or as specified above, whichever is greater. The minimum final resistance specified is for test purposes to determine minimum efficiency, not as a recommendation for actual use. Air cleaners used in homes may be changed or cleaned at a lower final resistance than that required by this standard.

Source: American Society of Heating, Refrigeration and Air-Conditioning Engineers, *ASHRAE Standard 52.2-1999 Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size.*

Table B-2
Cross-Reference of ASHRAE Standard 52.2 to ASHRAE Standard 52.1

MERV, Std. 52.2	Arrestance, Std. 52.1	Dust Spot Efficiency, Std. 52.1	Typical Controlled Particle Size and Contaminant	Typical Air Filter Media
20	N/A	N/A	≤0.30 μm Virus, carbon dust, all combustion smoke, radon progeny, sea salt	HEPA/ULPA filters
19	N/A	N/A		
18	N/A	N/A		
17	N/A	N/A		
16	N/A	N/A	0.3-1.0 μm All bacteria, most tobacco smoke, most smoke, cooking oil, droplet nuclei, insecticide dust, most face powder, most paint pigments	Bag filters Box filters
15	N/A	>95%		
14	>98%	90-95%		
13	>98%	80-90%		
12	>95%	70-75%	1.0-3.0 μm Legionella, humidifier dust, lead dust, coal dust, milled flour, auto emissions, nebulizer drops, welding fumes	Bag filters Box filters
11	>95%	60-65%		
10	>95%	50-55%		
9	>90%	40-45%		
8	>90%	30-35%	3.0-10.0 μm Mold, spores, hair spray, fabric protector, dusting aids, cement dust, pudding mix, snuff, powdered milk	Pleated filters Cartridge filters Throwaway
7	>90%	25-30%		
6	85-90%	<20%		
5	80-85%	<20%		
4	75-80%	<20%	>10.0 μm Pollen, dust mites, Spanish moss, sanding dust, spray paint dust, textile fibers, carpet fibers	Throwaway Washable Electrostatic
3	70-75%	<20%		
2	65-70%	<20%		
1	<65%	<20%		

Sources: American Society of Heating, Refrigeration and Air-Conditioning Engineers, *ASHRAE Standard 52.2-1999 Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*, and American Society of Heating, Refrigeration and Air-Conditioning Engineers, *2000 ASHRAE Systems and Equipment Handbook, Chapter 24: Air Cleaners For Particulate Contaminants.*

B.4 Tests of Portable Household Electric Cord-Connected Air Cleaners

The Association of Home Appliance Manufacturers (AHAM) has developed a standard for room air cleaners. This standard was recognized as an American National Standard in April 2002 and now bears the name ANSI/AHAM AC-1-2002. The characteristics of Standard ANSI/AHAM AC-1-2002 are summarized in Table B-3. The purpose of this standard, which is voluntary, is to:

- Establish uniform, repeatable procedures and standard methods for measuring product characteristics of portable household electric cord-connected room air cleaners

- Provide a means to compare and evaluate different brands of portable household electric cord-connected room air cleaners

Table B-3
Method for Measuring Performance of Portable Household Electric Cord-Connected Room Air Cleaners, ANSI/AHAM AC-1-2002

Characteristics	ANSI/AHAM AC-1-2002 Method for Measuring Performance of Portable Household Electric Cord-Connected Room Air Cleaners
Applicable Air Cleaners	Portable Electric Cord-Connected Room Air Cleaners that can be moved from room to room
Test Particulate Matter	Cigarette Smoke: particle sizes ranging from 0.9 μm to 1.0 μm diameter Arizona Road Dust: particle sizes ranging from 0.5 μm to 3.0 μm diameter Paper Mulberry Pollen: from 5 μm to 11 μm diameter
Measure of Air Cleaner Performance	Clean Delivery Rate (CADR) is the rate of contaminant reduction in the test chamber when the unit is turned on, minus the rate of natural decay when the unit is not running, times the volume of the test chamber as measured in cubic feet.[a]
Conformance	Voluntary
Safety Requirements	Recommended that household air cleaners meet UL Standard 867 (standard for electrostatic air cleaners) and UL 507 (standard for fans)

[a] CADR is always the measurement of a unit's performance as a complete system, and it has no linear relationship to air movement or to the characteristics of any particular filter media.

Source: Association of Home Appliance Manufacturers, *Method for Measuring Performance of Portable Household Electric Cord-Connected Room Air Cleaners*, ANSI/AHAM AC-1-2002.

Table B-4
ARI Standards 850 and 680

ARI Requirements	Commercial and Industrial Filter Equipment	Residential Filter Equipment
Applicable ARI Standard	ARI Standard 850-93 Commercial and Industrial Air Filter Equipment	ARI Standard 680-93 Residential Air Filter Equipment
Applicable Filters	Factory-made air filter devices and air filter media for removing particulate matter in inhabited spaces in commercial and industrial facilities	Factory-made air filter devices and air filter media for removing particulate matter in inhabited spaces in residents
Filters Not Applicable	HEPA filters Air filters removing abnormally high concentrations of specific contaminants	HEPA filters Air filters removing abnormally high concentrations of specific contaminants
Air Filter Device Classifications	Group I: Unit or panel type air cleaners Group II: Self-cleaning, self-renewable, or any combination thereof Group III: Extended surface type air cleaners Group IV: Electronic air cleaners Group V: All air filter media used in Group I, II, III or IV [a]	Group RI: Unit of panel type air cleaners Group RII: Extended surface type air cleaners Group RIII: Electronic air cleaners Group RIV: All air filter media used in Groups RI, RII, or RIII [a]
Method of Testing for Rating	Testing of Groups I, II, III, and IV air filters shall be in accordance with ASHRAE Standard 52.1 – 1992	Testing of Groups RI, RII, and RIII air filters shall be in accordance with ASHRAE Standard 52.1 – 1992
Method of Testing for Ozone Generation	Testing of Group IV shall be in accordance with ARI Standard 850 using an ozone monitor. No Group IV device shall have a maximum ozone concentration in the effluent air exceeding 0.050 ppm	Testing of Group IV shall be in accordance with ARI Standard 650 using an ozone monitor. No Group RIII device shall have a maximum ozone concentration in the effluent air exceeding 0.050 ppm
Conformance	Voluntary	Voluntary

[a] Only included for classification purpose. Performance ratings cannot be applied to filter media alone, but only to those air filter devices in which the media component has been tested.

Sources: Air-Conditioning and Refrigeration Institute, *Standard 850-93 Commercial and Industrial Air Filter Equipment*, and Air-Conditioning and Refrigeration Institute, *Standard 680-93 Residential Air Filter Equipment*.

B.5 Test Methods for Commercial and Residential Air Filter Equipment

The Air Conditioning and Refrigeration Institute has developed two standards for residential and commercial air filter equipment, ARI Standards 680 and 850. The main characteristics of the standards are presented in Table B-4. The purposes of the two standards are to establish:

- Definitions and classifications
- Requirements for testing and rating
- Specification of what constitutes standard performance requirements
- Conformance conditions
- Literature and advertising requirements

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