THE APPLICATION OF NANOFIBROUS MEMBRANES WITH ANTIMICROBIAL AGENTS AS FILTERS

by

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Abstract

Nanofibers are classified as fibers less than 1 micrometer in diameter. These fibers can be layered to form nanofibrous membranes, and these membranes offer great potential in the filtration industry. The membranes' smaller fiber diameters and pore sizes permit such filters to filter out more and smaller particulate. Additionally, antimicrobial agents can be incorporated into the membrane to inhibit fungal and bacterial growth on the membrane’s surface. This report evaluates nanofibrous membranes with antimicrobial agents and their potential in two specific locations: cleanrooms and protective environment rooms, where bacterial and fungal growth would have a detrimental effect on the process or occupant of the space.

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Dedication

I would like to dedicate this report to my parents, Chuck and Maureen Gregg, because of their constant support in all my endeavors. They have truly taught me that I can accomplish anything I set my mind to.

CHAPTER 1 - Introduction

This report will evaluate nanofibrous membranes in cleanroom and protective environment room applications and their ability to incorporate antimicrobial agents to inhibit *bacterial* and *fungal* growth on the membrane. Nanofibrous membranes are filter media comprised of fibers whose diameters are smaller than 1μm, and they have a large amount of surface area per unit mass (Graham et al., 2002). The report covers membranes' filtration characteristics and how they can be advantageous in removing small particulate from the air stream in the following instances. First, cleanrooms are spaces where particle concentration is controlled to protect the process or test occurring within the space (ISO, 1999). Second, protective environment rooms are found in healthcare facilities to protect patients with weakened immune systems from particulate and *bacteria* from other hospital occupants. Cleanrooms and protective environment rooms both require a high level of filtration to protect the occupant or process within the space. High levels of filtration are also considered when exhausting air from a space, for example a laboratory running experiments with deadly materials. Such air must be filtered to ensure that any hazardous materials discharged into the air are not transferred to the surrounding community in a dangerous concentration. Therefore, the report discusses replacing the required traditional High Efficiency Particulate Air (HEPA) filter with nanofibrous membranes with antimicrobial agents. Nanofibrous membranes are a fairly new type of filter media, but they offer great potential because of their fibers' small diameters and the small pores within the membrane.

Cross-contamination, the indirect transfer of *bacteria* or *contaminants* between occupants or objects, is a critical issue when dealing with cleanroom and laboratory applications as particulate could be transferred from one object to another within the space, thus altering test results. Also, health care facilities tend to be places where *cross-contamination* occurs if stringent design conditions are not met (NAFA, 2001). Both cleanrooms and protective environment rooms within hospitals require control of airborne contamination, which can be accomplished with a proper air filtration system. Also, both of these spaces could be compromised if *bacteria* or *fungus* accumulates on the filter media, so an antimicrobial agent can be added to suppress these *microorganisms*' growth. This document will evaluate the current filtration systems, assess the design requirements of protective environment rooms and cleanrooms, and evaluate the feasibility of nanofibrous membranes with antimicrobial agents for such filtration systems.

This report consists of six chapters. This chapter, chapter one, will provide background on the necessity of clean air and some of the main issues that could arise with improper filtration. The chapter begins by identifying issues involving filtration and how these issues can directly affect the building occupants, use, and mechanical equipment. The chapter then introduces nanofibrous membranes and their potential use as filters within a traditional air filtration system. Chapter two gives an overview of the history and discovery of filtration, an introduction of methods of filtration, and the tests used to determine a filter's efficiency. Chapter three contains information on various filter characteristics and parameters, types of commercial filters, and the process to select a filter. The chapter concludes with general information on the maintenance and cost of filters. Chapter four addresses nanofibrous membranes and properties that make them suitable for filtration applications and compares the filtration capabilities to those of traditional commercial filters. Chapter five introduces antimicrobial agents and how they apply to traditional filters and nanofibrous membranes, and then concludes with applications where nanofibrous membranes with antimicrobial agents could be used. Finally, chapter six concludes by addressing where further research is needed. Following the references is a glossary in Appendix A, which defines the terms which are italicized throughout the report. Next, Appendix B consists of acronyms and abbreviations used throughout the report. Finally, Appendix C includes republication releases for the tables and figures referenced within the report.

1.1 Importance of Clean Air

A heating, ventilating and air conditioning (HVAC) system that has proper filtration is important to prevent problems such as decreased efficiency, damage to mechanical equipment, the spread of *viruses* and *bacteria*, product contamination in a manufacturing process and many more. Clean air is important and even vital for people and equipment in a space to perform a specific function. However, clean air cannot be given a concrete definition as it is dependent on the space and its specific use. To clarify, an office building will have a different standard of clean air than a warehouse, and both will have a different standard of clean air than a patient room in a hospital. This also applies to different types of spaces within the same building; for example, an operating room within a hospital will have a different definition of clean air than the waiting area in the same hospital. Therefore, as designers, it is important to properly define the "clean air" needed for the space being designed, and understand that the design criteria to meet this definition will change based on the application.

Specifically, air filtration is an important consideration to achieve the defined clean air level for a given space. When designing a space for which the health and welfare of occupants is the primary concern, it is important to consider the size of particulate within the space. As particles become smaller in diameter they are able to travel further into the lung and cause infections. In particular, particles with diameters greater than 10μm generally do not get caught in the respiratory system, while particles with a diameter in the 3-10μm range can become caught in the lungs' cilia but are not considered *respirable* (SMACNA, 1998). However, particles with diameters smaller than 3μm are considered *respirable* particles, which means these particles can pierce the human lung when inhaled (SMACNA, 1998). If these particles become caught in the lung tissue, they have the potential to become *carcinogenic* (SMACNA, 1998). These particles become of greater concern when considering *immunocompromised* occupants, those with weakened immune systems, because their bodies are not capable of properly protecting themselves from these particles (ASHRAE HVAC Design Manual, 2003). Therefore, a designer must understand the potential for transmission of these particles through the air distribution system within healthcare facilities or other critical spaces, and how to remove the particles through proper filtration.

In addition to the concern about occupant health, particles smaller than 3μm become an issue within manufacturing or test facilities. While particles of all sizes could alter the final product being produced or tested, particles smaller than 3μm are more difficult to remove. In this situation, the occupant is not the main concern as the filtration system is required to protect the process. Spaces where clean air may be required to protect the specific function of the space could include a pharmaceutical manufacturing plant or a laboratory testing a specific chemical reaction. The introduction of any particulate into these spaces may alter the outcome of the product or test. Thus these spaces may have different filtration requirements depending on the level of clean air required within the space.

A third consideration for a proper filtration system is the need to protect the life and efficiency of the mechanical equipment serving the facility. Particulate accumulation on the mechanical equipment increases static pressure and reduces the equipment's efficiency; for example, the heating and cooling coils will not achieve the desired heat transfer from the coil to the air stream or vice versa. The accumulation of particles could also severely limit the airflow across the coils. Also if the equipment is not properly protected from particulate accumulation, the equipment will not last to its rated life. Both of these issues will result in higher costs for the building owner. Reduced equipment efficiency will result in increased energy consumption and higher energy bills while shorter equipment life will result in replacement units purchased earlier than if the equipment was properly protected. Although this is a major concern for a system, the scope of this report will not include further discussion on this issue; instead, the following section will introduce nanofibrous membranes and their potential as filters to protect the occupants and processes downstream.

1.2 Design Concept of Nanofibrous Membranes

Nanofibrous membranes are composed of *nanofibers*, which are fibers with diameters smaller than 1µm. *Nanofibers* have been incorporated into "protective clothing, biomedical applications including wound dressings… [and] structural elements in artificial organs and in reinforced composites" (Ahn et al., 2006, p. 1030). *Nanofibers* also offer great potential to the filtration industry, because of their larger surface area and smaller pore sizes when compared to current commercial filter media (Ahn et al., 2006). Nanofibrous membranes are currently produced by Donaldson Company Inc., Finetex Technology Co., Freudenberg Nonwovens and Amisol Ea Air Filters, for a variety of applications including dust collectors, air filters, water purification, and automotive filtration.

Nanofibrous membrane fiber range from 40-200nm in diameter, whereas traditional commercial filters' fibers range from 0.1-30µm, or larger, depending on the type of filter. *Nanofibers*' small diameters and long lengths have raised some initial concerns as they show similarities to asbestos fibers; however, while research has not shown that *nanofibers* have carcinogenic affects, further research is needed to confirm or disprove this concern. This report assumes the fibers do not have *carcinogenic* effects. If future research determines that these *nanofibers* are cancerous, their use should be discontinued. Meanwhile, nanofibrous membranes have great potential as filters because of their ability to remove small particulate from the air stream with a membrane thickness of only 100µm or smaller compared to traditional commercial filters ranging in thickness from 1 inch to 30 inches (Edelman, 2008). Shin, Chase and Reneker (2005) note that nanofibrous media are advantageous in filtration applications because of their *high efficiency* and economical energy cost, given the generally lower pressure drop and large surface area per unit mass. While nanofibrous membranes have much smaller pores than traditional commercial filters, they are still highly permeable to airflow; therefore, the pressure drop across the membrane is not greatly increased. Thus, a membrane with the same efficiency as a traditional filter may have a slightly smaller pressure drop because of the increased permeability.

These membranes have the potential to be installed as media on their own or to be affixed to another filter to increase efficiency. Installed on their own, they must be installed with a substrate, a *low efficiency* nonwoven mat, which acts as a support for the nanofibrous membrane and gives it greater physical strength, because of the membrane's weak and thin structure. Podgórski, Balazy, & Gradoń (2006) recommend that the substrate is to be relatively thin composed of "fibers…dozens of micrometers in diameter" (p. 6814), which are densely packed to provide the needed strength to the membrane. A commercially available disposable panel filter, further discussed in subsection *3.2 Filter Types*, could be used as the substrate. If a nanofibrous membrane were installed in a system without a substrate, it would become damaged quickly from the impact of particles being filtered from the air. Another possibility for installing *nanofibers* is to incorporate the fibers into other filter media at the time of manufacturing, to increase the filter's efficiency without drastically increasing the pressure drop across the filter. This report will focus on the idea of a nanofibrous membrane applied to a substrate and acting as a filter on its "own" to show the potential to replace traditional commercial filters. Figure 1 is a Scanning Electron Micrograph (SEM) of a nanofibrous membrane applied to a substrate.

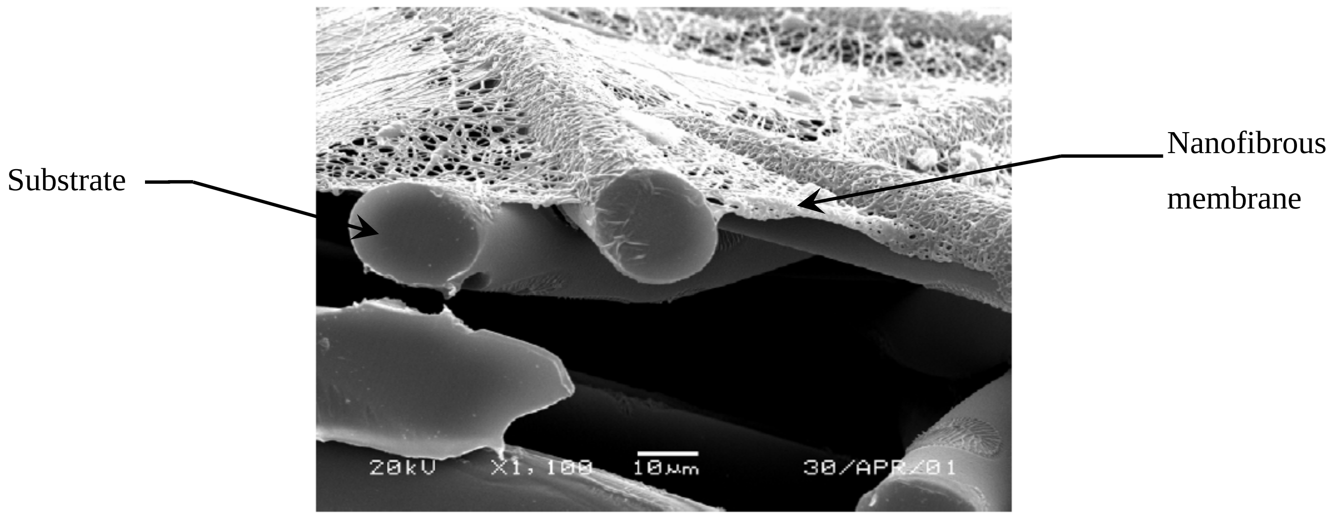

Figure 1: Nanofibrous membrane applied to a substrate
(Grafe & Graham, 2002, p. 4)

Figure 1 shows the drastic difference in fiber diameters and pore size of the nanofibrous membrane and its substrate. The nanofibers are approximately 250nm in diameter while the substrate's fibers are greater than 10µm in diameter (Graham et al., 2002). Nanofibrous membranes and *nanofibers* are a fairly new concept when compared to the early idea of filtration, but these membranes have gained great interest in the filtration industry, because of their construction and the ability to control the membrane composition. Nanofibrous membranes and their filtration parameters will be addressed further in a later chapter. Meanwhile, the following chapter will discuss the history of filtration, the methods of removing particles from the air stream, and the filter efficiency rating system. The rest of the report will address the structure and filtration characteristics of traditional commercial filters and nanofibrous membranes, and will conclude by discussing nanofibrous membranes with an antimicrobial agent for cleanroom and hospital protective environment room applications.

CHAPTER 2 - Filtration Background

This chapter will give a brief background on filtration, beginning with the history of filters and their various uses over the years. Next, the chapter addresses the filter's methods of removing particulate from the air stream and the methods of removal depending on the size of the particulate. Then, the chapter will discuss the current filtration standards that determine a filter's efficiency. The chapter will conclude with a brief overview of the various tests performed on filters to determine a filter's efficiency based on particulate size.

2.1 History of Filtration

Filters have been around for hundreds of years, but the early developments of filters did not involve HVAC systems as they are commonly used today. Figure 2 is a timeline depicting the first application of filters and the journey filters have taken with advancements in technology and increased concern for clean air within commercial buildings. The paragraphs following the timeline will discuss the major advancements of filter design and construction through the years.

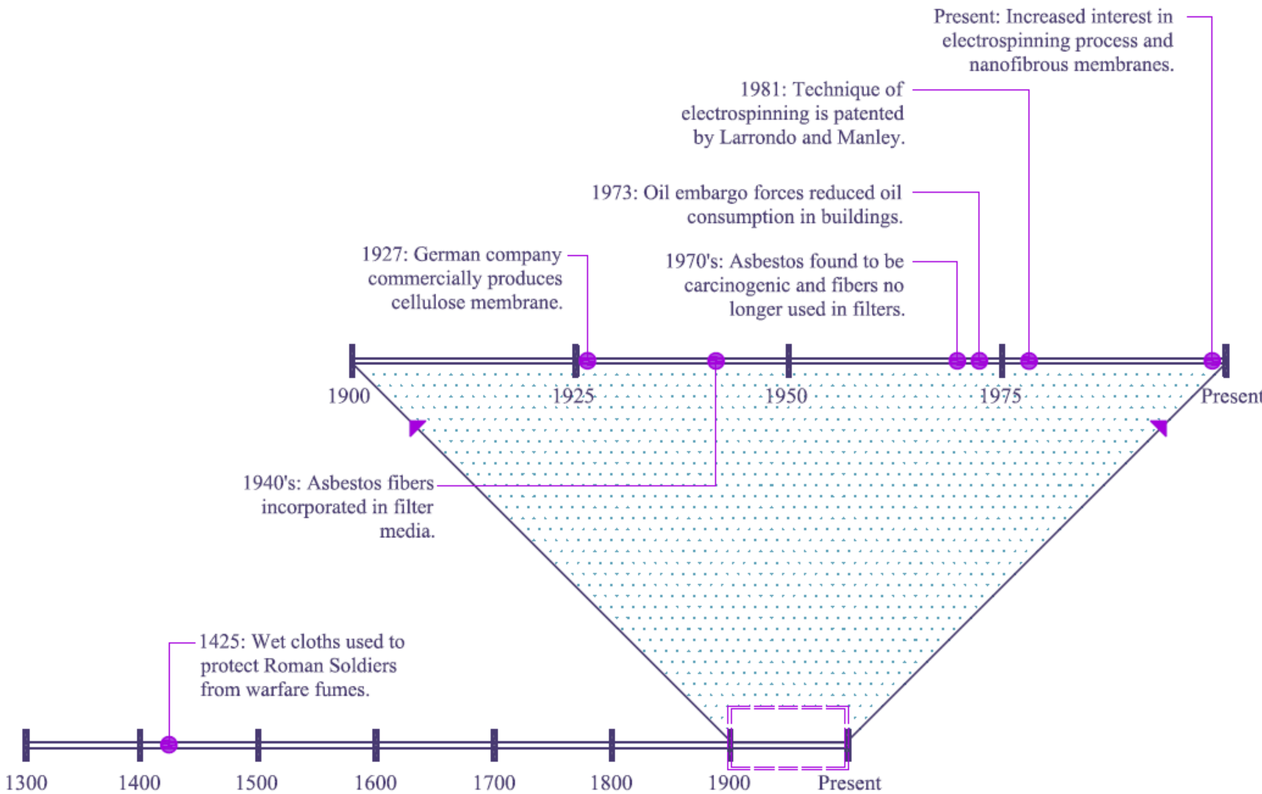

Figure 2: Filtration timeline

1425-1519: Roman soldiers used wet cloths to protect themselves from fume exposure in warfare (Spurny, 1998).

19^{th} Century: E. M. Shaw and John Tyndall of England created a filter mask for fire fighters constructed of cotton and wool (Spurny, 1998).

20^{th} Century: Great advancements were made during this era in understanding filtration and the idea of particle removal, although filtration for HVAC purposes had yet to be considered (Spurny, 1998).

1920-1930: In 1927, cellulose membranes were commercially produced as filters by Sartorius, a company in Germany, for use in colloid chemistry. (Spurny, 1998).

1930-1940: Filters of this era had very low filtration efficiencies and were constructed of porous materials such as fibrous glass, animal and synthetic fibers but were still used minimally in HVAC applications (Edelman, 2008). Also during this time period, N. L. Hansen created the first electrically charged filter by applying an electrically insulated resin to a wool filter (Spurny, 1998). Between 1934 and

1944, Formhals had a number of patents that used electrostatic forces to create polymer fibers, which showed the early developments of *electrospinning* (Sawicka and Gouma, 2006).

1940-1950: Albrecht and Kaufman of Germany developed a mask of fibrous pads during World War II to remove toxic chemicals within the air (Spurny, 1998). Filter construction changed during this time as filters started to incorporate asbestos fibers for approximately 20% of the fiber media (Spurny, 1998). The filters that incorporated asbestos fibers saw a major improvement in filtration efficiency because of the small diameters of the asbestos fibers (Edelman, 2008). HEPA filters comprising asbestos and cellulose fibers had an efficiency of 99.95%, removing particles smaller than 0.3μm (NAFA, 2001). Towards the end of this decade, filters started to become more common in building HVAC systems, but their main purpose was not to protect the occupants, but rather the mechanical equipment, as the filters were designed to reduce dust accumulation on the coils (Edelman, 2008).

1970-1980: Production of filters with asbestos fibers ceased because of the cancerous effects of the fibers if they the lungs of occupants (Spurny, 1998). Asbestos fibers were replaced by glass, carbon, and ceramic fibers, but these fibers had larger diameters than the asbestos fibers, resulting in decreased filter efficiency (Spurny, 1998). In 1973, the oil embargo forced companies and building owners to determine ways to reduce oil consumption, and a mandatory cutback by President Nixon required space heating to reduce petroleum consumption by 25%, (Carter, 1974). This forced buildings to incorporate more efficient systems. Selecting a filter with a smaller pressure drop was one method to reduce energy consumption because it decreased the amount of work the fan must exert to supply the same amount of air across the filter while still cleaning the air to maintain equipment performance.

1980-1990: Filters were installed to clean the air and protect the occupants given increased concern about indoor air quality (Edelman, 2008). Research continued to create fibers of smaller diameter as Larrado and Manley patented the *electrospinning* technique in 1981 (Sawicka & Gouma, 2006). *Electrospinning* is the process of applying an electrostatic force to a polymer solution to create fibers with diameters smaller than 1µm.

1990-Present: The *electrospinning* process and the production of *nanofibers* did not gain great interest until the mid-1990s (Sawicka & Gouma, 2006). A number of groups have researched the production and testing of membranes comprising electrospun *nanofibers* in filtration applications because of the membranes' small diameters, small pore sizes, and high permeability (Barhate & Ramakrishna, 2007).

2.2 Particle Filtration

Given that a filter's main purpose is to remove particulate and *contaminants* from the air stream to protect the occupants and mechanical equipment downstream, the following subsections will discuss particle sizes and means of filtration to remove these particles. Lastly, this section will address the idea of particle bounce and how it affects particle detachment from the filter media.

2.2.1 Particle Sizes

Prior to addressing the various methods of filtration, designers must understand the wide range of particle sizes found within the airstream. Filtration depends greatly on particle sizes, as the efficiency of a filter can change significantly depending on the desired size range of particulate being removed. Thus, a filter will have a higher efficiency in removing larger particles than particles with smaller diameters. The increased efficiency is due to the larger surface area of the particles; therefore, such particles have a greater chance of coming in contact with the surrounding filter media. The particle size is also of great concern when determining the level of clean air desired or required within the space. If a space has a specific and critical purpose, such as a laboratory or cleanroom, and dust and *bacteria* could greatly alter the results of the study, a filter with greater efficiency in removing dust and *bacteria* particles would be needed. Therefore, the definition of clean air depends on the space function and the occupants within the space. From these factors, the level of clean air must be determined by the designer.

Filters are designed to remove particles in the 0.3 to 10 *micron* range because particles of this size can be detrimental to the health of the occupants or to the HVAC equipment. The main focus of this report will be on particles on the smaller end of the range, 0.3-1.0 *microns*, since these smaller particles differentiate cleanroom and hospital protective environment room design applications from more typical design applications such as offices and cleanrooms. Figure 3 illustrates the wide range of particle sizes.

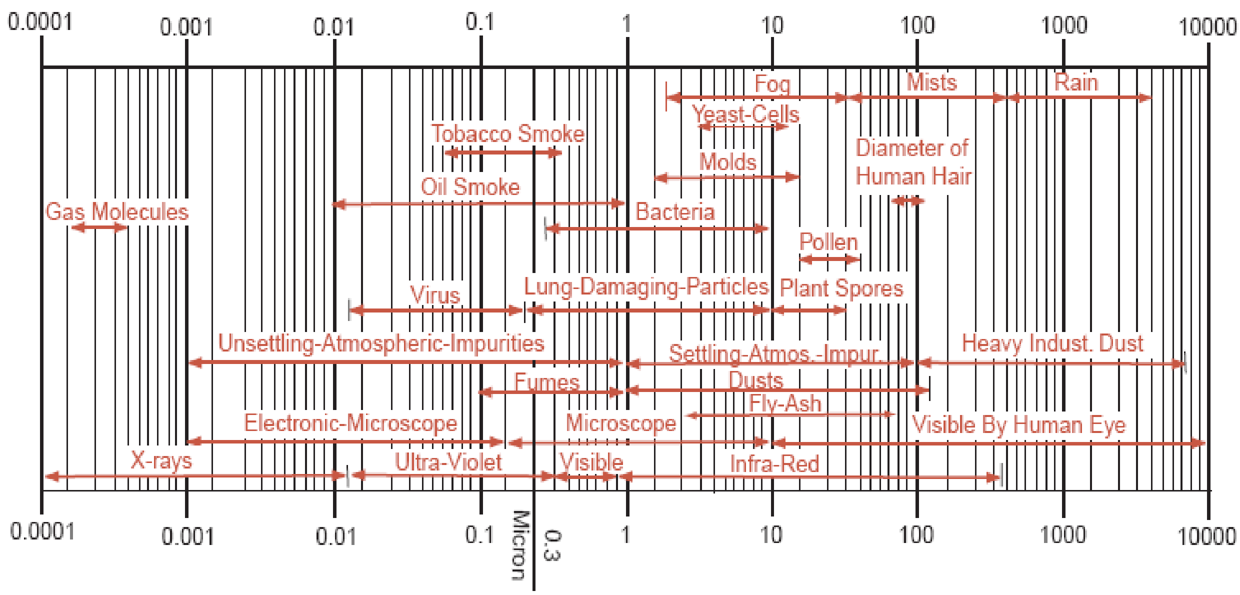

Figure 3: Relative size chart of common air contaminants

(Loren Cook Company, 1999, p. 47)

Figure 3 shows the size range of various particulates possible in the airstream; particles within the 0.3-1.0 *micron* range include fumes, *bacteria*, oil smoke, atmospheric impurities, and the larger particles of tobacco smoke. These particles are just barely visible to the human eye and are capable of penetrating and damaging the human lung. It is difficult to fully comprehend the size of these particles, because their diameters are measured in *microns*, which equates to 10^{-6} meters or 3.281×10^{-6} feet, or fractions of *microns*. Figure 4 shows the size relationship between a particle with the diameter of 10 *microns* (µm) and another particle with a diameter of 0.3µm.

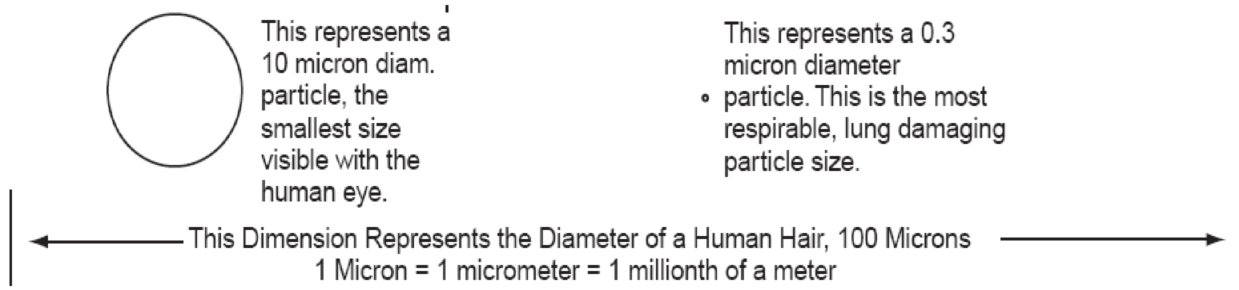

Figure 4: Particle size relationship

(Loren Cook Company, 1999, p. 47)

In Figure 4, both particles are then shown with respect to the diameter of a human hair, which puts into perspective the size of small particles. Depending on the relative size of the particle, the particle can be removed from the airstream by one of the five methods. Large, dense particles will be filtered out of the airstream in a very different manner than particles with small diameters. For this report, small particles will refer to particles with diameters smaller than 1.0 µm, and large particles will be classified as particles larger than 1.0 µm. The various filtration methods and the size of the particulate removed are discussed next.

2.2.2 Methods of Filtration

A filter can remove particulate through gravity, straining, inertial impaction, interception, and diffusion. This subsection will address each method of filtration and discuss the relative size of particles removed with each method. It is difficult to give a specific particle size range for each method of filtration because the size range is dependent on the specific filter, and the fiber diameters and pore sizes within the filter. However, a general particle size range in removing particulate by the various methods of filtration is shown in Figure 5.

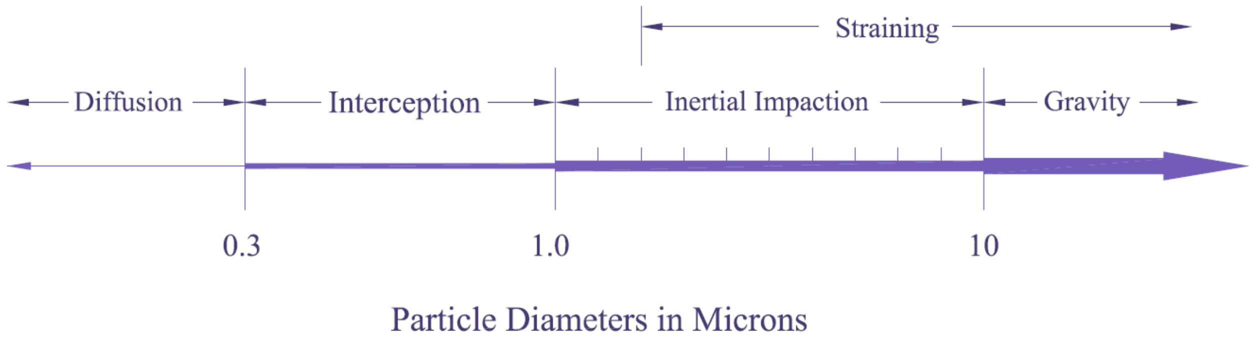

Figure 5: Particle size range for methods of filtration

(Barhate & Ramakrishna, 2007)

Gravitational filtration is for large particles, which Barhate and Ramakrishna (2007) state as particles greater than 10µm. Filtration due to gravity occurs when a particle is unable to follow the air stream and settles out of it before encountering the mechanical filter. These particles can be seen as dust accumulation on various surfaces within the space. Gravitational filtration is not a method of filtration within the filter but rather within in the space or duct system.

Straining, which is also known as sieving, occurs when particles in the air stream are larger than the free spaces between fibers within the filter, which causes the particle to become caught between the filter's media and removed from the air stream (Robinson & Oullet, 1999). Straining, illustrated in Figure 6, is the main form of filtration in *low efficiency* filters, often used as pre-filters for higher efficiency filters downstream. The *low efficiency* filters remove large pieces of dust and particulate from the air stream, increasing the life of the higher efficiency filters, which are more expensive to replace. The effects of straining can be observed by the accumulation of lint and large particulate on the surface of a filter (ASHRAE Handbook-HVAC systems and equipment, 2008). Throughout, this report references low, medium, and high efficiency filters. Their efficiencies will be further defined in section *2.3.1 Filter Rating.*

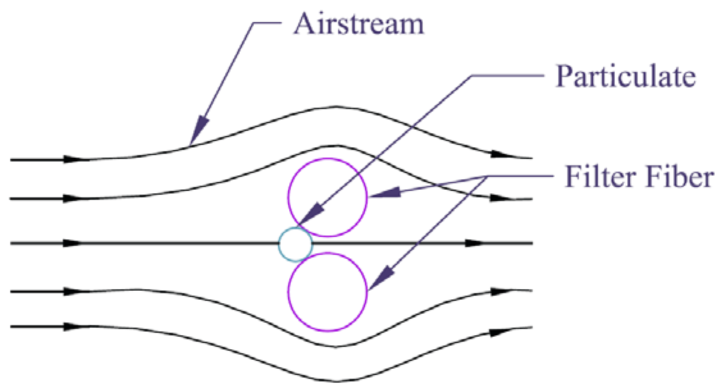

Figure 6: Particulate removal through straining

Inertial impaction occurs when a particle is dense and unable to follow the air stream around the filter's fibers (Robinson & Oullet, 1999). This results in the particle directly colliding with the filter media and becoming attached to the filter media as shown in Figure 7 (Robinson & Oullet, 1999; ASHRAE Handbook- HVAC systems and equipment, 2008). Inertial impaction is also seen in filters with lower efficiencies. The particles removed may have diameters smaller than the particles removed through straining, but their larger *density* results in the particles being filtered out of the air stream.

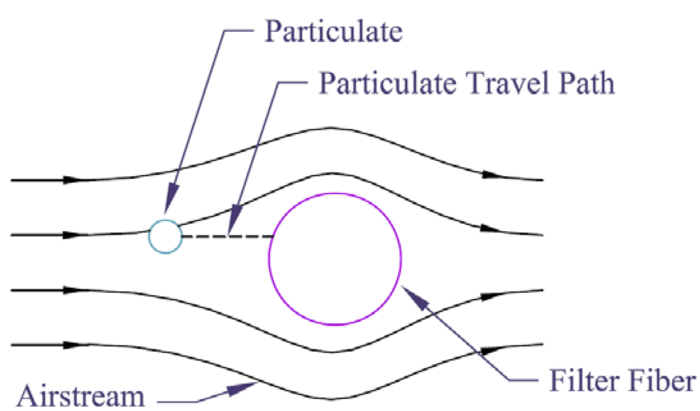

Figure 7: Particulate removal through inertial impaction

Direct interception occurs when a particle travels within the air stream close to the filter fiber and contacts the filter's media, becoming attached (HVAC Handbook- systems and equipment, 2008). Direct interception is illustrated in Figure 8. The particle's size is important when considering direct interception because larger diameter particles are more likely to be captured by surrounding filter media than particles with smaller diameters (Brown, 1993). Direct interception is the main method of filtration in medium to *high efficiency* filters and is less common for *low efficiency* filters. This is because of the larger voids in such filter media, which is efficient in removing particles large in mass and physical size that are unable to follow the airstream, but inefficient in removing particles that are capable of following the airstream. As the particles accumulate on the filter, the filter's efficiency in removing them through direct interception increases because particles within the airstream have a greater potential in attaching to particles that have already been captured by the filter media (ASHRAE Handbook- HVAC systems and equipment, 2008). Notably, the airflow velocity supplied across the filter must be low for direct interception to be effective because high velocity airflow could potentially dislodge particles from the filter media (NAFA, 2001). Maximum velocity of air flow is listed the manufacturer's data, and if exceeded, the filter performance is typically compromised.

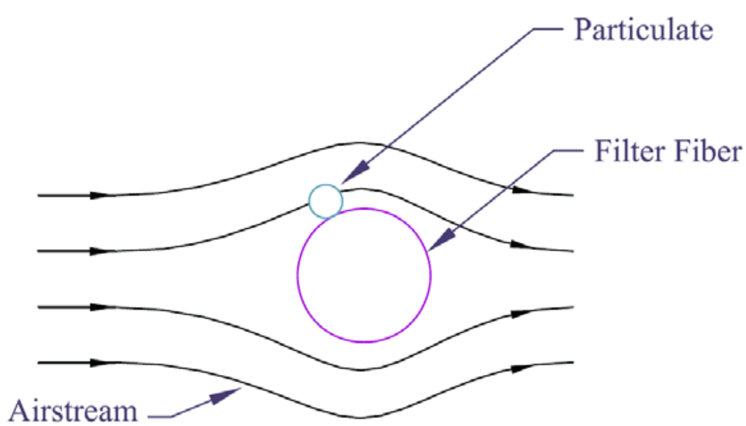

Figure 8: Particulate removal through direct interception

Diffusional deposition, also known as diffusion, occurs when a particle is small enough it bumps into the surrounding air molecules. The collision with surrounding air molecules causes the particle to have an irregular and uncontrolled path, which causes the particles to come close to surrounding filter media and thus be captured through interception as shown in Figure 9 (ASHRAE Handbook- HVAC systems and equipment, 2008). Diffusional deposition is the most common form of filtration for small particulate and *high efficiency* filters (Brown, 1993). As particles decrease in size and as velocity of the airstream increases the efficiency of filtration through diffusional deposition increases (ASHRAE Handbook- HVAC systems and equipment, 2008). This increase in efficiency occurs because the less controlled paths of the particles force them to collide with air molecules and other particles, whereas, the path of large particles would not be affected by surrounding air molecules and smaller particles. As is the case with all filtration methods, as particles accumulate on the filter media, filtration efficiency increases through interception, which also holds true for diffusional deposition because the particles in the air stream collide and attach to the particles that have already been captured by the filter media (ASHRAE Handbook- HVAC systems and equipment, 2008).

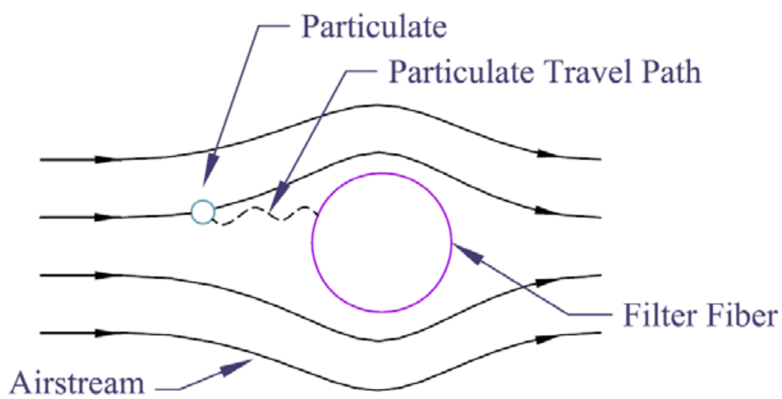

Figure 9: Particulate removal through diffusional deposition

This section focused on the means of removing particulate from the airstream as that is the main purpose of a filtration system, although one concern that needs to be discussed is the potential for particles not to be removed from the air stream. The following subsection will address this issue of particle detachment.

2.2.3 Particle Detachment

Some particles will be capable of making it completely through the media without being filtered out, simply because they are small enough to not be captured by the filter media. The amount of particulate that can penetrate the filter without being removed depends on the filter's efficiency. A filter with a higher efficiency is capable of removing more particulate; therefore less particulate passes through the filter compared to that in a filter with lower efficiency. Also, particles may potentially come in contact with filter media but become detached and re-enter the air stream. This concept is known as particle bounce. Any increase in the air stream's velocity will increase the effects and efficiency of diffusional deposition, but it can also increase particulate bounce, resulting in the particles detaching from the fiber they initially contacted. Particle bounce occurs with the transfer of energy as a particle collides with a fiber (Brown, 1993). A particle will have an initial velocity of V_i and a reduced velocity, immediately after the collision, of V_f, where both variables are measured in ft/s or m/s. The reduced velocity will depend on the coefficient of restitution, e_r, which is unitless. These variables are represented in the equation,

$$V_f = e_r V_i \quad (1)$$

Determining if the particle will become detached from the filter media and re-enter the air stream depends on the particle's velocity after its collision with the filter fiber. To clarify, a particle that contacts a fiber through inertial impaction has a greater chance of leaving the surface, compared to any other means of filtration, because the particle has a larger initial velocity, thus a larger velocity after impact (Brown, 1993). The larger velocity after impact yields a higher kinetic energy, which increases the distance the particle bounces away from the fiber, and potentially prevents it from re-entering the air stream. Particle detachment is most likely during the moment of collision with a filter fiber; therefore, a particle that does not bounce when it contacts the fiber will rarely become detached from the filter media later (Brown, 1993).

Particle detachment causes concern for designers because particles re-enter the airstream and thus can potentially be transported to the conditioned spaces. For example, the particle might pass through the filter after becoming detached because of the various pore sizes and fiber diameters within a filter. Variation in fiber diameters and pore sizes results in varying efficiencies across the filter, which may allow particulate that detaches to make it through the rest of the filter media. This creates problems with the design when particles expected to be removed by the filter, find their way into the occupied spaces. Since particle removal is directly related to the efficiency of the filter, to create a direct comparison between different filters and their efficiencies, a set of standards were created to provide consistent testing procedures.

2.3 Filtration Standards

This section will describe the standard rating system developed to determine a traditional filter's rated efficiency based on the amount of particulate removed of a specified size range. The section will also address the standard that developed the testing procedures and rating system for filters, and then discuss the modifications made to the standard over time to more effectively compare filter efficiency to specified particle size.

2.3.1 Filter Rating

Currently, a filter's efficiency is classified based on the Minimum Efficiency Rated Value (MERV) rating system. MERV was developed by the American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) and the American National Standards Institute (ANSI) and documented in ANSI/ASHRAE Standard 52.2-2007- *Method of Testing General Ventilation Air Cleaning Devices*. This standard defines the testing methods for determining a filter's efficiency, which is rated by the percent of particulate removed with diameter in the 0.3-10 micrometer range. As the MERV numerical rating increases, the associated filter's efficiency increases in removing particulate. The MERV rating system allows a comparison of filter efficiencies in removing particulate in one of three ranges: 0.3-1.0µm, 1.0-3.0µm, and 3.0-10.0µm.

ANSI/ASHRAE Standard 52.2 (1999) explains how the 0.3-10µm size range was determined to test filters. The upper limit of 10µm was selected as particles of this size may cause health problems if they become caught in the occupant's nose (ANSI/ASHRAE, 1999). Particles larger than 10µm are unlikely to remain in the airstream long enough to make it to the filter; therefore, these particles are neither considered nor tested against the MERV rating system (ANSI/ASHRAE, 1999). However, particles with diameters of approximately 10µm are known to cause problems with mechanical equipment because they deposit onto coils, which leads to biological growth and corrosion of the coils (ANSI/ASHRAE, 1999). Finally, the lower limit of 0.3µm was selected because of the commercial availability of equipment that is capable of counting particles of this size (ANSI/ASHRAE, 1999).

Table 1 was recreated from ANSI/ASHRAE Standard 52.2 (2007) and shows the efficiencies of MERV filters for three particulate size ranges, 0.3-1.0µm, 1.0-3.0µm, and 3.0-10.0µm. As the particulate size range decreases, each specified MERV filter has a lower efficiency for removing these particles as smaller particles are more difficult to capture. The table shows that MERV 12 filters and lower are inefficient for removing particulate in the 0.3-1.0µm range, but are capable of removing particulate in the larger size ranges. The information provided in this table is important to designers because depending on the necessity to remove particulate in the 0.3-1.0μm range, a filter with a lower MERV rating may be acceptable in some applications and not in others. Given the importance of this size range for cleanrooms and protective environment rooms applications, this particle size column has been highlighted in red in Table 1.

Table 1: Percent of particulate removed by size for MERV filters

Standard 52.2				Approx. Std 52.1 Results	
MERV	Average Particle Size Efficiency, % in Size Range, µm			Dust Spot Efficiency	Arrestance
	0.30-1.0	1.0-3.0	3.0-10.0		
1	n/a	n/a	< 20	< 20	< 65
2	n/a	n/a	< 20	< 20	65-70
3	n/a	n/a	< 20	< 20	70-75
4	n/a	n/a	< 20	<20	75-80
5	n/a	n/a	20-35	< 20	80-85
6	n/a	n/a	35-50	< 20	85-90
7	n/a	n/a	50-70	25-30	> 90
8	n/a	n/a	≥ 70	30-35	> 90
9	n/a	< 50	≥ 85	40-45	> 90
10	n/a	50-65	≥ 85	50-55	> 95
11	n/a	65-80	≥ 85	60-65	> 95
12	n/a	≥ 80	≥ 90	70-75	> 95
13	< 75	≥ 90	≥ 90	80-90	> 98
14	75-85	≥ 90	≥ 90	90-95	> 98
15	85-95	≥ 90	≥ 90	> 95	n/a
16	≥ 95	≥ 95	≥ 95	n/a	n/a

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For the purpose of this report, *low efficiency* filters will mean filters with Minimum Efficiency Rated Value (MERV) ratings less than 6, *medium efficiency* filters will mean filters with MERV ratings between 7 and 12, and lastly, *high efficiency* filters will mean filters with ratings greater than MERV 13. These relative efficiencies are equivalent to the stated efficiencies in National Air Filtration Association's (NAFA) *Installation, operation and maintenance of air filtration systems* (1997). Depending on the space served, different filter types and MERV ranges are recommended from Standard 52.2-2007. Table 2 provides a list of applications where various traditional commercial filters would be selected relative to the particle size and MERV rating. The table illustrates that less stringent applications, such as residential and some commercial applications, typically use filters with lower MERV ratings. Applications with critical air cleanliness, including health care facilities and cleanrooms, use filters with higher MERV ratings.

Table 2: Filter applications

MERV	Particle Range	Filter Type	Applications
1-4	> 10 µm	Disposable panel	Minimum residential filtration, window AC units
5-8	3.0-10 µm	Pleated or disposable panel	Commercial buildings, better residential filtration, industrial workplaces
9-12	1.0-3.0 µm	Bag	Superior residential, better commercial filtration, hospital laboratories
13-16	0.3-1.0 µm	Bag	Superior commercial, general surgery, hospital inpatient care
17-20	≤ 0.3 µm	HEPA/ULPA	Cleanrooms, pharmaceutical manufacturing, locations with carcinogenic or radioactive materials, orthopedic surgery

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Prior to the MERV rating system, a filter's efficiency was only compared to other filters' efficiencies, but the particle size range was not considered. Fortunately, the new testing procedures allowed for better comparison and evaluation of filters and their ability to remove particulate from the air stream. Meanwhile, ASHRAE Standard 52.2 is continually being updated to incorporate new technology and better practices. These changes to the document are further discussed in the next sub-section.

2.3.2 Change in Standards

Filtration testing procedures were first specified by ASHRAE Standard 52.1-1992, *Gravimetric and Dust-Spot Procedures for Testing Air-Cleaning Devices Used in General Ventilation for Removing Particulate Matter*. The standard included tests to determine the "filter resistance as a function of flow…[,] resistance rise when a coarse synthetic dust was fed to the filter[,] and dust removal efficiency" (Tronville & Rivers, 2006, p. 60) at specified particulate size ranges. These tests provided means to evaluate filters by comparing their performance, but the tests were unable to directly compare the efficiency with a specified size range of particles because Standard 52.1-1999 did not have provisions to measure the effectiveness of removing particulate of a certain size range (Tronville & Rivers, 2006; ASHRAE, 1992). The lack of more precise efficiency data gathered per the testing procedures outlined in ASHRAE Standard 52.1-1992 led to the development of Standard 52.2-1999.

The new standard, ASHRAE Standard 52.2, incorporated modifications that included "methods that determine filter efficiency vs. particle diameter" (Tronville & Rivers, 2006, p. 60). McQuinston, Parker and Spitler (2005) state that the new testing procedures introduced in 52.2-1999 were primarily created for *high efficiency* filters. The former standard, Standard 52.1-1992, states that the "standard is not intended for testing air cleaners exhibiting ASHRAE dust-spot efficiencies of greater than 98%" (ASHRAE, 1992, p. 1), which equates to a MERV 16 filter, and so this clause was removed from the scope when Standard 52.2 was created. Standard 52.2 continues to be updated as new technologies are discovered and spaces have increased filtration requirements, the most recent being published in 2007. As standards continue to change and become more stringent, Tronville and Rivers (2006) note the importance of the filter testing conditions adequately representing practical applications and installations to give realistic evaluations of the tested filters.

2.4 Filter Testing

A filter's efficiency is attainable through various tests depending on the type of filter being analyzed. The testing of a filter's efficiency is important to designers because different testing procedures apply to filters with different efficiencies. Filters with low efficiencies undergo a different test than filters with medium and high efficiencies, whereby, for instance, filter's efficiency increases, the tests become more stringent. It is more critical that *high* *efficiency* filters meet their required performance to ensure the space is properly protected. The following paragraphs will explain the weight arrestance test, the staining test, the particle concentration efficiency test, and the dioctphthalate (DOP) efficiency tester, and the procedure for each test to determine the filter's efficiency. The subsections will also address the type of filters generally analyzed with each efficiency test.

2.4.1 Weight Arrestance Test

The weight arrestance test, based on ASHRAE Standard 52-76 "Method of Testing Air Cleaning Devices in General Ventilation for Removing Particulate Matter", which originated in 1968 (Purchas, 1996),is applicable when the mass of dust is the main concern to the mechanical system (ASHRAE Handbook- HVAC systems and equipment, 2008; Purchas, 1996). The weight arrestance test is performed with a known weight of test dust added to the air stream and drawn over the test filter (Sutherland, 2008; Purchas, 1996). The synthetic dust used in the weight arrestance test is coarse with large particle diameters (ANSI/ASHRAE, 1992). After the test is complete, the filter is weighed and compared to the initial weight of the filter. The change in the filter's weight is compared to the known amount of test dust that was added to the airstream to determine the filter's efficiency (Sutherland, 2008). The closer the increase in the filter's weight is to the initial weight of dust added to the air stream the more efficient the test filter is in removing particulate in the size range of the test dust. The weight arrestance test is used to test the efficiency of *low efficiency* filters, such as panel filters, because they are designed to remove large pieces of dust and particulate. The weight arrestance test would not be used for *high efficiency* filters because it is not precise enough to determine the efficiency of small particulate removal since a much smaller change in weight would occur creating results that would be less accurate.

2.4.2 Staining Test

The staining test, also known as the atmospheric dust spot efficiency test, is based on ASHRAE Standard 52-76. The test is performed by drawing ambient atmospheric dust, as stated in Standard 52.1-1999, through a test filter, and the amount of stain on the filter represents the amount of particulate removed from the air stream (Sutherland, 2008). The greater the amount of stain on a filter, the higher the filtration efficiency for that filter demonstrating it is able to remove a large amount of the atmospheric dust. An opacity meter monitors the concentration of stain, which gives a more exact measurement of the amount of particulate drawn through the filter (Purchas, 1996). The dust spot is used to test *medium efficiency* filters as it is capable of testing for smaller particulate compared to the weight arrestance test, but it is still inaccurate for testing *high efficiency* filters.

2.4.3 Particle Concentration Efficiency Test

The particle concentration efficiency test uses *aerosols* with particle diameters smaller than 1μm to test the filters (Sutherland, 2008). A device that measures the particle concentration within the air stream is installed upstream and downstream of the filter, after which, test dust is added to the air stream and drawn across the filter. After all of the air and test dust are supplied, the particle concentration upstream of the filter is compared to the particle concentration downstream (Purchas, 1996). The difference in the two concentrations yields the filter's efficiency in removing particles of the size range of the test dust. The efficiency of a filter can be determined by the particle size removal efficiency (PSE) equation:

$$PSE = [1- (PC_d / PC_u)] \times 100 \quad (2)$$

where PC_d and PC_u are the particle concentration downstream and the particle concentration upstream of the test filter, respectively (ANSI/ASHRE, 2007). This equation determines the measured efficiency of the filter in removing particulate within the air stream, by comparing the initial concentration of particles upstream of the filter to the concentration of particles downstream. The greater the difference between the two concentrations, the more efficient the filter is at removing particles within that size range. The particle concentration efficiency test is used on *higher efficiency* filters, including HEPA filters.

2.4.4 DOP Efficiency Tester

The DOP efficiency tester is for HEPA filters and measures the penetration of particles through the filter, which equates to the filter's efficiency. The DOP tester also measures the pressure drop of the filter being tested (NAFA, 2001). The test *aerosol* is required to be *monodispersed*, meaning all particles are of the same size, to ensure the test can accurately determine the filtration efficiency of removing particles of a specified diameter (NAFA, 2001). This is important when testing HEPA filters because they are required to have an efficiency of 99.97% in removing particle with 0.3μm diameters. The test starts with hot liquid DOP, which is then cooled so the vapor condenses and forms liquid *aerosol* with consistent diameters of

0.3μm (NAFA, 2001). Concern has risen about DOP as the test *aerosol*, because DOP has potentially *carcinogenic* properties, and this has led to some facilities switching to less hazardous materials, such as DES (diethylsebacate), for the test aerosol (NAFA, 2001).

CHAPTER 3 - Traditional Filtration Systems

This chapter addresses traditional air filtration systems and the characteristics of filters that are commonly used in commercial HVAC design. First, the chapter will define filter characteristics that directly affect the filtration process and discuss five different types of commonly used commercial filters based on construction, filtration efficiency, and typical applications. The chapter then will outline a step by step process for selecting the proper filter for a system and items to consider when selecting one filter over another. The chapter will conclude with a discussion of the operational life and required maintenance of filters and their general costs.

3.1 Filter Composition

A filter's ability to remove particulate from the air stream depends on the filter's material and construction. The following paragraphs describe the different characteristics of filters including filter media, fiber diameter, airflow resistance, and efficiency and how each of these characteristics impacts performance.

3.1.1 Filter Media and Fiber Diameter

A filter can be constructed from a variety of materials depending on its use; however, filters are commonly made of metal, glass, synthetic, fiberglass, cellulose or carbon fibers. Filter media vary because of the need for specific filtering capabilities attained by using different diameters of fibers. This section will generally discuss filters comprising of synthetic fibers and glass fibers, as these are the most common materials in today's commercial filters.

Flat panel and pleated filters are typically constructed of cotton polyester blends or synthetic blends, while higher efficiency filters may be constructed of synthetic media, fiberglass or cellulose fibers (Edelman, 2008). Polyester is the most common synthetic fiber, but polypropylene, nylon and modacrylic fibers can also be used (NAFA, 2001). Synthetic fibers have a greater physical strength compared to glass fibers; therefore, synthetic fibers are generally used in filters required to remove larger particulate, minimizing the concern about potential damage (NAFA, 2001). Synthetic fibers also have a variety of fiber diameters, depending on the specific synthetic material used, although Purchas (1996) notes that cellulose fibers are approximately 30μm. Synthetic fiber diameters are measured by denier, which is a measurement of weight but is associated with a fiber diameter (NAFA, 2001). Denier is a universal comparison measurement for different fiber materials and is determined based on the weight of a 29,520 ft (9000 m) long fiber of a specified diameter (NAFA, 2001). Table 3 shows "some relationships between typical polyester fiber denier and diameters in micrometers" (NAFA, 2001, p. G-3). The table shows that the increase in denier and fiber diameter is not a linear relationship. For example, a six denier fiber equates to a diameter of approximately 25µm, while a 40 denier fiber correlates to a 64µm fiber diameter.

Table 3: Denier and fiber diameter relationship

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Denier	Diameter (µm)
1	10.1
2.25	15.2
3	17.5
6	24.8
15	39.2
25	50.6
40	64
100	101.3
200	143.2

High efficiency filters are constructed of glass fibers with diameters in the range of 4µm to less than 0.5µm, which are significantly smaller than those for both cellulose and synthetic fibers (Purchas, 1996). High Efficiency Particulate Air (HEPA) and Ultra Low Penetration (ULPA) filters are made of glass fibers with even smaller diameters as the fibers can have diameters as small as of 0.1µm. Glass fiber diameters are not compared to denier because their diameters are much smaller than these in the denier comparison, as shown in Table 3. As a filter's fibers decrease in diameter and the fibers are placed closer together, the filter's efficiency in removing particulate increases, which explains why glass fibers are beneficial in higher efficiency filters. The smaller diameters of fibers are capable of forming smaller pores within the filter, which enables the filter to remove more smaller particulate through straining, interception, impaction and diffusion.

3.1.2 Airflow Resistance

The airflow resistance is the measured pressure drop across the filter at a given velocity of air flow (ASHRAE Handbook- HVAC systems and equipment, 2008). The pressure drop is directly influenced by the filter's thickness and fiber diameters, the air's coefficient of viscosity, and the velocity across the filter media (Brown, 1993; Whyte, 2001). Generally, a filter with a greater thickness and smaller fiber diameters will typically have a greater pressure drop than a filter with a smaller thickness and larger fiber diameters because of the higher porosity of the filter. This is because a thicker filter with smaller fiber diameter offers greater filter surface area, which increases the resistance to airflow. The difference in pressure drop between these two filters is a result of the air's ability to freely move through the filter without changing direction. The pressure drop is proportional to the air velocity supplied across the filter; therefore, an increase in the air flow rate will directly increase the resistance across the filter. Reduced airflow velocity across a filter will increase filter area to provide the needed air to the space. A filter generally has a maximum air flow velocity in which the filter functions properly and this is based on the manufacturer's data.

Airflow resistance is an important characteristic for selecting a filter because it affects the energy consumed by the mechanical equipment. Thus, a filter with a greater pressure drop than another will require more energy from the fan to draw the same amount of air across the filter. If energy consumption is a major concern, the designer should select a filter with a lower pressure drop while still meeting required MERV ratings because it will reduce energy costs within the system as a result of the fan overcoming a smaller resistance to supply the required amount of air (Matela, 2006). Arnold, Matela, and Veeck (2005) demonstrate the difference in energy consumption by comparing two filters with similar efficiencies but slightly different initial pressure drops. Table 4 illustrates the different energy costs of filters with pressure drops that differ initially by 0.1" w.g.

Table 4: Energy cost comparison

(Arnold et al., 2005)

	Filter A	Filter B
Filter Style	12" Rigid Filter	12" Bag Filter
Initial Pressure Drop	0.54" w.g.	0.44" w.g.
Final Pressure Drop	1.00" w.g.	1.00" w.g.
Energy Costs	$290/ year	$276/ year

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The energy costs listed in the table assume that operation would occur 24 hours a day, 365 days a year with an efficiency (η) of 58% (Arnold et al., 2005). The following equation was used to determine the energy consumption,

$$\frac{Q(dP)t}{1000\eta} \qquad (3)$$

where Q and dP are airflow and pressure, respectively, across the filter. The energy costs for each filter were then determined based on an electric utility rate of $0.08/kWh (Arnold et al., 2005). The final pressure drop of a filter would be determined by the manufacturer's recommendation, but for this comparison a final pressure drop of 1.00" w.g. was selected. The table illustrates that a filter with a slightly larger initial pressure drop resulted in $14 extra energy costs per year. The difference in energy costs shown in Table 4 is for a single filter, so the total energy savings would depend on the total number of filters installed within the system. For example, Arnold et al. (2005) compare a system with 40 filters, which resulted in a $569 annual energy savings, by selecting a bag filter over the rigid filter. Selecting a filter with a lower initial pressure is an important concept for designers as it could offer large energy savings for the owner over the life of the filter, as demonstrated in the study performed by Arnold et al. (2005). Finally, this comparison does not suggest that one type of filter be used over another but rather demonstrating the different energy costs of filters with different initial pressure drops, as Table 4 does not consider the initial cost of the two filters, which is another factor that should be considered when selecting a filter.

3.1.3 Filter Efficiency

Possibly the most important filter characteristic to consider is the filter's efficiency. Efficiency is a filter's ability to capture particulate and remove it from the airstream (ASHRAE Handbook- HVAC systems and equipment, 2008). Each filter is given a MERV rating that corresponds to an efficiency as classified by the MERV rating system developed by ASHRAE.

Over the course of its life, the filter will become more efficient in removing particles because as particles accumulate on the filter's surface, there is a greater chance of particles becoming attached to particles that are already captured within the filter media. In fact, some filters, when initially purchased, may not perform to their rated efficiency because that efficiency may be based on the filter having some particle accumulation on the filter surface (SMACNA, 1998). If a space must have a specified MERV rating for its filtration system, the designer should verify with the manufacturer if the listed efficiency of the filter is initial efficiency or sustained efficiency. Along with the filter's efficiency increasing over time, the pressure drop across the filter increases. Thus, as the filter accumulates more particulate and becomes more beneficial to the occupants because more particulate is removed from the airstream, delivering cleaner air to the space. The increased pressure drop also results in increased energy consumption and greater stress on the mechanical equipment. Therefore, the designer must determine at what point the loaded filter is uneconomical for the system due to the additional pressure drop. Determining when a filter should be replaced will be discussed further in subsection 3.4 Filter Life and Maintenance.

While *high efficiency* filters offer "cleaner air" because they remove more particles from the air stream, they are not installed in every application. Many times filters with a greater efficiency have a larger pressure drop across the filter because of the smaller pores and fiber diameters within the filter media. The designer must consider what the most important aspect of the system design is: removing a greater amount of particulate within a certain size range or installing a smaller fan, resulting in lower energy consumption. Some HVAC systems may have a limitation to the amount of static pressure the system is capable of overcoming, therefore limiting the maximum pressure drop of a filter for the system. A designer may encounter this situation when designing or redesigning a space within an existing system, in which case the equipment is already installed and has a maximum resistance it can overcome and still function properly.

In some applications, all particulate of a certain size range must be removed for the space and/or the occupants to be protected, for example in cleanrooms and protective environment rooms in hospitals. In these cases, a filter with a higher MERV rating would be required to ensure the particles are removed. Other applications may favor lower energy bills, while small particles are not a major concern within the space, such as in an office building or a retail space. In these applications, a lower efficiency filter would be sufficient. Depending on the level of filtration needed for the space, a variety of filters can meet such filtration requirements. The different types of traditional commercial filters will be addressed in the following subsection.

3.2 Types of Filters

When designing an air filtration system for a HVAC system designers can choose from various types of filters to remove particulate from the airstream. The following paragraphs will address flat panel, pleated, bag, HEPA, and ULPA filters and their construction, filtration characteristics, and types of applications. This section will also briefly introduce electronic air cleaners, while the less traditional nanofibrous membranes will be discussed in chapter four.

The flat panel filter is a *low efficiency* filter as it typically removes particles from the air stream through straining and impaction (Edelman, 2008). This filter effectively removes large particulate or dust, but is unable to remove *respirable* size particulate, which are particles smaller than 3µm (Dagostino & Wujek, 2005). Flat panel filters are generally rated as MERV 5 or lower because they have an efficiency of less than 35% in removing particles within the size range of 3-10 *microns* and are inefficient at removing particulate in the 0.3-1.0µm and 1.0-3.0µm range (Edelman, 2008). The flat panel filter is sometimes called a throw away filter because it is inexpensive relative to other filters (Edelman, 2008). These filters are used in residential applications where minimal filtration is required, or they are frequently installed in commercial applications as a pre-filter (ANSI/ASHRAE , 1999). As a pre-filter, the flat panel filter would be located upstream of a more efficient and more expensive filter. The flat panel filter would remove large particulate and dust from the air stream, which would extend the life of the higher efficiency filter downstream. Since flat panel filters are generally less expensive than higher efficiency filters, this would save the owner money as the *high efficiency* filter would not have to be replaced as often. Figure 10 is an example of a flat panel filter comprising polyester fibers.

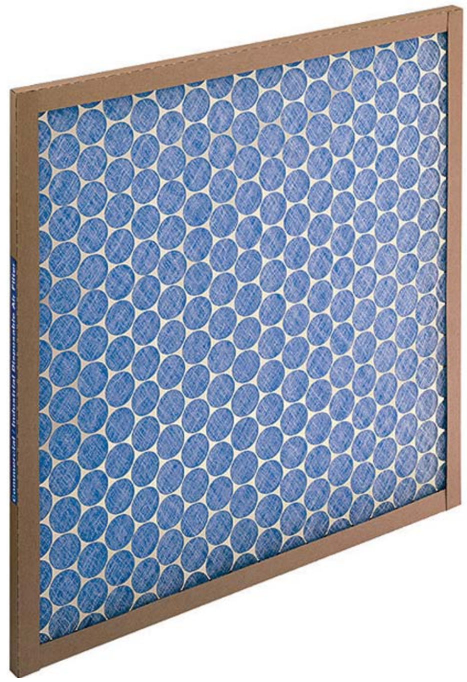

Figure 10: Flat panel filter
(Koch Filter Corporation)

Pleated panel filters are typically *medium efficiency* filters constructed of synthetic fibers or a blend of cotton and polyester fibers, and the filter thickness generally ranges between 1-4 inches, but it can be thicker (Edelman, 2008). These filters are sometimes referred to as extended surface filters because the filter media area is greater than the filter's face area (NAFA, 2001). These filters remove particles through straining, impaction, interception, and diffusional deposition (Edelman, 2008). Pleated filters are typically MERV 6-11 and are capable of removing 85-95% of particles in the 3-10 *micron* range but inefficient at removing particulate in the 0.3-1.0μm and 1.0-3.0μm range (Edelman, 2008). These filters are commonly installed in commercial and industrial applications (ANSI/ASHRAE, 2007). An example of a pleated filter constructed of synthetic fibers is shown in Figure 11.

Figure 11: Pleated panel filter

(Koch Filter Corporation)

The third type of filter is a bag filter, which, similar to a pleated filter, is also known as an extended surface filter. It is constructed of synthetic, fiberglass, or a blend of cellulose and glass fibers and generally has a filter depth of 12-30 inches (Edelman, 2008). The filter's pockets are sewn to form a series of tubes, which increases the efficiency of the filter without increasing the pressure drop (NAFA, 2001). The stitching within the filter keeps the pockets open while controlling the filter, so it does not balloon when air passes through (NAFA, 1997). Similar to pleated filters, bag filters remove particles from the air stream through a combination of straining, interception, impaction, and diffusional deposition. Bag filters are MERV 11-15, which equates to filter efficiencies greater than 90 percent at removing particles greater than 3 *microns* (Edelman, 2008). The higher efficiency bag filters, MERV 14 and 15, are capable of removing 75-95% of particulate in the 0.3-1.0μm size range. Edelman (2008) states that bag filters have *high efficiency* at a low pressure drop, which allows these filters to have a long service life. These filters are typically used in commercial buildings with higher filtration needs and in hospital inpatient care and general surgery rooms (ANSI/ASHRAE, 2007). One concern when using bag filters is they could collapse during maintenance, and the particles on the surface of the filter could become detached and released downstream of the filter ultimately entering the protected space (ASHRAE, 2003). Designers must consider these concerns when selecting bag filters for health care applications and other spaces requiring higher levels of filtration. An example of a bag filter, which can comprise synthetic or glass fibers, is shown in Figure 12.

Figure 12: Bag filter
(Koch Filter Corporation)

HEPA filters are required to have a minimum efficiency of 99.97% for removing particles with a diameter of 0.3µm (ASHRAE, 2003). Therefore, HEPA filters are required in many healthcare spaces because of their *high efficiency* and because they remove *viruses*. *Viruses* as small as 0.1µm can be extracted because the *virus* spores attach to slightly larger particles, which are removed by the HEPA filter's filter media through diffusion and interception (ASHRAE, 2003). *Viruses* and *bacteria* can also be removed from the filter through diffusion, as the particles' paths are affected by surrounding particles and air molecules. HEPA filters can be either deep-pleated or mini-pleated filters (Cardwell & Whyte, 1991). Mini-pleated filters are more commonly used for *high efficiency* filters because this type of construction offers a larger amount of surface area with a smaller pressure drop than the deep-pleated filters (Cardwell &

Whyte, 1991; Whyte, 2001). HEPA filters with mini-pleats are constructed by filter media being folded back and forth over ribbons or glue strings in six or twelve inch widths (Cardwell & Whyte, 1991). HEPA filter thickness can vary, and Figure 13 shows two types, one with a thickness of 2 ¾" inches and the other two with 12 inch thicknesses. These HEPA filters in Figure 13 are made of microfiberglass fibers.

Figure 13: HEPA filter with varying thicknesses
(Koch Filter Corporation)

Figure 14 represents a HEPA filter's efficiency versus particle diameter showing that efficiency decreases significantly with particles 0.1-0.5µm. The lowest efficiency on the curve occurs when particles have a diameter of 0.3 µm, which is why NAFA states 0.3µm to be the Most Penetrating Particle Size (MPPS). A HEPA filter's efficiency is based on the penetration of 0.3µm particles since they are the MPPS for the filters (NAFA, 2001; Barhate & Ramakrishna, 2007). Particles smaller than 0.3 µm are not considered MPPS because they are more efficiently removed from the HEPA filter through diffusion. The smaller particles have a more erratic path through the filter as they bump into surrounding particles and air molecules, which results in the small particulate colliding with the filter media. The curve also shows the size ranges when diffusion, interception, and impaction are the main methods of filtering particles out of the air stream.

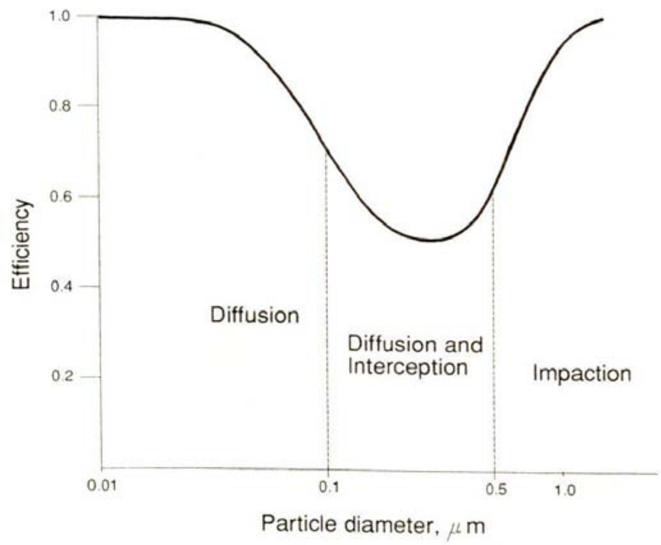

Figure 14: Efficiency curve for HEPA filter
(Cardwell & Whyte, 1991, p. 186)

While HEPA filters are efficient at removing particulate smaller than 0.3µm, the Ultra Low Penetration Air (ULPA) filter was developed to have even greater efficiency than standard HEPA filters (Cardwell & Whyte, 1991). These filters are required to have efficiencies greater than 99.999% at removing particles in the 0.1-0.2µm range (Whyte, 2001; Cardwell & Whyte, 1991). These filters are used in the most stringent cleanroom applications. The different classifications of cleanrooms will be discussed further in chapter five.

Table 5 compares filters previously discussed. The table compares the filters on their efficiency, method of removing particulate, application, and average price. The prices in the table are based on the average price determined from quotes from two manufacturers and the prices listed in the RSMeans Mechanical Cost Data 29th Annual Edition (2006). The filter prices were quoted by Brent Chamberlain with Koch Filter Corporation and Steve Dexter at Air Filter Solutions Inc, quoting Camifil Farr filters, both through email correspondence in July 2010.

Table 5: Comparison of traditional commercial filter types

Filter Type	MERV Rating	Method of Particulate Removal	Material	Price (MERV Rating)	Application
Flat Panel	5 or lower	straining, impaction	cotton or polyester blends	$3.30 (3)	Residential
Pleated	6-11	straining, impaction, interception, deposition	synthetic, cotton or polyester	$6.80 (8)	Commercial and industrial workplace
Bag	11-15	straining, impaction, interception, deposition	synthetic, fiberglass, or blend of cellulose and glass	$52 (13)	Hospital impatient care and general surgery
HEPA	99.97%*	impaction, interception, deposition	glass	$246 (17)	Hospital isolation rooms and cleanrrom applications
ULPA	99.999%*	impaction, interception, deposition	glass	$412 (19)	Most stringent cleanroom applications
* Efficiency in removing particulate smaller than 0.3µm					

The filters previously discussed and shown in Table 5 are considered mechanical filters. Another type of filter, known as an electronic air cleaner, removes particles by introducing an electric field into the airstream, which then captures charged particles (Dagostino & Wujek, 2005). Electronic air cleaners the capture particles and remove them from the airstream using an electrostatic precipitator or electrostatic charged filter media. The electrostatic precipitator, as shown in Figure 15, collects particles with a series of horizontal flat panels.

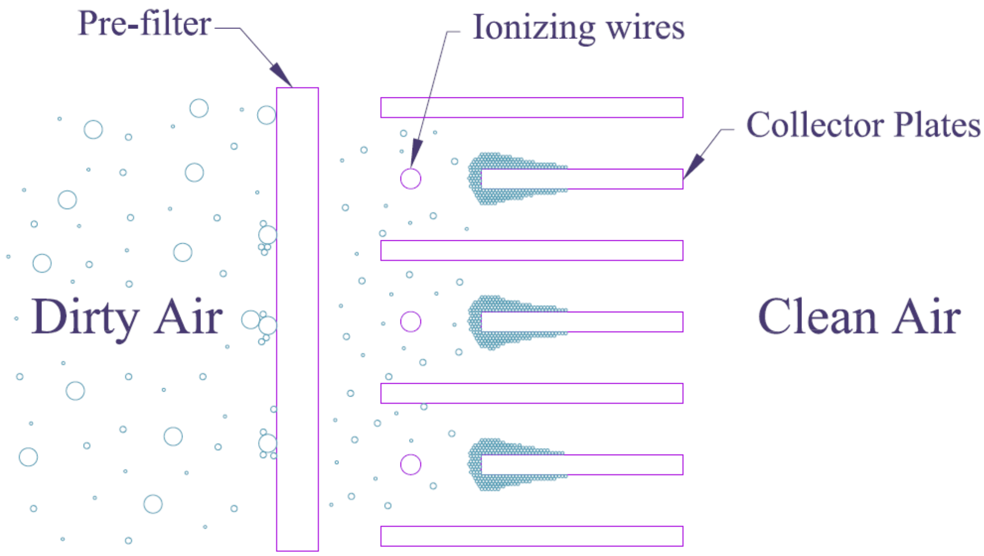

Figure 15: Electrostatic precipitator diagram

Figure 15 illustrates how the electrostatic precipitator removes particles from the air stream. Dirty air enters a pre-filter, which removes large particulate and dust from the air stream. The electrostatic precipitator consists of two sections, an ionization section and a collection plate section. After the air passes through the pre-filter, it enters the ionization section, which consists of small wires that create a positive current between 6-25kV, and the voltage charges the particulate in the airstream (ASHRAE Handbook- HVAC systems and equipment, 2008). The air then moves through the collecting plate section, which consists of equally spaced plates. The plates alternate between grounded plates and plates with a positive voltage of 4-10kV, which results in the charged particles becoming attracted to plate surface (ASHRAE Handbook- HVAC systems and equipment, 2008). Electrostatic precipitators are not tested with the same tests as listed in Standard 52.2-2007 because the test dust used "contains very conductive carbon that may cause electrical shorting" (ANSI/ASHRAE, 2007, p. 1). Electrostatic precipitators have reported initial efficiencies of 98% at 150-350 fpm, when tested against the arrestance test, which equates to a 13-14 MERV rating (ASHRAE Handbook- HVAC systems and equipment, 2008). A designer must evaluate whether or not the electrostatic precipitator's performance is worth the additional energy use for the current applied to charge the particles and attract them to the charged plates. If the precipitator has a lower pressure drop than a mechanical filter and the additional energy consumption from the precipitator's ionization section and collection plate section does not exceed that of the mechanical filter, then the precipitator might be justifiable. A major problem with these filters is that their efficiency decreases over the course of their life compared to that of traditional mechanical filters, whose efficiency increases with use (ANSI/ANSHRAE, 2007).

Another filter that uses electrostatic charges to remove particulate is the passive electrostatic fibrous media. In this application, charged filter media attract particles resulting in their capture and removal by the filter's fibers (Dagostino & Wujek, 2005). The electrostatic charge is applied to the filter surface during the manufacturing process (ANSI/ASHRAE, 2007). To increase filter efficiency, the particles in the airstream may be ionized, similar to the electrostatic precipitator, prior to the particles being supplied across the electric air cleaner (Dagostino & Wujek, 2005). Again, similar to the electrostatic precipitator filter, these filters see a reduced efficiency over time and a potential for the tested efficiency may be higher than the efficiency when installed in an application (ANSI/ASHRAE, 2007). The lowest efficiency electrostatic fibrous filters will offer is the rated efficiency of the filter media itself. When the electrostatic charge completely diminishes, however, the owner is left with a standard filter. These filters are not commonly seen in commercial applications.

3.3 Filter Selection

The previous section discussed a variety of filters commercially available, but designers must ultimately determine what type of filter should be installed for certain applications, which requires considering many elements. ASHRAE Handbook- HVAC Systems and Equipment (2008) lists criteria for designing an air filtration system:

1. Air cleanliness required in the space
2. Particle size of concern
3. Particle concentration
4. Pressure drop across the filter

Each space will have different requirements for filtration, requiring that a designer consider each of the criteria when selecting a filter and the selection may be determined by the minimum required MERV ratings for the specific space. A required MERV rating is the minimum accepted efficiency for the filter at a specified particle size. Determining the MERV rating a filter must meet within the filtration system many times is based on a design reference manual.

For example, minimum MERV ratings for spaces within a hospital can be referenced in Guidelines for Design and Construction of Health Care Facilities (AIA, Facility Guidelines Institute, 2006). Meanwhile, a filter's minimum MERV rating for spaces other than healthcare facilities will be determined in the following paragraphs.

A step-by-step by process is outlined below, which a designer can easily reference to determine the type of filter to install. The list considers the criteria addressed, at the beginning of this section, from ASHRAE Handbook- HVAC Systems and Equipment (2008) while also including other important factors when selecting a filter. Included in the steps are questions and/or small discussion points to consider.

Step 1: Determine the MERV rating based on the space, particle size, and concentration of particles

If particle size and concentration levels are known, determine the MERV rating required based on Table 1, within this report, which can also be found in ANSI/ASHRAE Standard 52.2-2007. If the particle size and maximum level of concentration of that particle size is not known, reference a range of MERV ratings based on the type of space and from Table 2, within this report, which can also be found in ANSI/ASHRAE Standard 52.2-2007. From this range of MERV ratings, then determine the appropriate MERV rating for a filter selection.

Determine if the space requires initial efficiency or sustained efficiency. Some filters initially have a lower efficiency than their MERV rated value, because the filter's efficiency is rated for when the filter has a certain amount of particle build up on the surface. The MERV ratings determined in ANSI/ASHRAE Standard 52.2-2007 are based on the performance of the filter in removing particulate "as the device becomes loaded [with]…dust…to simulate accumulation of particles during service life" (p. 2), which equate to sustained efficiency. When selecting a filter, verify the reported MERV rating with the manufacturer to determine if it is the initial efficiency or sustained efficiency.

Step 2: Determine the amount of air being delivered to the space

The supply air cubic feet per minute (CFM) is determined based on heating and cooling load or other design requirements. This paper will not further discuss the CFM, as the purpose of this research is filtration in the HVAC system.

Step 3: Select HVAC Equipment

Many modular pieces of equipment have a set size for the filter housing. Filters come in a variety of sizes, and designers must select a filter or multiple filters that will fit in the filter housing in the mechanical equipment or wherever the filter is installed.

Step 4: Determine maximum pressure drop and maximum velocity

Determine the maximum pressure drop the HVAC air circulation equipment can handle while performing properly. The mechanical equipment, including air handling units, fans, etc. is rated for a specific external static pressure, and the system must not exceed that static pressure. The equipment's maximum static pressure can be determined from manufacturer's data. Higher pressure drops may require a larger fan to supply the air across the filter. Higher static pressure will also result in higher energy consumption and energy; bills, therefore minimizing the static pressure is in the best interest of the owner over the life of the building. Due to the increased energy consumption, a designer should try to select filters with smaller pressure drops. Here, the designer must know the maximum pressure drop the equipment can handle in case a filter with a small pressure drop cannot be selected. When determining the total pressure drop within the system, the designer should use the filter's final pressure drop to ensure the equipment will function properly throughout the life of the filter.

Determine the maximum velocity of the air traveling over the filter. This information can be attained from the manufacturer's data on the filter. The velocity at the filter's surface can be easily calculated by taking the maximum airflow through the filter and dividing it by the face area of the filter. The air distribution system's velocity must not exceed the maximum velocity listed by the manufacturer; if it does, it is likely the filter will not perform to the established ratings.

Step 5: Select a filter based on MERV rating, CFM and velocity

Determining which filter to select depends on the filter manufacturer, which means referencing the manufacture's data to ensure a certain filter will meet the predetermined filtration needs. The designer must also determine if a pre-filter is required or recommended upstream of the final filter, depending on the space being served.

Step 6: Specify the proper filter housing and or gaskets recommended by manufacturers

Proper filter housing is critical to ensure the filter's efficiency. A space may require a *high efficiency* filter, such as a MERV 15 filter, but if the filter is not installed with proper housing and gaskets, the filter will have a much lower efficiency. This is the result of particles finding their way into the space through air gaps around the edge of the filter. Information about the proper housing for filters is found in the manufacturer's data.

When a filter is initially selected for a system, a designer must realize that the filter will require maintenance and eventually replacement. The following section will address the importance of maintenance. This section will also discuss the change in pressure drop across a filter over the course of the filter's life.

3.4 Filter Life and Maintenance

A filter's life depends on the dust loading capacity of the filter, which is the amount of particulate that a filter can hold on the filter surface without restricting the air flow across a filter. Accumulated dust and particulate on a filter's surface increases the resistance to air flow, also known as pressure drop, and when the filter reaches a point that prevents adequate flow across the filter, it must be replaced (Kalayci, Ouyang, & Graham, 2006). Currently, no code requirements state when air filters be changed, but proper maintenance and regular replacements will provide a safe environment for the occupants, protect the equipment, and reduce energy consumption.

Ultimately, determining the frequency of replacing filters depends on the cost of replacing the filter compared to the increased energy consumption due to the increased static pressure from to the "dirty" filter within the system (ASHRAE, 2003). The designer must decide at what point replacing the filter is most economical to reduce the energy costs exerted by the fan in the mechanical equipment. NAFA (1997) states that many filter manufacturers will provide a filter's final pressure drop, which is the recommended pressure drop when the filter should be changed, but this is not specific to the economics of a particular system. An analysis would be necessary for each design to accurately determine the optimum time for replacing the filters. When final pressure drop information is not provided in the manufacturer's literature, Whyte (2001) recommends that a filter should be replaced when a filter's pressure drop becomes 2.5-3 times the filter's initial pressure drop. Again, this is a general rule for when a filter should be replaced, but does not guarantee optimum efficiency of the system.

When a filter is initially installed, the rate of increased pressure drop is relatively slow, but the rate of increasing pressure drop significantly speeds up over the life of the filter (NAFA, 1997). Table 6 shows a filter with an initial pressure drop of 0.35" w.g. and the increase of the pressure drop over the life of the filter. Initially, the filter's life the table shows it would take 1000 hours for the pressure drop to increase 0.5" w.g., while it would only take approximately 250 hours for the pressure drop to increase 0.1" w.g. towards the end of the filter's life.

Table 6: Typical filter operation in pressure drop ranges

Reprinted with permission from the National Air Filtration Association (NAFA) from the text *Installation, Operation and Maintenance of Air Filtration Systems* 2nd Edition.

Pressure Drop Range (in w.g.)	Time to Operate in Range (hrs)
0.35-0.4	1000
0.4-0.5	1250
0.5-0.6	750
0.6-0.7	550
0.7-0.8	450
0.8-0.9	350
0.9-1.0	250

Figure 16 provides a graphical representation of the increase in pressure over the course of the filter's life. Table 6 and figure 16 should not be used to determine when a filter should be changed, but rather each provides a visual of how quickly the pressure drop across the filter will increase towards the end of the filter's service life. The exponential growth of pressure drop across a filter illustrates the importance of monitoring a filter's resistance. A differential pressure gauge can be installed near filters, to measure the static pressure and helps to signal when the filters should be replaced.

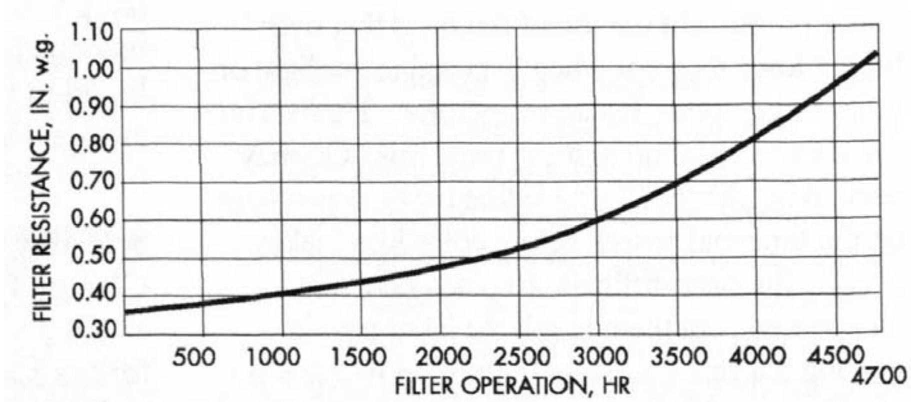

Figure 16: Typical filter life curve

Reprinted with permission from the National Air Filtration Association (NAFA) from the text *Installation, Operation and Maintenance of Air Filtration Systems* 2nd Edition.

Multiple costs are associated with replacing a filter, including the initial cost of the new filter, the cost of labor to remove the old filter, repair the filter's frame and fasteners as needed and install the new filter, and the cost associated with proper disposal of the old filter (NAFA, 2001). Such costs are discussed in the following section.

3.5 Cost of Filters

Many times, filter selection is determined solely by the filter with the lowest initial cost as many owners are focused on first costs. However, this approach is not financially advantageous when the energy consumption of a filter is much greater than its initial cost (Matela, 2006). Energy costs may be as much as ten times the amount of the initial price of pleated filters, and four to five times as much as the price of higher efficiency filters (Matela, 2006). A filter affects energy consumption based on the fact that energy is required for the fan to provide the required airflow across the filter. The initial investment and maintenance of filters is approximately 18.5% of the filter's life cycle cost, while the energy consumption related to the filter is 81% of the filter's life cost, and disposal accounts for the last 0.5% of the life cost (Matela, 2006; Arnold et al., 2005). Figure 17 gives a graphical representation of the life-cycle cost of a filter.

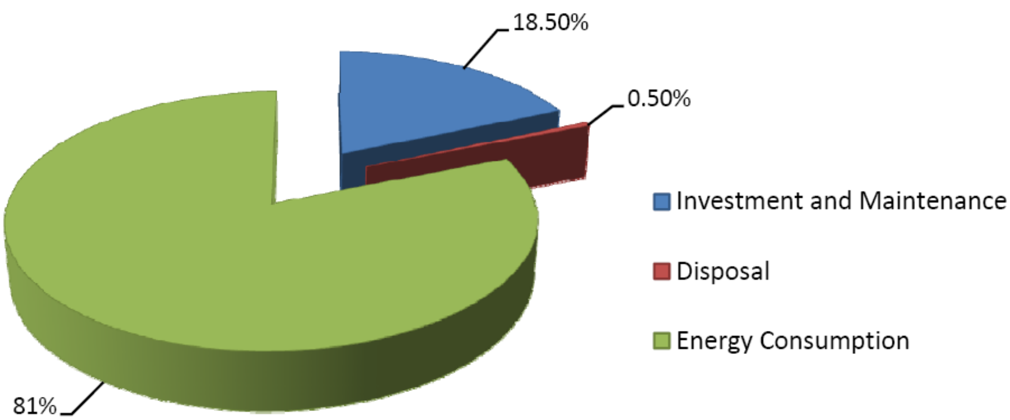

Figure 17: Filter life-cycle cost components

(Arnold et al., 2005)

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The designer's filter selection has great potential to save the owner money over the life of a system since over four-fifths of the filter's life cost is the energy consumed to overcome the filter's resistance. To select a filter with a lower pressure drop, while maintaining the same efficiency may require a more expensive filter initially. However, the fairly quick payback period for the more expensive filter will typically render a good investment because of the savings in energy consumption. Another potential savings is the opportunity to select a smaller fan to deliver the same amount of required air. The smaller fan would result in a smaller electrical circuit breaker, wiring and disconnecting means. This concept is important to designers to provide the most cost efficient system to the owner and reduce energy consumption for lower energy bills.

This chapter focused on traditional commercial filters that are commonly seen in HVAC applications and discussed their filter properties. The following chapter will introduce nanofibrous membranes and how their unique construction offers new potential for the filtration industry.

CHAPTER 4 - Nanofibrous Membranes

The previous chapter discussed the composition and efficiency of commercial filters commonly used in filtration systems. Next, the research considers how to increase filter efficiency without a drastic increase in the pressure drop across the filter is to offer a greater amount of particulate removal without a large increase in the system's energy consumption. Nanofibrous membranes offer great potential in this respect because the membranes' small fibers and pore sizes offer greater particulate removal with minimal increase in pressure drop. This chapter will begin by addressing the processes to create nanofibrous membranes and then discussing the membranes' filtration characteristics. The chapter will then discuss some of the concerns about such membranes and will conclude by comparing of nanofibrous membranes with traditional commercial filters.

4.1 Membrane Construction

A nanofibrous membrane has fibers with diameters smaller than 1µm, referred to as *nanofibers* (Graham et al., 2002). These *nanofibers* can be created by a couple of processes: the jet *electrospinning* process and the melt blown process. These *nanofibers* can then be combined to form nanofibrous membranes for a variety of applications, but this chapter will address only their potential in filtration applications. The manufacturing processes will be discussed in the following subsections because the various processes yield different *nanofibers* with varying fiber diameters. The discussion of these processes is important as it will give a foundation for later subsections when addressing the ability to control the fiber diameters and the membranes' filtering capabilities.

4.1.1 Electrospinning

Jet *electrospinning* to create nanofibrous membranes is the most commonly used method when creating nanofibrous membranes for testing. Figure 18 is a schematic of the equipment used to create *nanofibers* and nanofibrous membranes using the jet electrospinning process.

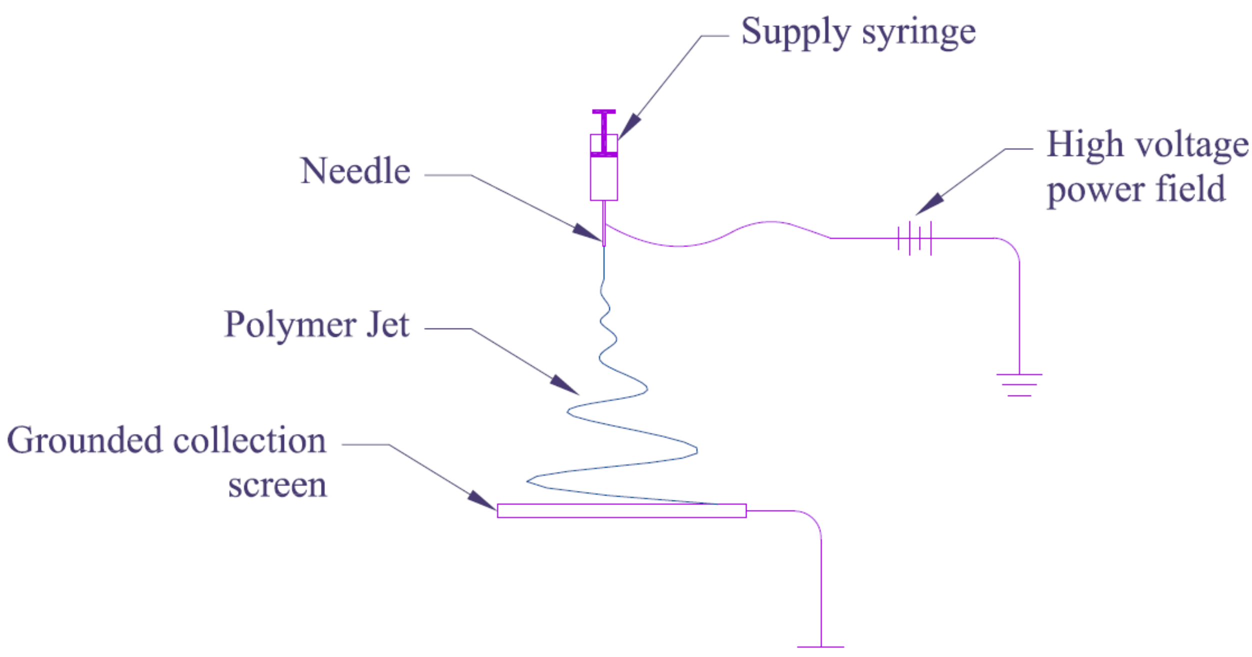

Figure 18: Electrospinning diagram

The equipment needed for the *electrospinning* process includes a voltage supply as large as 30 kV, a programmable supply syringe, a needle, and a grounded collector screen (Sawicka & Gouma, 2006). The electrical high voltage is applied to a polymer solution, and when the voltage "overcomes the surface tension of the solution" (Ahn et al., 2006, p. 1031), it causes the solution to deform and lengthen, forming a solution with *nanofibers* (Kalayci et al., 2006). The solvent then evaporates out of the solution, leaving the *nanofibers* to collect randomly on the grounded screen (Shin et al., 2005; Sawicka & Gouma, 2006). The membrane can be removed from the screen, or the *nanofibers* can be electrospun directly onto a substrate, which would then become the filter media. The substrate offers extra physical strength to the electrospun membrane, so the membrane does not become damaged upon being installed in the filtration system. Figure 19 is a schematic and a stroboscopic photograph of the formation of *nanofibers* through jet *electrospinning*. The schematic illustrates various instabilities the jet goes through as the fiber is formed, while the photograph shows the fiber diameter significantly decreasing as it gets further from the nozzle.

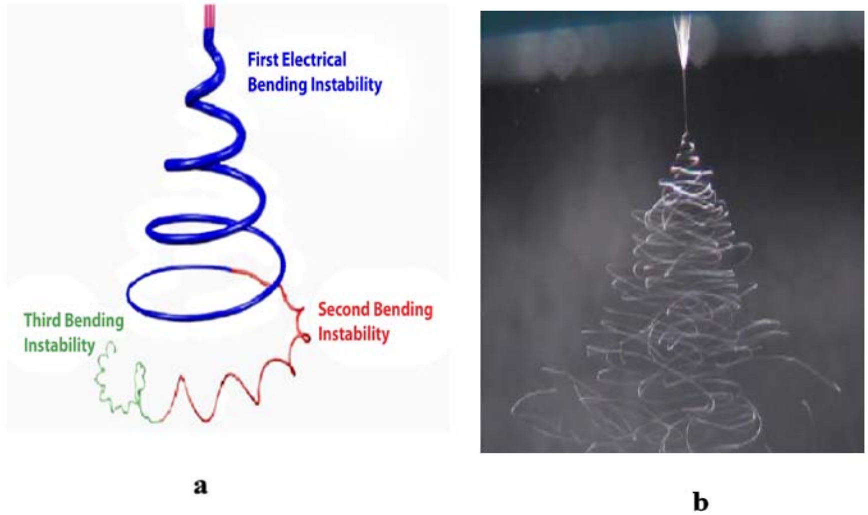

Figure 19: Electrospinning jet (a) schematic, (b) photograph

Courtesy of Elmarco (Petrik & Maly, 2009, p. 2) and Darrell Reneker (personal communication, September, 27, 2010)

The nanofibrous membranes can be formed on the screen or substrate in any size and shape to any desired thickness; size and thickness depend on the volume of solution that is electrospun and the amount of layering of the fibers. This process is advantageous as these membranes can be customized to replace filters of various sizes. The size of the membrane may be controlled by the size and shape of the space in which air is being distributed or by the size of the holding frame located in a piece of mechanical equipment. Either way the membrane thickness will be defined by the desired efficiency of the membrane. As the membrane's thickness increases, the efficiency increases as a greater amount of particulate will be removed depending on depth filtration. A thicker membrane, or any filter for that matter, offers a greater amount of filter media a particle must pass through, therefore increasing the possibility of the particulate being removed from the air stream. While thicker filter media offer increased efficiency, the added thickness also results in additional pressure drop across the membrane. As with traditional filters, the added pressure drop across the membrane would directly affect the fan size and selection and also energy consumption. Therefore, depending on the membrane's application and allowable pressure drop, the membrane can vary in membrane thickness and *nanofiber* density. Figure 20 demonstrates the various densities possible using *nanofibers*. The SEM on the left shows *nanofibers* incorporated with a substrate's substantially larger fibers, and the SEM on the right shows a nanofibrous membrane more densely packed with *nanofibers*. The figures demonstrate the versatility of *nanofibers*.

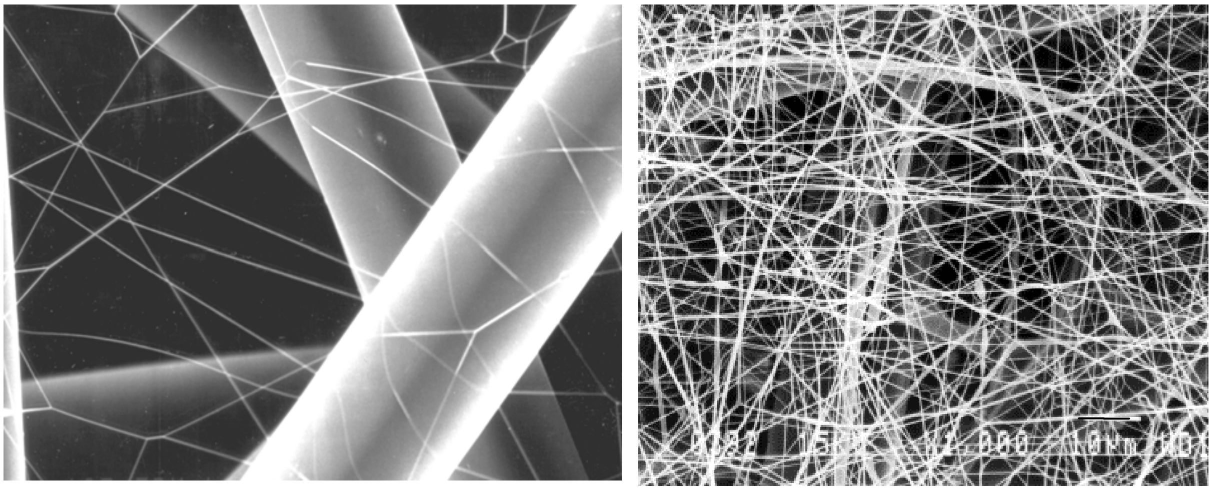

Figure 20: Nanofibrous membranes of various densities
(Grafe & Graham, 2002, p. 6)

Through the jet *electrospinning* process, the production of a single membrane could take hours, depending on the desired size and thickness, as a single jet produces one continuous fiber to form the membrane. Clearly, to make jet *electrospinning* an economical means of producing *nanofibers*, multiple jets, possibly thousands, would need to be used at one time (Petrik & Maly, 2009). Accordingly, a nozzle-less jet *electrospinning* process has been developed to increase production of *nanofibers* without sacrificing the quality and consistency of the fibers. The nozzle-less process consists of a rotating electrode, which is dipped into the polymer solution, forming a small layer of the solution on the electrode (Petrik & Maly, 2009). As with the jet nozzle *electrospinning* process, a voltage is applied, but rather than a single jet, multiple jets are formed across the electrode. Figure 21 shows a photograph of the nozzle-less *electrospinning* process and the different spinning electrodes that can be used.

a b

Figure 21: Nozzle-less electrospinning (a) process with rotating electrodes, (b) various spinning electrodes

Courtesy of Elmarco (Petrik & Maly, 2009, p. 4)

Nanofibrous membranes can also be formed with composite materials and various additives that offer specific membrane characteristics. Sawikca and Gouma (2006) mention the possibility of incorporating additives such as, “soluble drugs, *bacterial* agents and metal oxide sol-gel solution” (p. 770) by directly applying the additives to the nanofibrous membranes after the membrane has dried, or directly adding the additives to the polymer solution to be electrospun. The first method of creating a composite nanofibrous membrane places a dry electrospun membrane in a composite solution whereby the composite particles directly absorb into the membrane, but Sawicka and Gouma (2006) state two major concerns with this application; (1) there is little control over the amount of the composite solution or antimicrobial agent actually absorbed within the membrane and (2) the process takes approximately 36 hours to construct the composite membranes. The second process of creating composite membranes is to add the composite solution directly to the polymer solution, which offers more control over the composite to polymer solution ratio (Sawicka & Gouma, 2006). This option also reduces the amount of time needed to create the composite nanofibrous membrane, as it is a single step process since the polymer composite solution is electrospun together. The benefits of adding antimicrobial agent to polymer solution will be further discussed in chapter 5.

4.1.2 Melt Blown

Melt blown fibers is the second method of constructing nanofibrous membranes. This process typically produces fiber diameters five to ten times larger than fibers created by *electrospinning* (Podgórski et al., 2006). Petrik and Maly (2009) state the melt blown process produces fibers with diameters of 800-2500 nm compared to the nozzle-less electrospun process, which produces fibers with diameters of 80-500 nm. Kalayci et al., (2006) say that *nanofibers* created from the nozzle *electrospinning* process are capable of having diameters as small as 40 nm and up to 500 nm. A nanometer (nm) is 1/1000 of a micrometer (µm). Figure 22 is a schematic of the melt blown process.

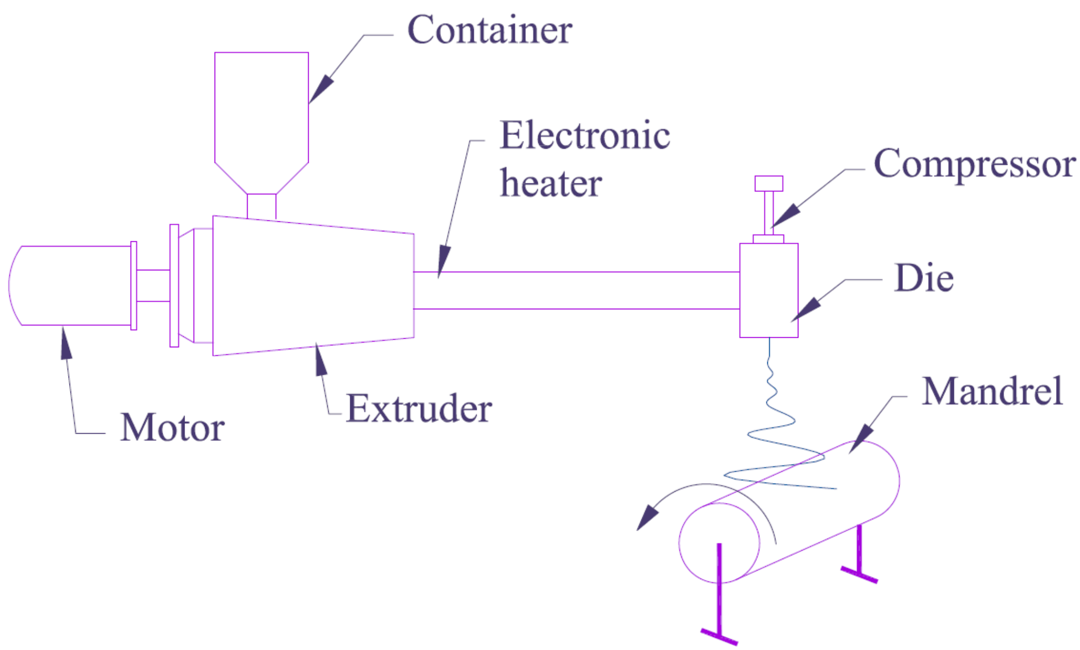

Figure 22: Melt blown diagram

(Podgórski et al., 2006, p. 6808)

A polymer solution is placed in a container, which is then supplied to the extruder. The polymer solution is then transferred through the electric heater into the die with the flow rate being controlled by the motor (Podgórski et al., 2006). The polymer solution is then forced through a row of nozzles within the die, and hot air from the compressor transforms the solution into the desired fiber diameters (Podgórski et al., 2006). The fibers are finally collected on a rotating mandrel that moves back and forth to create a membrane of desired size and thickness

(Podgórski et al., 2006). The melt blown process offers potential for commercial applications because of ability to produce large quantities of nanofibrous membranes at a relatively low cost (Podgórski et al., 2006). Currently, research is geared at improving the melt blown process to produce fibers with smaller diameters (Barhate & Ramakrishna, 2007).

Table 7 compares the melt blown process and the two electrospun processes of producing *nanofibers* on the bases of voltage required to form the *nanofibers*, the diameters of fiber created, and the variation of the diameters within the fibers. The melt blown and nozzle-less methods are currently ready for large scale production while the jet nozzle electrospun process needs further research to make it economical for production. Regarding the variation of fiber diameters for each of the processes, the nozzle-less fibers' diameters have 30% variation, which is much less than that of the melt blown process with 200% variation. The nozzle *electrospinning* process does not have a set standard deviation because the variation of fiber diameters depends on the length of fibers created. As fibers are electrospun through the nozzle method, the smaller the diameters, the larger the variation in fibers; this will be further discussed in section *4.2.1.1 Fiber Diameters and Pore Sizes*. The variation in fiber diameter is important to designers because it shows the consistency of the process and results in a more efficient membrane. If two membranes are created with similar fiber diameter but offer differing variations of the fiber diameters, the membranes will not have the same filtration capabilities. The membrane with greater variation in fiber diameter will likely have a lower efficiency because of the inconsistency across the membrane surface.

Table 7: Methods of nanofiber production

Courtesy of Elmarco (Petrik & Maly, 2009)

Production Method	Melt Blown	Electospun	
		Nozzle	Nozzle-less
Voltge (kVA)	0	5-20	30-120
Fiber Diameter (nm)	800-2500	<500	80-500
Standard Deviation of Diameters	+/- 200%	Varies with fiber length	+/- 30%
Ready for Production	Yes	No	Yes

Petrik and Maly (2009) state that these different methods of producing *nanofibers* are "complementary rather than competing" (p. 7) because of the different *nanofibers* produced by each of the different methods. Petrik and Maly (2009) believe the melt blown process will be beneficial in "cost sensitive applications like hygiene nonwovens" (p. 7) because of the larger fiber diameters with less uniformity, while the electrospun *nanofibers* would more likely apply in air filtration applications because of the need for more uniform fibers.

4.2 Membrane Composition and Performance

Nanofibrous membranes offer large potential for filtration applications because of the membrane's construction. It is important that designers understand the composition and structure of nanofibrous membranes, as this is a new concept compared to the composition of traditional commercial filters; these newer membranes did not gain interest until the mid-1990s. Therefore, this section will discuss the membranes' properties, such as fiber diameter, pore size, and air flow resistance and will conclude with an evaluation of the membranes' efficiencies in removing particulate from the airstream.

4.2.1 Membrane Properties

Nanofibrous membranes can be formed from a variety of polymer and polymer blends, which offers variety in composition. Additionally, the membrane's fiber diameter, porosity, texture, and structure can be changed by using different polymer solutions (Burger, Hsian, & Chu, 2006). The ability to control construction offers opportunities to create a membrane with characteristics designed to match a specific application.

4.2.1.1 Fiber Diameters and Pore Sizes

Nanofiber diameters can vary from 40-200 nm depending on the specific polymer and solvent combination (Kalayci et al., 2006). An experiment performed by Yun et al. (2007) determined that with proper polymer concentration, the diameters of fibers created by the *electrospinning* process were more uniform than the fiber diameters in commercially produced filters. The *nanofibers*' diameters can also be changed by altering the concentration of the solution used in the electrospun or melt blown manufacturing process. Thus, a less concentrated solution creates a thinner fiber than does a more concentrated solution, but two concerns arise with lowering the concentration of the solution (Podgórski et al., 2006). The first concern is the increase in toxins and hazardous vapors released from the *electrospinning* process, which creates additional costs and supplies to the process, to ensure these vapors are properly disposed of (Podgórski et al., 2006). The second issue with *electrospinning* a solution with too low of a concentration is the formation of small beads, rather than the desired continuous jet (Shin et al., 2005). The beads form because the solution has a lower viscosity, which results in extra polymer solution being released from the jet because the electric field is unable to stretch the solution properly (Patanaik, Jacobs, & Anandjiwala, 2010). Bead formation will directly affect the membrane's performance because it creates a large variation of fiber diameters throughout the membrane. This variation creates inconsistency throughout the membrane, which results in uneven loading, lower efficiency, and increased pressure drop. Figure 23 shows the variation of fiber diameters and bead formation caused by changing the concentration of the solution prior to *electrospinning*. The figures are SEMs of Nylon 6 *nanofibers* electrospun with a voltage of 25 kV, 5 cm from the collector, with 15%, 18%, 21% and 24% solution concentrations (Ahn et al., 2006). The SEMs shows that with decreased concentration, smaller fibers are formed, but a greater amount of bead formation occurs throughout the membrane. The membrane with 24% concentration has the largest fiber diameters at 200nm, compared to the 15% concentration fiber diameters of 80 nm (Ahn et al., 2006). The increased concentration restricts the amount of stretching the fibers will undergo, therefore resulting in larger fiber diameters (Ahn et al., 2006). Bead formation has occurred in the 15% and 18% Nylon 6 concentrations, because the extra solution could not properly stretch to form consistent *nanofibers*.

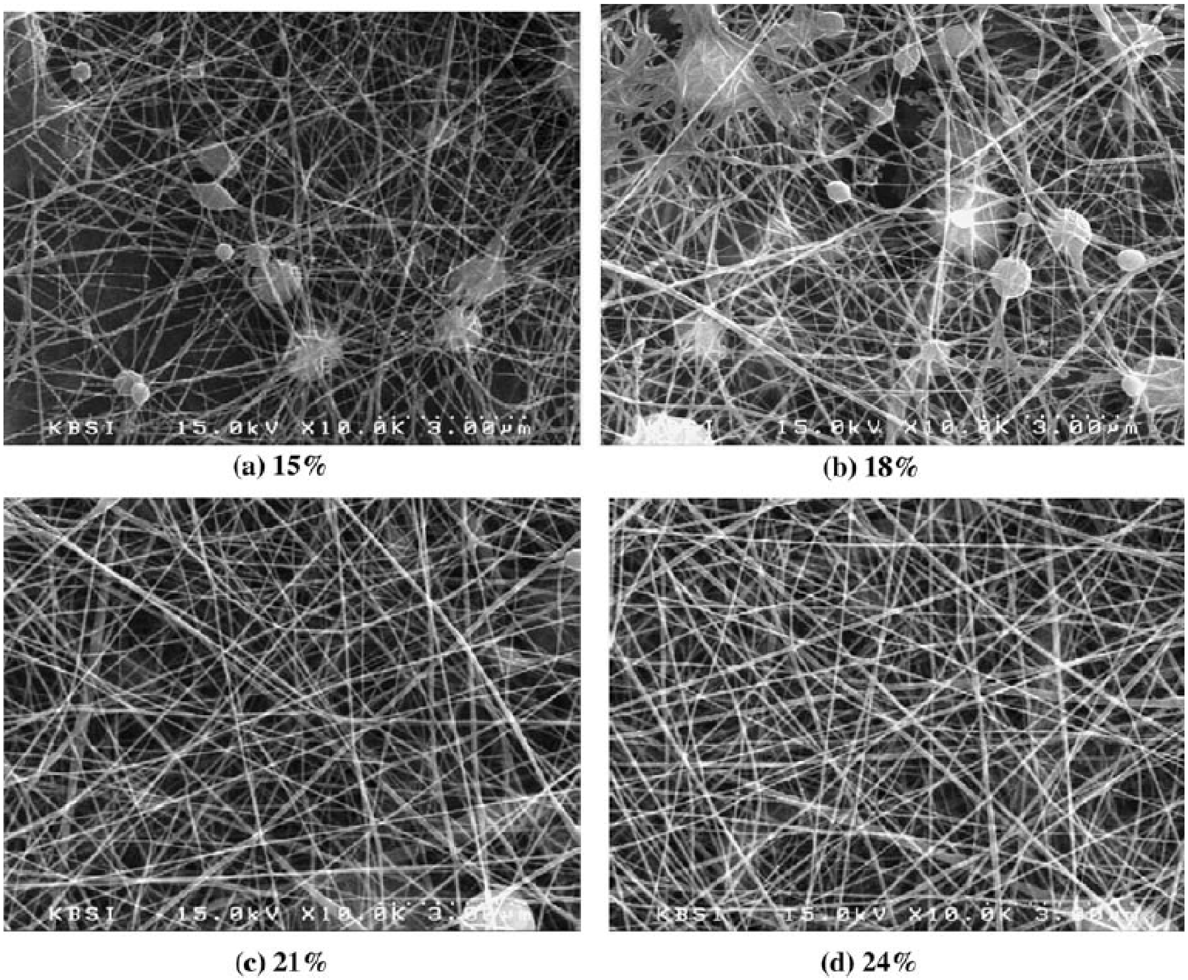

Figure 23: Nylon 6 nanofibers formed from various concentrations of solution
(Ahn et al., 2006, p. 1033)

Another factor that directly affects the fiber diameters of the membrane is the distance the collection surface is from the jet, also known as the spinning distance. When the spinning distance becomes shorter, the electric force increases, which places a greater amount of stress on the solution (Ahn et al., 2006). The increased electric force allows the solution to be stretched further, which results in smaller fiber diameters. Figure 24 shows SEMs of 24% concentration for Nylon 6 *nanofibers* electrospun with a voltage of 25kV at spinning distances of 5 cm, 8 cm, 11 cm and 14 cm. The SEMs show that the fibers formed at a spinning distance of 14 cm are slightly larger than the fibers created from a spinning distance of 5 cm.

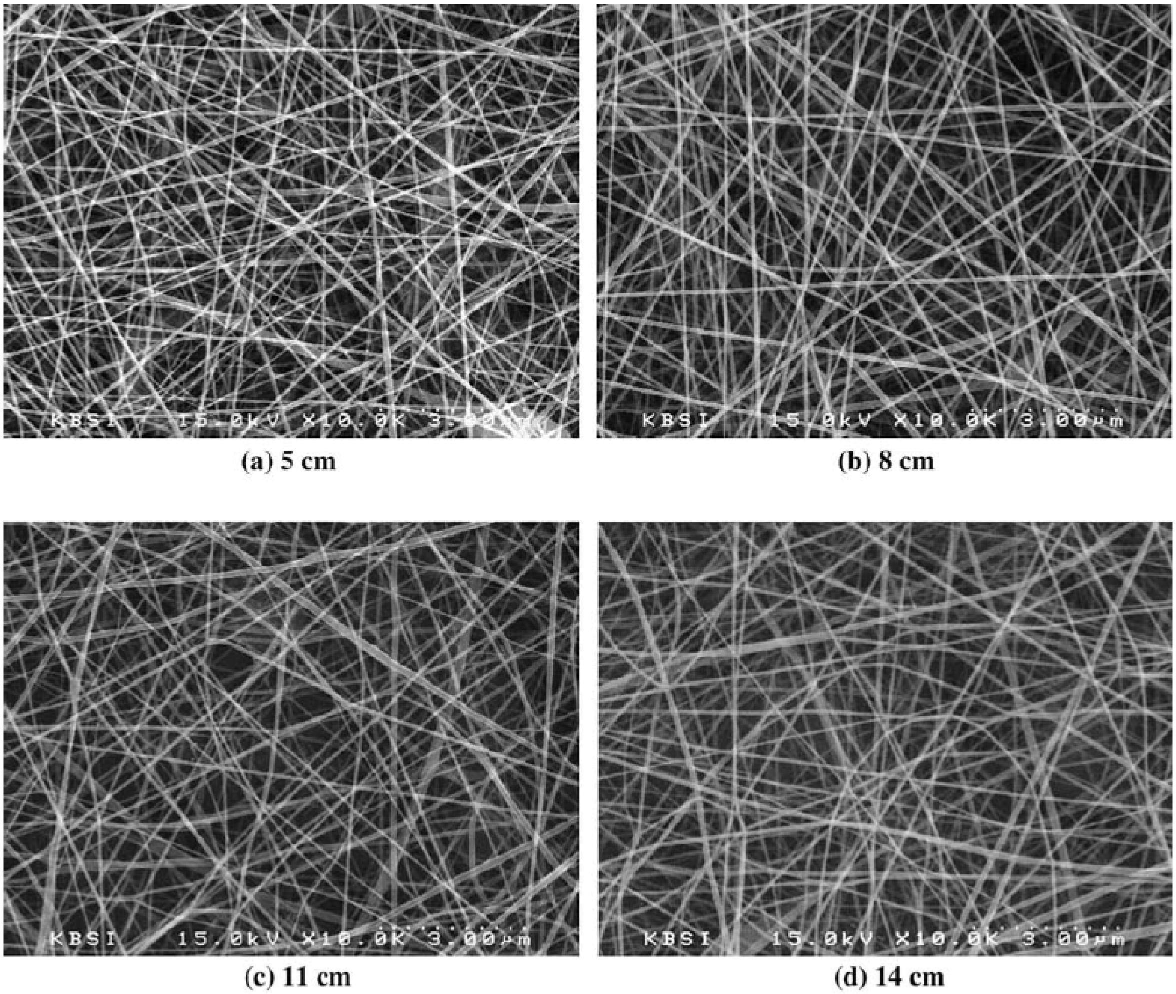

Figure 24: Nylon 6 nanofibers with varying spinning distances
(Ahn et al., 2006, p. 1033)

Another important property is the pore sizes within the membrane. Three types of pores are found in filter media: closed pores, blind pores, and through pores (Patanaik et al., 2010). Closed pores do not allow air to pass through the filter media, while blind pores are initially open pores that become closed within the filter media and do not allow the passage of air (Patanaik et al., 2010). Through pores are open throughout the whole filter media depth, allowing air to move completely through the filter. These through pores and their size are most important for filtration because they allow air passage (Patanaik et al., 2010). Additionally, the nanofibrous membrane’s small pores allow for greater removal of small particulate through interception and straining compared to the more traditional filters used in the commercial building design industry. Straining is typically the only efficient means of filtration for large particulate, and as a membrane's pores become smaller, a greater amount of smaller particulate can be removed through straining. Additionally, these membranes are still very porous to the airstream. High porosity across a filter offers the potential for greater efficiency without increasing the pressure drop across the membrane because of the effects of slip flow, which will be further discussed in subsection *4.2.1.2 Airflow Resistance*.

A study performed by Patanaik et al. (2010) determined the fiber diameters and pore sizes of polyethylene oxide (PEO) electrospun membranes. The researchers tested the membranes with solution concentrations of 3%, 4.5%, and 6%. For each concentration there was a single nanofibrous membrane (NFM), a nanofibrous membrane on a nonwoven substrate (NW+NFM) and the nanofibrous membrane between two nonwoven substrates (NW+NFM+NW) (Patanaik et al., 2010). The NW+NFM+NW membrane composition was calendared, which means rollers increased the bonding of the nanofibrous membranes to the two nonwoven substrates (Patanaik et al., 2010). The nonwoven substrate(s) used in the second and third set gave the nanofibrous membranes greater physical strength. Applying substrates to nanofibrous membranes is typical for filtration applications because of the membranes' weak physical strength. Table 8 shows the fiber diameters, membrane thickness, and weight of each of the membranes.

Table 8: Filtration properties of filter media

(Patanaik et al., 2010)

Membranes	Fiber Diameter (nm)	Thickness		Area Weight (g/m^2)	Average Pore Size (µm)
		µm	inch		
NW	30000	2510	0.0988	95	154.29
3% NFM	85	62.03	0.0024	59	-
4.5% NFM	98	34.68	0.0014	2	-
6%NFM	125	26.34	0.0010	0.4	-
NW + 3%NFM	-	2572.03	0.1013	154	62.58
NW+ 4.5%NFM	-	2544.68	0.1002	97	34.6
NW + 6%NFM	-	2536.34	0.0999	95.4	29.29
NW + 4.5%NFM + NW	-	3544.68	0.1396	192	18.14
NW + 6%NFM + NW	-	3506.34	0.1380	190	13.16

The increase of PEO concentration resulted in an increase in the average diameter of the membrane's fibers, as seen in Table 8. The membranes with greater PEO concentration also had greater uniformity in fiber diameter compared to the fibers from lower concentration of the solution (Patanaik et al., 2010). As the concentration reduced, the variation of the fiber diameters increased because the solution was not accurately stretched; exact variations can be found in their 2010 study "Performance Evaluation of Electrospun Nanofibrous Membrane" (Patanaik et al.). Uniformity in fiber diameters is important as it directly affects the filtration efficiency of the membrane. Lack of uniformity in the fiber diameters would result in different areas of the membrane having different filtration efficiencies, and uneven loading of filtered particles across the membrane. The uneven loading of particles could also lead to shorter membrane life because of the increased pressure drop from the fiber variations.

Table 8 shows that the increase in solution concentration also led to smaller pore sizes in each of the membranes (Patanaik et al., 2010). The larger fiber diameters and smaller pore sizes within the membrane resulted from the increased uniformity of the fiber diameters within the membranes electrospun from higher concentration solutions (Patanaik et al., 2010). The membranes applied to a single substrate (NW+NFM) or between two substrates (NW+NFM+NW) underwent a cyclic compression test to represent the compression and decompression a membrane would undergo if installed as a filter within the air distribution system. Patanaik et al. (2010) noted a small increase in pore sizes after the cyclic compression in the NW+NFM+NW membrane, compared to a much larger increase in the NW+NFM membrane. This was most likely because of the strong bonds formed in the calendaring process. The small increase in pore size is a good indication of a long service life of the composite membrane (NW+NFM+NW) as it can handle continuous loading without greatly damaging the membrane (Patanaik et al., 2010).

4.2.1.2 Airflow Resistance

Generally, as fibers decrease in size, the pressure drop related to a filter increases because of the smaller pores formed from the overlapping fibers. However, nanofibrous membranes have small pores but no dramatic increase in their pressure drop because of the concept of slip flow, whose effects are applicable because of small diameter fibers within nanofibrous membranes. Slip flow is the drag force that occurs on a small fiber, because "the molecular movements of the air molecules are significant in…relation to the size of the fibers" (Graham et al., 2002, p. 3). The importance of considering slip flow can be determined by a fibers Knudsen number, Kn:

$$Kn = \lambda / R \tag{4}$$

where λ is the mean free path of air molecules, and R is the fiber's radius (Brown, 1993). The mean free path is "the dimension of the noncontinuous nature of the molecules" (Barhate & Ramakrishna, 2007, p. 5) of the air. When Kn is greater than 0.1, slip flow should be a factor considered for filtration, and when Kn is greater than 0.25, slip flow definitely needs to be considered (Graham et al., 2002). Barhate and Ramakrishna (2007) identify 0.066µm as the mean free path for standard air conditions; therefore slip flow must be considered for fibers with diameters smaller than 0.5µm. Graham et al. (2002) state that "due to slip at the fiber surface, drag force on a fiber is smaller than that in the case of non-slip flow, which translates into lower pressure drop" (p. 3).

Yun et al. (2007) found that a filter comprising electrospun polyacrylonitrile (PAN) fibers was capable of removing the same amount of nanoparticles as standard HEPA and ULPA filters, but the filter comprising *nanofibers* had a smaller pressure drop. Historically, a higher efficiency filter meant a higher pressure drop, but contrary to this belief, *high efficiency* filters or membranes can be installed without sacrificing pressure drop if they have nanofibrous membranes (Matela, 2006). Podgórski et al. (2006) state that nanofibrous membranes have a significantly greater efficiency of removing the most penetrating particle size (MPPS), 0.3µm, compared to standard fibrous filter with only a slight increase in pressure drop. This would then mean a nanofibrous membrane with the same efficiency as a traditional filter would register a smaller pressure drop. Research is limited and offers differing results, but most studies note a decrease in pressure drop for nanofibrous membranes compared to that of a traditional filter with the same efficiency.

4.2.2 Membrane Efficiency

Nanofibrous membranes' small pores offer greater efficiency for straining smaller particulate from the air stream, compared to traditional filter because of slip flow. Slip flow increases the amount of air traveling past the fiber, which increases the filtration of particles through diffusion, interception, and inertial impaction (Graham et al., 2002). Another factor that greatly increases efficiency is the large surface area to volume ratio in these nanofibrous membranes. The large surface area of nanofibrous membranes offers more filter media that can remove particulate from the air stream, which keeps the membranes thin compared to traditional filters. Yun et al. (2007) state that the efficiency of these membranes directly depends on the thickness of the membrane because particulate has a greater chance of becoming filtered out of the airstream with any increase in the membrane's depth, which can apply similarly for other filter media. However, when a filter's or membrane's thickness is increased, the pressure drop across the membrane is also increased, as stated earlier; as with traditional filters, this trade-off should be carefully considered.

This report next presents three different studies of nanofibrous membranes and their results. The first study performed by Wang, Zheng, and Sun (2007) tested two electrospun membranes' efficiencies for removing particles smaller than 10µm. The two membranes were electrospun from two different solutions: one polyethylene oxide (PEO) and the other polyvinyl alcohol (PVA) (Wang et al., 2007). The PEO membrane had 92.8 percent efficiency while the PVA membrane had 97.6 percent efficiency in removing particulate smaller than 10µm (Wang et al., 2007). While the membranes created by Wang and team were efficient in removing particles smaller than 10µm, the membranes would not replace HEPA filters because they do not meet the filtration efficiencies required to remove 99.97% of particles with 0.3µm diameter.

The study performed by Patanaik et al. (2010), which was introduced in section *4.2.1.1 Membrane Fiber Diameters and Pore Sizes*, compared the efficiencies and pressure drop of the NW+NFM and NW+NFM+NW membranes with test dust of 0.6-180 nm diameter range (Patanaik et al., 2010). The results for the membranes' efficiencies and pressure drops are in Table 9, and these values are based on the average of ten separate measurements.

Table 9: Filtration parameters before and after cyclic compression

(Patanaik et al., 2010)

Membranes	Efficiency (%)	Pressure Drop	
		Pa	Inches w.g.
NW	55.23	16	0.06
NW + 3%NFM	69.49	33	0.13
NW+ 4.5%NFM	80.53	26	0.10
NW + 6%NFM	90.75	22	0.09
NW + 4.5%NFM + NW	88.29	29	0.12
NW + 6%NFM + NW	97.15	25	0.10

Table 9 shows that increased solution concentration resulted in higher membrane efficiency, along with a higher pressure drop across each of the membranes. Also, the NW+NFM+NW membranes saw a smaller decrease in efficiency after the cyclic compression than did the membranes applied to a single substrate (NW+NFM), which could again be attributed to the strong bonding formed in the calendaring process.

A third test performed by Ahn et al., (2006) compared the efficiencies of two membranes comprising Nylon 6 *nanofibers* to that of a standard commercial HEPA filter with test dust of 0.085-2.0µm diameters (Ahn et al., 2006). The characteristics of the two Nylon 6 membranes characteristics can be found in their report "Development of High Efficiency Nanofilters Made of *Nanofibers*." The two Nylon 6 membranes were tested for their efficiency and pressure drop at a face velocity of 3-10 cm/s, which is approximately 6-20 ft/min. The pressure drop and efficiency of the two membranes were then compared to those of a standard commercial HEPA filter. Figure 25 is a graph representing the efficiency of the two Nylon 6 membranes compared to the HEPA filter versus the face velocity of the supplied air. Notably, HEPA filters are required to remove 99.97% of particles with diameters of 0.3µm, which the HEPA filter has proven to accomplish. Membrane 1, labeled as Sample 1 in the figure, has a lower efficiency than the standard HEPA filter and dips below the minimum efficiency of 99.97% at a face velocity of 10 cm/s. Membrane 2, Sample 2 in the figure, has a higher efficiency than the standard HEPA filter across the whole range of face velocities tested. Membrane 2 remains at or about 99.99% efficiency, making it an acceptable filter media in applications that require HEPA filters. Figure 25 and Figure 26 show velocity in cm/s, which equates to about 2 ft/min.

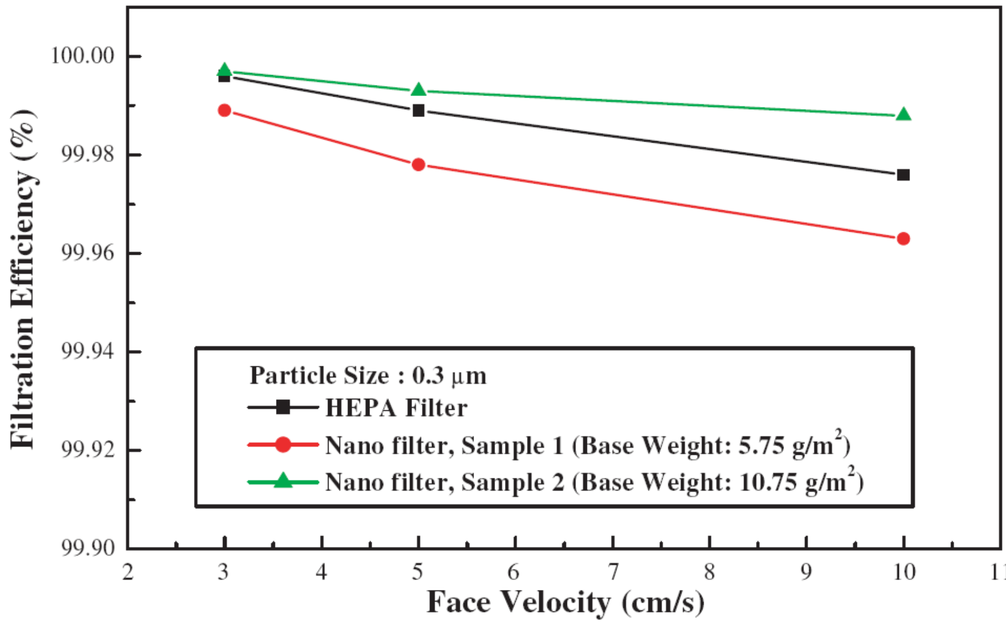

Figure 25: Filtration efficiency versus face velocity for HEPA filter and nylon 6 membranes (Ahn et al., 2006, p. 1034)

The pressure drops of the two Nylon 6 membranes and the HEPA filter versus the face velocity of the air tested are shown in Figure 26. The figure measures the pressure drop in mmAq, millimeters of water, which can also be written as mmH_2O, while 1" wg, or 1 inH_2O, equals 25.4 mmAq. Membrane 1 had a similar pressure drop to the HEPA filter, while membrane 2 had a much greater pressure drop than Membrane 1 and the HEPA filter. The rate of increase of pressure drop versus face velocity for Membrane 2 was significantly larger than for the other membrane and the HEPA filter. While Membrane 2 had a higher efficiency than a standard HEPA filter, the significantly larger pressure drop would make the membrane uneconomical for installation due to higher energy consumption.

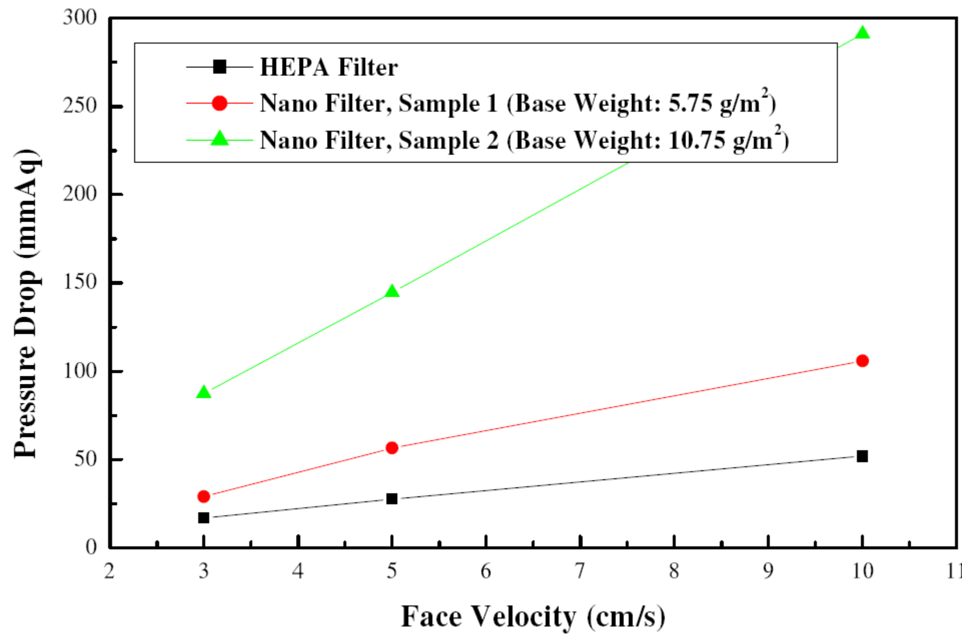

Figure 26: Pressure drop versus face velocity for HEPA filter and nylon 6 membranes (Ahn et al., 2006, p. 1034)

While numerous tests have determined the efficiencies of nanofibrous membranes, currently no set of criteria is established to test the efficiency and filtration properties of nanofibrous membranes. Instead the efficiencies of these membranes have been determined using similar testing procedures that exist for standard filters, but such tests introduce inconsistency when evaluating the particle size and face velocity. For example, this section discussed three separate studies determining the efficiency of nanofibrous membranes, performed by Wang et al. (2007), Patanaik et al. (2010) and Ahn et al. (2006). However, each of the nanofibrous membranes from the studies had different testing conditions, which resulted in efficiencies that varied greatly from one to another, making it difficult to directly compare membrane performance. The variation in test results show that nanofibrous membranes can be created with a variety of efficiencies, offering the potential for these membranes to be installed in a large range of applications. The study from Ahn et al. (2006) indicated that nanofibrous membranes are capable of competing with HEPA filters because the membrane exceeded the 99.97% efficiency minimum required by HEPA filters, although further research needs to occur because of the membrane's high pressure drop. The membrane studied by Patanaik et al. (2010) had an efficiency of 97.15% in removing particles 0.6-180 µm. Although efficiency was less than required efficiencies of HEPA filters, the membrane could potentially replace HEPA filters depending on its efficiency with 0.3μm because the membrane's pressure drop of 0.1" w.g. is much smaller than the pressure drop of typical a HEPA filter, which is generally 1.5". Clearly, for the nanofibrous membranes to be a competitive option in the HEPA filter industry the pressure drop would need to be equivalent to or lower than that of current filters to ensure system efficiencies. The varying results of the three tests introduced within this section indicate that a set of testing standards needs to be developed to test and compare nanofibrous membranes directly. These membranes have had much laboratory testing, but testing needs to be done on membranes installed in a HVAC system as to provide needed information of the membranes' performance in an actual application.

4.3 Membrane Performance Compared to Traditional Filters

Earlier chapters introduced traditional filtration systems and the types of filters commercially available, and this chapter has discussed how nanofibrous membranes offer potential as new filtering media for the filtration industry. This section will directly compare between the traditional filters and nanofibrous membranes. Specifically, Table 10 compares the filter properties of commercial filters to these of nanofibrous membranes introduced earlier in this chapter. The filters and membranes are compared on media construction and filtration performance. The commercial filters are compared at a face velocity of 500 FPM, except the panel filter, as the manufacturer's data did not include the panel filter's efficiency and pressure drop at that velocity. The nanofibrous membranes were tested at varying face velocities, which demonstrates the need for set testing conditions to more accurately compare membranes to traditional commercial filters. A price comparison is shown for traditional filters, but prices are not listed for the nanofibrous membranes as it would not show an accurate comparison. The commercial filters are produced in large scale production, whereas the membranes were created for testing purposes. The lack of information on the cost of nanofibrous membranes was also an issue. The table also shows the filters with smaller diameters generally had higher efficiencies because smaller particulate is removed from the air stream. Finally, the table demonstrates that as filters' efficiencies increase and the test particulate decreases, the filter's initial cost also increases as does pressure drop.

Table 10: Commercial filter and nanofibrous membrane comparison

	Filter/ Membrane	Fiber Diameter (µm)	Test Particulate (µm)	Efficiency (MERV)	Face Velocity (FPM)	Pressure Drop in "w.g. (Pa)	Thickness in inches (µm)	Initial Cost per 24x24 Filter
Commercial Filters	Panel	varies	3.0-10	< 20% (3)	300	0.05"	1-4	$ 3.30
	Pleated	varies	3.0-10	70% (8)	500	0.24"	1-4	$ 6.80
	Bag	30	0.3-1.0	< 70% (13)	500	0.4"	30	$ 52
	HEPA	0.1-10	0.3	99.97% (17)	500	1.4"	12	$ 246
	ULPA	0.1-10	0.1-0.2	99.999%	500	1.5"	12	$ 412
Nanofibrous Membranes	PVA*	0.5	0.5-8	97.6%	-	4.42" (1100)	.0157 (400)	
	PEO**	0.125	0.6-180	97.20%	787	0.1" (25)	0.138 (3506)	
	Nylon 6***	0.2	0.085-2.0	99.99%	20	11.4" (2844)	0.004 (100)	

* Membrane from Wang et al. (2007)
** Membrane from Patanaik et al. (2010)
*** Membrane from Ahn et al. (2006)

Another method of comparing filters and membrane performance is by determining the quality factor of the filter or membrane. The quality factor, QF, can be determined by the following equation:

$$QF = -\ln(1-\eta) / \Delta p \quad (5)$$

where η is the efficiency, and Δp is the pressure drop across the filter media (Brown, 1993). The larger the quality factor, the better the filter performance. The quality factor equation is many times used by researchers to compare performance of filtration media because the larger number is a result of a higher efficiency, lower pressure drop, or both. The quality factor equation would be a good comparison tool for designers to use when trying to select a filter for a specific system. However, Podgórski et al. (2006) note that the quality factor equation would be more realistic if it considered the change in efficiency and pressure drop of the filter and membrane over the course of the media's service life. Table 11 calculates and compares the quality factor of those traditional filters and membranes introduced in Table 10.

Table 11: Quality factor comparison of commercial filters and nanofibrous membranes

	Filter/ Membrane	Efficiency	Pressure Drop in "w.g.	Quality Factor (QF)*
Commercial Filters	Panel	20%	0.05	4.46
	Pleated	70%	0.24	5.02
	Bag	70%	0.4	3.01
	HEPA	99.970%	1.4	5.79
	ULPA	99.999%	1.5	7.68
Nanofibrous Membranes	PVA	97.6%	4.42	0.84
	PEO	97.20%	0.1	35.76
	Nylon 6	99.99%	11.4	0.81

* QF= $-\ln(1-\eta) / \Delta p$

While the quality factor provides a single number to directly compare filters and membranes based on the information provided in Table 11, some variables that affect a filter's performance are not considered in the quality factor. For instance, accurately comparing the filters and membranes is difficult because the filters and membranes were tested under varying conditions, depending on who developed the membrane or the type of filter. Next, the quality factor takes only the pressure drop and efficiency into consideration, while the size of the test particles and the velocity, also important factors, are disregarded in the quality factor equation. The varying performance parameters indicate that a set of testing standards needs to be developed for direct comparison. The standard test could determine the filter's efficiency and pressure drop at a specific velocity and particle size. The manufacturer could then provide additional information about the filter's performance at other velocities and particle sizes. The additional information would allow the designer to determine the pressure drop and efficiency of a filter not at the set standard conditions. This would also enable nanofibrous membranes to be compared to commercially available filters.

Also, the panel and pleated filters were tested with larger particulate; therefore, they had higher efficiencies than they would have had if they had been tested with the smaller particulate used in the other filters and membranes, resulting in possibly misleading higher quality factors. Also, most of the filters and membranes were tested at different face velocities. Generally, as the face velocity increases, the pressure drop across the filter also increases, which would alter the quality factor calculated in Table 11. However, the ULPA and HEPA filters' quality factors can be directly compared because their pressure drops are based on similar testing conditions, but a comparison cannot be made to the nanofibrous membranes. This further illustrates the need for a standard set of testing conditions so nanofibrous membranes and filters can be directly compared on performance. Also, a designer must consider a filter's performance and life cycle cost before selecting a specific filter for a system. Ultimately, standard testing conditions would allow the designer to compare two factors: quality factor and the price.

4.4 Concerns with Nanofibrous Membrane

Nanofibrous membranes do have some possible drawbacks for use in filtration applications. The main issues are their weak physical strength and their similar fiber characteristics to asbestos. The membranes' lack of mechanical strength and durability pose problems as the membranes are currently not capable of being installed on their own (Podgórski et al., 2006). The small fibers become damaged from the macroscopic impact of particles from the air stream causing the membranes to become inefficient (Barhate & Ramakrishna, 2007). To solve this problem, nanofibrous membranes must be used with an additional nonwoven substrate to provide the needed support and protection. In particular the substrate acts as a backing so the membrane does not become damaged (Grafe & Graham, 2002; Barhate & Ramakrishna, 2007).

Because the *nanofibers* have such small diameters, compared to the length of the fibers, they are similar to asbestos fibers. Asbestos fibers were common in filters in the 1970s until researchers determined that asbestos fibers had *carcinogenic* effects. Health concerns occur when an asbestos fiber enters the lungs and a single cell tries to absorb it because of the fiber's small diameter (Timmer, 2008). However, the cell is unable to fully absorb the fiber because of the fiber's length, which causes "perpetual inflammation, combined with the cellular damage" and then forces the "cell into a cancerous state" (Timmer, 2008). Research has shown that any fiber with a length-to-thickness ratio greater than seven that is capable of entering the lungs could cause similar issues as asbestos fibers (Timmer, 2008). Most *nanofibers* have length-to-thickness ratios greater than seven, as *nanofiber* diameters can range from 50-2500 nm and have lengths of tens of *microns*, depending on the method use to create the fiber (Petrik & Maly, 2009). Thus, based on the length-to-thickness ratio, *nanofibers* could be potentially harmful to humans if inhaled (Timmer, 2008). Timmer (2008) mentions a study that involved injecting mice with carbon *nanofibers*, and comparing the effects to those in a control group of mice that were injected with asbestos fibers. The two groups of mice saw "statistically indistinguishable" (Timmer, 2008) inflammation, although this study did not confirm if the *nanofibers* are capable of reaching the lung, or whether or not this inflammation causes mesothelioma. In 2006, it was reported that the government spent over one billion dollars on nanotechnology research, yet only 1-4% percent of that funding went to research the risks with this technology (Consumer Reports, 2007). This demonstrates that further research must be done to fully understand the benefits and concerns of incorporating *nanofibers* into everyday products. The research needs to confirm or disprove claims that these membranes truly have *carcinogenic* effects.

Although this section addresses the concerns with nanofibrous membranes, the advantages of these membranes far outweigh the disadvantages, if considering the fibers do not have *carcinogenic* properties. Another great advantage of nanofibrous membranes is their ability to incorporate antimicrobial agents within the polymer solution prior to the electrospinning process. Such agents inhibit *fungal and bacterial* growth on the membrane. The following chapter will introduce antimicrobial agents and further discuss their benefits when incorporated with nanofibrous membranes.

CHAPTER 5 - Antimicrobial Agents Added to Filter Media

As dust and particulate accumulate on or within the filter media, there is potential for *bacterial* and *fungal* growth on the filter because the dust and particulate provide nutrients for such *microorganisms*. The following subsections will introduce antimicrobial agents and address adding these agents to commercial filter media and incorporating them into nanofibrous membranes. This chapter will conclude be addressing potential applications where nanofibrous membranes with antimicrobial agents should be considered to replace traditional commercial filters.

5.1 Antimicrobial Agents

Antimicrobial agents can be added to the filter media to inhibit *bacterial* and *fungal* growth, which could cause significant health problems as they may be transmitted through the air stream and "may cause a wide variety of illnesses when deposited in the respiratory tract" (Maus, Goppelsröder, & Umhauer, 2001, p. 105). The air conditions, filter characteristics, organisms of concern, and antimicrobial agents are all factors to consider when attempting to inhibit *bacterial* and *fungal* growth. Additionally, moisture in the supply air will greatly contribute to the growth of *microorganisms*. Some *microorganisms* are capable of growing with only small amounts of moisture, and fungi generally need less moisture than *bacteria* to grow (Foarde, Hanley, & Veeck, 2000). Matching *microorganisms* and their specific antimicrobial agents is important when trying to suppress the growth of such organisms. Foarde, Hanley and Veeck (2000) note that not all *bacteria* or *fungus* "are killed or suppressed equally by the same antimicrobial" (p. 52) agent. Therefore, an antimicrobial agent should be carefully selected based on the *microorganism*(s) intended to be suppressed on the filter media.

5.2 Antimicrobial Agents on Traditional Filters

The size and material used as media within a filter are important but so is the opportunity to increase performance by applying an antimicrobial coating. This coating can be added to the filter prior to its installation to prevent the growth of mold and *bacteria* on the filter surface (NAFA, 2001). As a filter becomes loaded with particulate and dust, *bacteria* and mold may grow because the collected particulate acts as a feeding ground for these *microorganisms*. In turn, the formation of *bacteria* and mold on filters could trigger allergies to mold spores transmit *bacteria* spores into the space.

Various studies have tested the ability of antimicrobial agents to kill or inhibit the growth of *microorganisms* on traditional commercial filters. A study by Verdenelli, Cecchini, Orpianesi, Dadea, and Cresci (2003) compared the growth of *microorganisms* on untreated HEPA filters to HEPA filters treated with two different types of antimicrobial agents. The researchers also compared the filters' performance in a new condition and a "used" condition. The "used" condition was simulated by supplying dust across the filter at 0.706 CFM (20 l/min) for 30 hours. The study showed that the treated filters showed less microbial growth than the untreated filters, both used and unused, which showed greater microbial growth (Verdenelli et al., 2003, p. 14). Verdenelli et al. (2003) also noted that antimicrobial A was more effective at inhibiting the growth of *bacteria* and *fungus* than antimicrobial B. This demonstrates that some agents are more effective at suppressing the growth of *microorganisms*, depending on the *microorganism* of concern. Also, the growth of *microorganisms* on the untreated filter media resulted in an increased pressure drop across the filter, compared to the filters treated with the two antimicrobial agents that had smaller MPPS and pressure drops (Verdenelli et al., 2003). In addition to increased pressure drop across the filter, filter life should be a concern since growth of microorganisms would require replacing the filter sooner, therefore increasing life cycle cost.

Another study performed by Foarde et al. (2000) proved the importance of testing antimicrobial agents on filters with an as-used test to ensure the agent is effective at inhibiting the growth of these *microorganisms*. Foarde et al. (2000) found that each of the three antimicrobial agents "undoubtedly showed that it was able to kill or inactivate many *microorganisms*" (p. 58) when efficacy tests were performed for the Environmental Protection Agency (EPA), although the field test performance showed different results. The panel filters in question were tested against two types of *bacteria* and three types of fungi, and an increase in the number of *microorganisms* on the filter media signified microbial growth. The test results are shown in Table 12.

Table 12: Microbial growth on filters

(Foarde et al., 2000)

Antimicrobial	Panel Filters	Treated?	RH % 70	75	80	85	90	94	97
1	New	Y							
		N							
	Dust Loaded	Y							
		N							
2	New	Y							
		N					X	X	X
	Dust Loaded	Y					X	X	X
		N					X	X	X
3	New	Y				X	X	X	X
		N					X	X	X
	Dust Loaded	Y			X	X	X	X	X
		N			X	X	X	X	X
X= Growth of microorganisms									

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Table 12 shows that new, treated filters had no growth of *microorganisms*, except when applied with the third antimicrobial agent; however, the growth of *microorganisms* occurred on almost all of the dust loaded filters, treated and untreated, except filters treated with antimicrobial 1. The table demonstrates that as the relative humidity (RH) increases, there is a greater chance for growth of *microorganisms*, which like warm, damp environments. Foarde et al. (2000) found that treated and untreated filters showed minimal differences in the amount of microbial growth on the filter media. The fact that this test's results contradict outcomes from the field tests and other research studies as to the efficiencies of antimicrobial agents could be attributed to agent concentrations being less than needed or to the selected agent being ineffective against the *microorganisms* in the test (Foarde et al., 2000).

Advantageously, antimicrobial agents can be added to the filter media during the manufacturing process (B. Chamberlain, personal communication, September, 29, 2010). Chamberlain stated that the treated media is purchased from the manufacturer, and the filters are then made with the treated media (personal communication, September, 29, 2010). Thus, the selection of antimicrobial agent on the filter media is limited to the manufacturer and is not specified by the designer. The most common antimicrobial agents used in industry are Aegis and Ultra-Fresh; Silver can also be used, but it is expensive (B. Chamberlain, personal communication, September, 29, 2010). Ultra-Fresh incorporates "9 different active ingredients each of which acts in a different way to control bacteria and fungi" (Thomson Research Associates). Yoon et al. (2008) raises the concern that antimicrobial agent applied to traditional commercial filters leaches out over time. This means that over time, the antimicrobial agent becomes inefficient in suppressing the growth of *bacteria* and *fungus* on the filter media. Chamberlain acknowledges that after a certain point the antimicrobial agent becomes ineffective, but the filter generally needs to be replaced before this occurs (personal communication, October, 15, 2010).

Chamberlain also stated that filters treated with antimicrobial agents are only a small percentage of those sold within a year at Koch Filter Corporation, which illustrates that treated filters are not a standard practice of design (personal communication, October, 15, 2010). One major reason for minimal use of treated filters is the additional cost. Chamberlain (September, 29, 2010) said adding antimicrobial agent to a HEPA filter would double the price, and adding the agent to a bag filter would increase the price 40%. A designer can justify the additional costs to the owner as increased protection from microbial growth; of course, the use of the agent depends on the liability of the owner to protect the space from these microorganisms. Therefore, if the owner is willing to invest in the added protection against *fungal* and *bacterial* growth, the designer would want to ensure the filter does not leach out the antimicrobial. Nanofibrous membranes offer that added security of the antimicrobial agent staying intact over the life of the membrane. This combination is further discussed in the following subsection.

5.3 Antimicrobial Agents Incorporated with Nanofibrous Membranes

Nanofibrous membranes could incorporate antimicrobial agents into the polymer solution prior to the *electrospinning* process. This manufacturing application identifies an advantage of nanofibrous membranes such that the composition maintains itself over the life of the membrane. Yoon et al. (2008) note that the process can be done with ease. For example, Jeong, Yang, and Youk (2007) tested the effects of ammonium compounds added to a polyurenthane (PU) polymer to act as an antimicrobial agent. The polymer was electrospun into a nanofibrous membranes, and the membrane experienced a 99.9% reduction in *bacterial* and *fungal* colonies after incubation for 24 hours (Jeong et al., 2007). The percent reduction was determined by the following equation:

$$(A-B)/A \times 100\% \quad (6)$$

where A is the number of microbes initially applied to the membrane ,and B is the number of microbes after a specified time (Jeong et al., 2007). Another study performed by Kim, Nam, Rhee, Park, and Park (2008) found that when benzyl triethylammonium chloride (BTEAC) was added to a polycarbonate (PC) solution, the number of *bacteria* colonies was reduced by 99.9% after 18 hours of incubation. A third test by Lala et al. (2007) tested the effectiveness of silver nanoparticles as an antimicrobial agent when incorporated into three different solutions prior to *electrospinning*. The three solutions were cellulose acetate (CA), polyacrylonitrile (PAN) and polyvinyl chloride (PVC). Table 13 shows each membrane's characteristics and reduction percentage of *microorganisms*.

Table 13: Reduction of microorganisms

(Lala et al., 2007)

Polymer	Average Diameter (nm)	Thickness (µm)	Reduction (%)
CA	296	67	99
PAN	200	31	99
PVC	543	46	60

Table 13 shows the percent reduction of *fungal* and *bacterial* growth when silver nanoparticles were incorporated into various polymer solutions. The CA and PAN nanofibrous membranes had a much greater rate of reduction at 99% than the PVC membrane reduction at only 60%. This signifies the importance of testing the polymer and antimicrobial mixture prior to installation. The three studies from Kim et al. (2008), Jeong et al. (2007), and Lala et al. (2007) indicate that adding antimicrobial agents was successful in suppressing the growth of *bacteria* and *fungus* on nanofibrous membranes.

Along with the benefit of suppressing the growth of *microorganisms* on the filter media, adding antimicrobial agents to the polymer solution offers other advantages. Kim et al. (2008) found in their study that adding BTEAC to the PC solution resulted in a decrease in the fiber diameters along with greater uniformity among the fiber sizes. As addressed earlier, greater fiber uniformity results in a uniform pressure drop and enhanced efficiency across the membrane. The nanofibrous membranes also have a greater ability to retain the antimicrobial agent within the filter media as established in a study by Lala et al. (2007).

5.4 Application of Nanofibrous Membranes with Antimicrobial Agents

Nanofibrous membranes' filtration characteristics, which are discussed in detail in chapter 4, demonstrate that these membranes offer great potential for various specialized filtration applications: isolation rooms, operation rooms, and manufacturing and process facilities to name a few. This chapter, however, will focus on nanofibrous membranes replacing commercial HEPA filters in cleanrooms and hospital protective environment rooms. Both of these spaces require a high level of filtration, and various studies have shown nanofibrous membranes have the ability to remove small particles with similar efficiencies as the traditional commercial filters required for these spaces. Adding antimicrobial agents to filter media is advantageous in applications where the growth of *bacterial* and *fungal* colonies is a concern. Spaces where reducing *microorganisms* is critical may include spaces "where human or animal indigestion can cause illness or where a manufacturing process is directly affected" (Cecchini, Verdenelli, Orpianesi, Dadea, & Cresci, 2003, pg. 372). The following subsections will discuss the specific level of filtration required within cleanroom and hospital protective environment room applications and the potential for replacing traditional commercial filters with nanofibrous membranes embedded with antimicrobial agents. These two spaces were selected because they both require high levels of filtration given the critical nature of their use and can justify the antimicrobial agents. For a cleanroom application, the additional cost of an antimicrobial agent to protect the millions of dollars spent to produce pharmaceutical drugs is an obvious advantage. For health care applications, adding an antimicrobial agent to potentially save a life that could be lost due to an infection from a *bacterial* spore being transferred to a wound again is an obvious advantage. The following sections will address how to incorporate the nanofibrous membrane into an air filtration system to protect and save the critical process or occupant downstream of the filter media.

5.4.1 Cleanroom Applications

Cleanrooms require a high level of filtration because of the sensitive tests or procedures performed within the space. The International Organization for Standardization (ISO) Standard 14644-1:1999 defines a cleanroom as a:

> room in which the concentration of airborne particles is controlled, and which is constructed and used in a manner to minimize the introduction, generation, and retention of particles inside the room, and in which other relevant parameters…are controlled as necessary (p. 1).

The following section will give a brief overview of cleanroom classification, describe the current design requirement of cleanrooms, and address the specified level or filtration required depending on the cleanroom's classification. Next, this section will evaluate the potential for installing nanofibrous membranes with antimicrobial agents where traditional commercial filters would normally be located.

5.4.1.1 Design Requirements

Cleanrooms are divided into two main types depending on how the air is distributed within the room: turbulently ventilated and unidirectional flow (Whyte, 2001). Turbulently ventilated cleanrooms are also referred to as conventional cleanrooms (NAFA, 2001). In a turbulently ventilated cleanroom, clean air is distributed through a ceiling diffuser, and the supply air mixes with the air in the room and removes the 'dirty' air, containing contaminants and particulate, through air outlets near the floor (Whyte, 2001). The design intent of turbulently ventilated cleanrooms is to surround the process or product with a large amount of clean air to prevent airborne contamination from the dirty air in the space (NAFA, 2001). This type of design relies on mixing and diluting the *contaminants* and particulate with the clean air (Whyte, 2001). A turbulently ventilated space is shown in Figure 27.

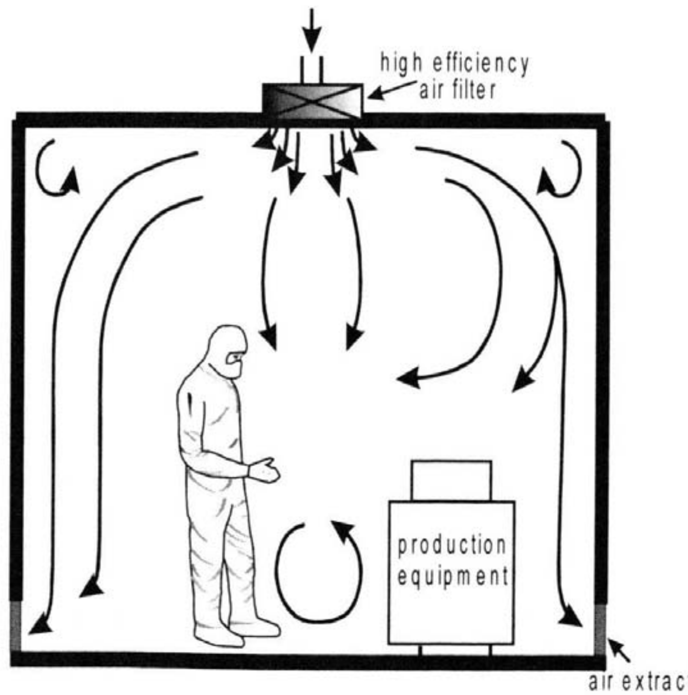

Figure 27: Turbulently ventilated cleanroom
(Whyte, 2001, p. 5)

The second type of cleanroom uses unidirectional flow, which is also known as laminar flow (Whyte, 2001). Unidirectional flow may be designed for a vertical or horizontal supply configuration. In a vertical unidirectional flow cleanroom *high efficiency* filters line the ceiling and the air is drawn across the filters with a downward distribution (Whyte, 2001). The air then exits through floor grilles or through continuous air outlets that line the base of the walls (NAFA, 2001). Horizontal unidirectional flow is similar to vertical unidirectional flow, but instead air is distributed through a wall lined with HEPA filters rather than through the ceiling (NAFA, 2001). The air is then removed through exit grilles located along the wall opposite of the distribution wall (NAFA, 2001). The design objective is to supply the air with a single pass through the room, as NAFA (2001) explains in a "piston-like effect". HEPA filters located in a laminar flow ventilation system are required to be leakage-free, because dirty air that leaks into a laminar flow cleanroom remains intact (NAFA, 2001). The leakage-free requirement requires a HEPA filter with a minimum efficiency of 99.99% in removing particulate (NAFA, 2001). A vertical unidirectional flow distribution is shown in Figure 28, and a horizontal flow distribution is shown in Figure 29. The figures show how the air is evenly distributed across the room and removed all along the floor or opposite wall. The piston-like distribution is shown as the air has a direct path from the inlet to the outlet; also, the air does not mix with the air in the space as it does with turbulent distribution.

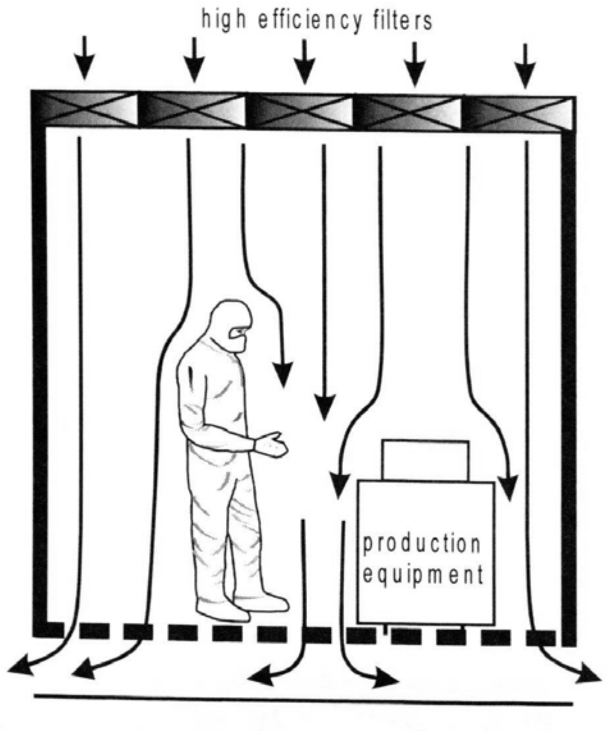

Figure 28: Vertical unidirectional flow cleanroom

(Whyte, 2001, p. 6)

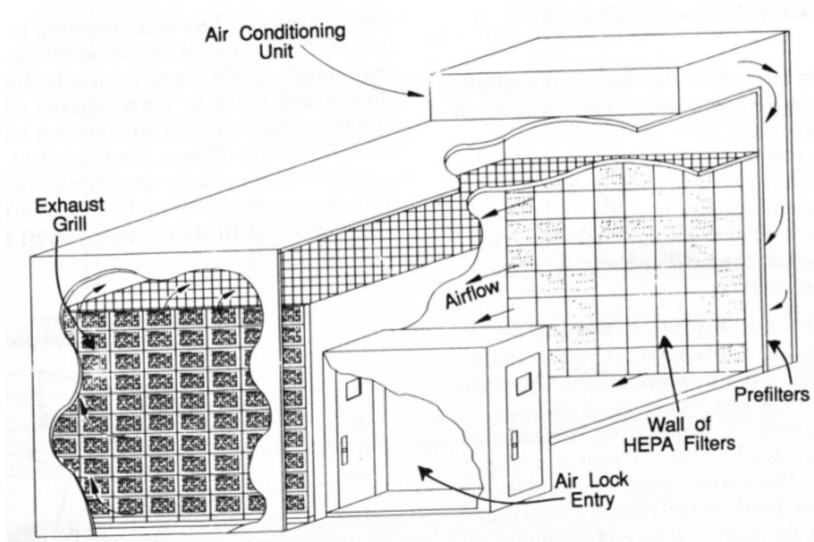

Figure 29: Horizontal unidirectional flow cleanroom

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The unidirectional flow system uses a larger amount of air than the turbulently ventilated system because air is distributed across the entire area of a ceiling or wall, rather than through the one supply point (Whyte, 2001). In this way, the unidirectional flow distribution minimizes the movement of contaminants throughout the space as the air moves across the contaminated surface with a single pass (Whyte, 2001). Alternatively, in turbulent flow distribution, clean air mixes with the *contaminants* within the cleanroom, potentially coming in contact with multiple surfaces before being removed through the air outlet. When minimal or no airborne contamination is the main objective for a cleanroom, unidirectional flow distribution is ideal because it is able to route the air stream containing particles and *contaminants* generated in the space out of the space more directly and quickly than turbulent flow can.

Not all cleanrooms are designed to have the same filtration and ventilation requirements, which depend on the process taking place within the cleanroom and the required cleanliness of the air. The level of filtration for a cleanroom depends on the cleanroom's classification as determined by two main standards— Federal Standard 209E, *Airborne Particulate Cleanliness Classes in Clean Rooms and Clean Zones*, and ISO Standard 14644-1. Initially, the Federal Standard 209E produced by the U.S. General Service Administration was used internationally as it was the only cleanroom code until May of 1993 when the International Standards Organization developed a technical committee TC 209, *Cleanrooms and Associated Controlled Environments* (Pacific Science Instruments, 1999). The new committee's purpose was to create a new international standard that included more cleanroom parameters than did Federal Standard 209E (FS209E) (Pacific Science Instruments, 1999). Indeed, the TC 209 committee has 10 documents dedicated to cleanrooms and clean zones. As stated earlier, different classifications of cleanrooms exist, depending on the level of clean air required within the space, and Standard 14644-1, *Cleanroom and associated controlled environments Part 1: Classification of airborne particulate*, addresses these different classifications. Table 14 shows the different classifications of cleanrooms and the maximum amount of particulate per cubic foot allowed for each classification, per ISO 14644-1.

Table 14: ISO 14644-1 class limits for particles per cubic foot

ISO 14644-1 Class Limits						
ISO Class	Particles per ft^3					
	≥ 0.1 µm	≥ 0.2 µm	≥ 0.3 µm	≥ 0.5 µm	≥ 1.0 µm	≥ 5.0 µm
Class 1	10	2				
Class 2	100	24	10	4		
Class 3	1,000	237	102	35	8	
Class 4	10,000	2,370	1,020	352	83	
Class 5	100,000	23,700	10,200	3,520	832	29
Class 6	1,000,000	237,000	102,000	35,200	8,320	293
Class 7				352,000	83,200	2,930
Class 8				3,520,000	832,000	29,300
Class 9				35,200,000	8,320,000	293,000

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Figure 30 is a graphical representation of the same information shown in Table 14. The figure and table illustrate that as class numbers become smaller, the cleanroom requires a higher level of clean air. Therefore, a Class 1 cleanroom is the most stringent cleanroom listed in

Standard 14644-1, by requiring a much lower concentration of particles greater than 0.1 µm and 0.2µm and not allowing any particulate greater than 0.3µm.

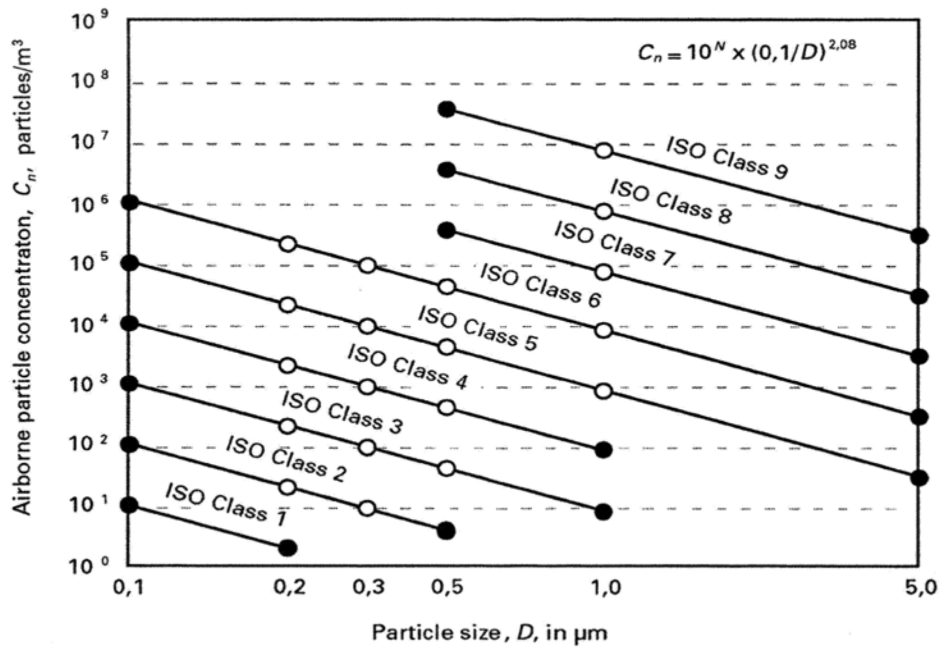

Figure 30: ISO class particle concentration versus particle size

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The ISO cleanroom classification is similar to the classes noted in Federal Standard 209E, but ISO Standard14644-1 created an extra three levels of cleanroom classifications: two more rigorous cleanroom classifications and one more lenient than the classification identified in FS209E. Table 15 shows the equivalent FS209E cleanroom classifications compared to the ISO Standard 14644-1 classifications.

Table 15: Comparison of ISO 14644-1 and FS209E cleanroom classifications

(Pacific Scientific Instruments, 1999)

ISO 14644-1 Class	FS209E
1	
2	
3	1
4	10
5	100
6	1,000
7	10,000
8	100,000
9	

To ensure the specified air cleanliness is met for a specified classification requires a certain level of filtration. Table 16 shows the various types of filtration systems required to ensure proper cleanliness levels are achieved. For example a cleanroom of ISO Class 8 requires a bag-type filter with an efficiency of 90% in removing particulate greater than or equal to 5μm (Whyte, 2001). A general design basis depending on the cleanroom ISO classification is shown in Table 16. For example, an ISO Class 6 cleanroom requires a HEPA filter with turbulent flow ventilation, while an ISO Class 5 cleanroom requires HEPA filters with unidirectional flow ventilation; whereas, a cleanroom of ISO class 4 or lower requires ULPA filters to cover the ceiling with unidirectional flow ventilation (Whyte, 2001).

Table 16: Filtration design based on ISO classification

ISO Class	Filter		Supply Flow
	Type	Location	
8 or lower	Bag	After central air conditioner	Turbulent
6-7	HEPA	At discharge	Turbulent
5	HEPA	At discharge	Unidirectional
4 or lower	ULPA	At discharge	Unidirectional

HEPA and ULPA filters in cleanroom applications have criteria that must be met for both the filter location and installation requirements. For example, the filters need to be installed where the air enters the room to eliminate the potential for intermediate sources of contamination to the supply air (NAFA, 2001). In non-cleanroom applications, filters are many times installed downstream of the mechanical equipment or directly within the equipment. When filters are within or just downstream of the HVAC equipment, particles could be drawn into the supply ductwork, or particles may become detached from the duct surface and these particles would then be distributed to the space being served (Whyte, 2001). Therefore, the HEPA and ULPA filters must be installed with fitted filter housing and rubber gaskets fitted into the filter frame to ensure unfiltered air doesn't leak into the cleanroom (Whyte, 2001; NAFA, 2001). As discussed earlier, if a filter does not have proper sealing, the filter's efficiency significantly decreases as air and *contaminants* find their way into the space through cracks around the filter. The air wants to take the path of least resistance, and a gap would allow air to flow more freely than the air drawn across the filter media.

5.4.1.2 Use of Nanofibrous Membranes with Antimicrobial Agents

Cleanrooms are used for a variety of applications in which a process or a test is required to be protected from dust and particulate that can be transmitted through the air distribution system. As stated in the previous subsection, there are different classifications of cleanrooms depending on the importance of particulate of a certain size to be removed from the air stream before entering the space. Nanofibrous membranes offer great potential to the filtration system within cleanroom applications because these membranes can be created to meet the specific filtration needs of the system given their varied performance capabilities.

Adding antimicrobial agent to the filter could ensure that *fungal* and *bacterial* growth would be inhibited on the membrane surface. This is important when designing cleanroom applications because of the critical use of the space. If *microorganisms* grow on the filter media serving the cleanroom, the microbial spores could be transmitted downstream into the cleanroom because the spores are smaller than the filter's pores. Any microbial spores are removed in the first place through diffusion, but if these *microorganisms* become detached and enter the space, they could then alter the results of the process or test within the space. The nanofibrous membrane with antimicrobial agent would offer longer term protection from *fungal* and *bacterial* growth, while maintaining the efficiency required by the filtration system at a lower pressure drop.

5.4.2 Protective Environment Room Applications

The Chartered Institution of Building Services Engineers (CIBSE) (2008) notes that "bacteria and fungi are always present in the indoor environment but in most cases not at levels to be significantly detrimental to healthy adults" (p.17-3), but these could cause major health problems for occupants with weakened immune systems. In particular a hospital protective environment (PE) rooms require a high level of filtration as these rooms are designed to protect the occupant from airborne contaminants and infectious organisms, which may arise "from pathogenic *microorganisms* shed by other occupants" (CIBSE, 2008, p. 17-2) and transferred within in the duct air system of the facility (ASHRAE, 2003). These *contaminants* may not affect a normal immune system, but could be dangerous and possibly life-threatening for these patients because of their physical state (ASHRAE, 2003). PE rooms are "for any condition that leaves a patient *immunocompromised*," which means leaving a patient with a weakened immune system, whether it be from an illness or a recent treatment (ASHRAE, 2003, p. 136). The following section will describe the current design requirement of protective environment rooms and the specified level or filtration required within the space. Next, the chapter evaluates the feasibility of installing nanofibrous membranes with antimicrobial agents to replace traditional commercial filters in pre-filter and final filter applications.

5.4.2.1 Design Requirements

The ASHRAE HVAC Design Manual for Hospitals and Clinics (2003) notes that protective environment rooms have two design requirements that must be considered to ensure protection of the occupants in the space: (1) the space must be positively pressured and (2) air distribution within the room must control airborne infection *contaminants*. The protective environment rooms shall have unidirectional flow served through a non-aspirating diffuser in the ceiling, and a HEPA filter shall be installed in the diffuser (ASHRAE, 2003). The protective environment rooms are also required to have another filter bed installed upstream of the room to pre-clean the supply air being served to such rooms. The first filter bed, which is to be located upstream of the air distribution equipment serving the space, shall be a MERV 8 filter or better (AIA, Facility Guideline Institute, 2006). The MERV 8 filter is installed as a pre-filter and is used to remove large particulate such as dust and lint from the airstream. This pre-filter is installed prior to the mechanical equipment to protect the heating and cooling coils and other components from large particles collecting on the pieces of equipment, which would lead to a reduction in the equipment's efficiency (HVAC Design Manual, 2002). The HEPA filter, which is equivalent to MERV 17, is installed to remove smaller particulate with a greater efficiency, thus protecting the patient in the protective environment room from small particulate and organisms.

The ASHRAE HVAC Design Manual for Hospitals and Clinics (2003) requires differential pressure gauges at all filters to measure the differential static pressure across the filter. The differential pressure gauge would notify the building manager or facility engineer when the filters need to be changed, based on resistance to air flow. As stated earlier, as the pressure drop across the filter increases the mechanical equipment is forced to work harder to supply the required air across the filter. If the differential static pressure becomes too large, the filter will prevent the air from being distributed. This leads to major issues where the equipment is over working, and air is not being delivered to the space as designed. This could result in a shortened life of the equipment, which could lead to large expenses for the owner. Furthermore, the PE room must receive the designated amount of air because the room must stay positively pressurized to the adjoining space to protect the patient within. If the room becomes neutral or, even worse, negative, contaminants from the connecting spaces will find their way into the PE room through cracks and doors, which puts the patient at a major risk of infection or illness. Therefore, filter maintenance will directly affect the function and design of the PE room, making it critical that the filters be replaced when the filter's resistance becomes inefficient in the design.

5.4.2.2 Use of Nanofibrous Membranes with Antimicrobial Agents

A nanofibrous membrane's filtration characteristics offer great potential for PE rooms because of its ability to serve as a pre-filter or a final filter in the air filtration system. Adding antimicrobial agents to the nanofibrous membranes makes the membranes even more efficient. The following paragraphs will discuss the potential for replacing traditional commercial filters with nanofibrous membranes with antimicrobial agents in both the pre-filter and final filter locations.

A pre-filter is designed to remove large particulate and dust from the air stream and thereby extending the life of the final filter. Since the pre-filter is the first filter within the air filtration system, this filter will have greater amounts of dust and particulate on the surface, which provides a feeding ground for *bacteria* and *fungus*. Then, as *bacteria* and *fungus* grow on the filter surface there is a greater resistance to airflow across the filter. This increase in resistance results in a shorter life of the pre-filter and increased energy bills because the fan must work harder to supply the air across the filter. Incorporating antimicrobial agents into a nanofibrous membrane allows the membrane to suppress the growth of *bacteria* and *fungus*, which reduced the chance for these *microorganisms* to be introduced downstream of the filter or within the space.

A final filter is designed to remove small particulate that is capable of passing through the pre-filter. The final filter generally has less dust and particulate matter on the filter surface compared to a pre-filter, but it is also the last place where particulate can be removed from the air stream. A nanofibrous membrane with an antimicrobial agent and an efficiency similar to that of a HEPA filter could be installed to ensure *bacterial* and *fungal* growth does not occur on the final filter. Currently, standards do not require an antimicrobial agent to be added to the final filter, but should be considered to provide extra protection to the occupants.

The main purpose of the PE room is to protect the occupant within the space, who most likely has a weakened immune system and could easily be affected by various *microorganisms*. The antimicrobial agent applied to a nanofibrous membrane offers the ability to inhibit *fungal* and *bacterial* growth on the filter media, and the agent will not leach out, which has been proven with agents on commercial filters. Clearly, nanofibrous membranes with antimicrobial agents have great potential in hospital PE rooms to increase protection to the occupant without sacrificing the performance of the air filtration system.

CHAPTER 6 - Conclusion

Nanofibrous membranes offer great potential for filtration, because the membrane is able to remove smaller particulate from the air stream without significantly increasing the pressure drop, and they are currently being manufactured by Donaldson Company Inc., Finetex Technology Co., Freudenberg Nonwovens, and Amisol Ea Air Filters. The membrane's filter characteristics can be controlled depending on the composition of the polymer solution prior to the *electrospinning* process. The ability to control the membrane characteristics, by changing the concentration of the polymer solution or adjusting the spinning distance, allows a membrane to be created for a specific application. Antimicrobial agents can also be incorporated into the polymer solution prior to the *electrospinning* process, and doing so inhibits *fungal* and *bacterial* growth on the membrane surface. While inhibiting the growth of microorganisms is beneficial in all applications, the increased initial investment may not be justifiable. *Bacterial* and *fungal* growth on filters could have a detrimental effect on all spaces, but some spaces carry a greater liability; in such instances, it is easier to justify the increased cost. Ultimately, nanofibrous membranes with antimicrobial agents offer the greatest opportunity for protection of spaces in which the process or occupant must be protected from airborne *microorganisms*.

The future use of nanofibrous membranes in the filtration industry by engineers and manufacturers depends on further research and testing of these membranes. Research must focus on the safety of the fibers used within the membranes to guarantee they do not have *carcinogenic* properties similar to those of asbestos fibers. Since the health of a building's occupants is the main concern, this further research would determine whether nanofibrous membranes should be used in filtration applications, depending on whether the tests confirm or disprove the fiber's *carcinogenic* affects.

Research should also be done to determine which antimicrobial agents are most effective in suppressing various *bacteria* and *fungus*. Many tests indicate that adding an antimicrobial agent is effective in killing or inhibiting the growth of *microorganisms*, but not all antimicrobial agents are effective against every strain of *bacteria* and *fungus*. It would be useful to know which antimicrobial agents should be incorporated with certain polymer solutions to suppress a specific microorganism.

Finally, a set of testing standards needs to be developed so these nanofibrous membranes can accurately be compared to other nanofibrous membranes and traditional commercial filters. While many research groups have created nanofibrous membranes and have tested their membranes' filtration characteristics under varying conditions, those different conditions make it difficult to provide a direct comparison of the various membranes' efficiencies and pressure drops. If a set of testing standards were to be developed, manufacturers and designers could directly compare nanofibrous membranes' performance. Such standards would also allow researchers to determine the most economical material and effective concentration of solution for creating nanofibrous membranes.

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Appendix A - Glossary

Aerosol: “smoke, mists, fumes, dry, granular particles, bioaerosols and natural and synthetic fibers…suspended in a gas” (ASHRAE, 2008, p. 28.1)

Bacteria: “single cell microorganisms ranging from harmless and beneficial to intensely virulent and lethal” (NAFA, 2001, p. G-2)

Carcinogenic: “causing cancer or contributing to the causation of cancer, pertaining to a carcinogen” (Medicine Net, Inc., 2001)

Contaminant: “any impurity, any material of an extraneous nature, associated with a chemical or pharmaceutical preparation, a physiologic principle or an infectious agent” (ASHRAE, 2003, p. 7)

Cross-contamination: indirect contamination, “especially the introduction of disease germs or infections material into or on normally sterile objects” (ASHRAE, 2003, p. 7)

Density: “weight per unit volume of a substrate” (Wirtz, 1998, p. 67)

Efficiency, high: MERV rating greater than 13

low: MERV rating less than 6

medium: MERV rating between 7-12 (NAFA, 1997)

Electrospinning: the process of creating nanofibers my supplying a high voltage to a polymer solution

Fungus: “parasitic lower plants that lack chlorophyll, including molds and mildews” (Wirtz, 1998, p.108)

Immunocompromised: “immune system has been weakened by a disease (such as AIDs) or medical treatment (such as chemotherapy)” (ASHRAE, 2003, p. 9)

Micron: “a metric unit. For length it is one millionth (1/1,000,000) of a meter. There are 25,400 microns in one inch” (Wirtz, 1998, p.158)

Microorganism: small living organism, including bacteria, viruses, and fungi

Monodispersed: particles having the same size diameters

Nanofiber: fibers with a diameter less than 1.0μm

Respirable: particles capable of piercing the human lung, with diameters generally smaller than 3μm (SMACNA, 1998)

Virus: “small living particles that can infect cells and change how the cell functions” (Medicine Net, Inc., 2004)

Appendix B - Acronyms and Abbreviations

ACH	Air Changes per Hour
AIA	American Institute of Architects
ANSI	American National Standards Institute
ASHRAE	American Society of Heating Refrigerating and Air-Conditioning Engineers
BTEAC	Benzyl Triethylammonium Chloride
BTU	British Thermal Units
BTU/h	British thermal units per hour
CA	Cellulose Acetate
CFM	Cubic Feet per Minute
CIBSE	Chartered Institution of Building Services Engineers
cm	Centimeter
cm/s	Centimeter per second
EPA	Environmental Protection Agency
ERH	Equilibrium Relative Humidity
ft/s	Feet per second
ft^2	Square feet
FPM	Feet Per Minute
g/m^2	Grams per meter squared
HEPA	High Efficiency Particulate Air
HVAC	Heating Ventilating and Air-Conditioning
ISO	International Organization for Standardization
KCl	Potassium Chloride
Kn	Knudsen number
MERV	Minimum Efficiency Rated Value
MPPS	Most Penetrating Particle Size
mmAq	Millimeter water
mmH_2O	Millimeter water
NAFA	National Air Filtration Association

nm	Nanometer (10^{-9} m)
PAN	Polyacrylonitrile
PE	Protective Environment
PEO	Polyethylene Oxide
PVC	Polyvinyl Chloride
SEM	Scanning Electron Micrograph
SMACNA	Sheet Metal and Air Conditioning Contractors' National Association
ULPA	Ultra Low Penetration Air
wg	Water Gauge
Δ	Represent the change or difference
λ	Mean free path of air molecules (µm)
µm	Micrometer (10^{-6} m)
η	Efficiency (%)

Appendix C - Republication Releases

Gmail by Google

Ann Gregg <agregg.ksu@gmail.com>

FW: Republication Release from Cleanroom Technology--Non RightsLink

1 message

Permission Requests - UK <permissionsuk@wiley.com> **Fri, Jul 9, 2010 at 5:13 AM**
To: "agregg.ksu@gmail.com" <agregg.ksu@gmail.com>

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Cassandra Fryer

Permissions Assistant

Wiley-Blackwell | 9600 Garsington Road | Oxford | OX4 2DQ | UK

| * cfryer@wiley.com

****

Ann Gregg <agregg.ksu@gmail.com>

FW: Republication Release from Cleanroom Design

1 message

Permission Requests - UK <permissionsuk@wiley.com> **Thu, Jul 8, 2010 at 8:43 AM**
To: "agregg.ksu@gmail.com" <agregg.ksu@gmail.com>

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Best Wishes

Cassandra Fryer

Permissions Assistant

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| * cfryer@wiley.com

****

Bob Valbracht <bvalbracht@lorencook.com> **Mon, Jun 7, 2010 at 4:30 PM**
To: Ann Gregg <agregg.ksu@gmail.com>
Cc: Loren Cook II <lc2@lorencook.com>

Ann,

Yes, you are welcome to include the chart “Relative Size Chart of Common Air Contaminants” in your Masters of Science report. Unfortunately, I no longer have the sources where we obtained this data, so hopefully you can work with the chart as-is. I can, however supply a high resolution version of the existing chart if that helps.

Sincerely,

Robert A. Valbracht, P.E.

Vice President of Engineering

Loren Cook Company

417-869-6474 x113

www.lorencook.com

LOREN COOK COMPANY

Ann Gregg <agregg.ksu@gmail.com> **Mon, Jun 7, 2010 at 1:51 PM**

To: rvalbracht@lorencook.com

Dear Bob Valbracht,

I am a Graduate student at Kansas State University requesting the republication release of the Relative Size Chart of Common Air Contaminants (pg 47) from "Engineering Cookbook". The request is for education purposes of completing a Masters of Science report with the potential for publication.

Sincerely,
Ann Gregg
Kansas State University
agregg.ksu@gmail.com
913.669.8526

David White <davidw@kochfilter.com> **Thu, Jul 1, 2010 at 2:14 PM**
To: Ann Gregg <agregg.ksu@gmail.com>

Yes

Thank you and good luck.

You are appreciated and I hope this finds you well,

David White

Koch Filter Corporation-Marketing

Direct Phone: 502-634-6275

Mobile Phone: 502-619-9272

Direct Fax: 502-635-2624

Email: davidw@kochfilter.com

www.kochfilter.com

Ann Gregg <agregg.ksu@gmail.com> **Thu, Jul 1, 2010 at 1:54 PM**
To: David White <davidw@kochfilter.com>

Mr. David White,

Attach is a letter requesting republication of filter figures located on the Koch Filter Corporation website. Please let me know if you need anything else. Thank you for your help.

Sincerely,

Andrea Gregg
Kansas State University
agregg.ksu@gmail.com
913.669.8526

[Quoted text hidden]

Koch Filter Figure Request.pdf
135K

Kansas State University
Department of
Architectural Engineering
and Construction Science
240 Seaton Hall
Manhattan, KS 66506-2903
785-532-5964

July 1, 2010

14702 Slater
Overland Park, KS 66221

Mr. David White
Koch Filter Corporation
625 W. Hill St
Louisville, KY 40208

Dear Mr. White,

I am a Graduate student in Architectural Engineering at Kansas State University requesting the republication release of filter figures located on the Koch Filter Corporation website. The request is for the release of the following figures:

- Commercial and Industrial Disposable Panel Filters
- Multi-Pleat Green13™ MERV13 Extended Surface Panel Filters
- Multi-Sak Extended Surface "Bag" Filters
- BioMAX CS HEPA Filter

The request is for education purposes of completing a Master's of Science report with the potential for publication.

Sincerely,

Andrea Gregg
Graduate Student
Kansas State University

Ann Gregg <agregg.ksu@gmail.com>

Permission and Licensing - KSU, ASHRAE Standard 52.2 and ASHRAE Journal

1 message

Comstock, Steve <comstock@ashrae.org> **Wed, Sep 8, 2010 at 7:37 AM**
To: "agregg.ksu@gmail.com" <agregg.ksu@gmail.com>
Cc: "Harr, Julie" <JHarr@ashrae.org>, "julia.keen@gmail.com" <julia.keen@gmail.com>

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If you have questions, please let me know.

Best Regards,

Steve Comstock

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Dear ASHRAE Permission and Licensing,

I am a Graduate student at Kansas State University requesting the republication release of tables and figures in "ANSI/ASHRAE: Standard 52.2-1999" and "Life-Cycle Costing of Air Filtration" by D. Arnold, D.M. Matela, and A.C. Veeck in the November 2005 issue of *ASHRAE Journal*. The request is for the following tables and figures:

- Table 12-1 Minimum Efficiency Reported Values (MERV) Parameters (Standard 52.2-1999, pg 26)
- Table E-1 Application Guidelines (Standard 52.2-1999, pg 39)
- Figure 1: Filter Life-cycle cost components (Arnold, et al, 2005, pg. 30)
- Table 4: Annual energy costs of comparable filters (Arnold, et al, 2005, pg 32)

The request is for education purposes of completing a Masters of Science report with the potential for publication.

Sincerely,
Ann Gregg
Kansas State University
agregg.ksu@gmail.com
913.669.8526

Tim Dovan <TDovan@ansi.org> **Fri, Jun 25, 2010 at 7:57 AM**
To: Ann Gregg <agregg.ksu@gmail.com>

Dear Ms. Gregg,

We are pleased to grant you permission to include Figure A-1 from ISO 14644-1:1999 in a paper you are writing toward the completion of your Masters of Science degree. The figure must be cited as follows:

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ANSI wishes you success with the completion of your Masters degree and in your future endeavors.

Regards,

Tim Dovan

Customer Service Manager

ANSI

Ph: 1-212-642-8910

Fx: 1-212-302-1286

tdovan@ansi.org

tom.birchard@elmarco.com <tom.birchard@elmarco.com> **Mon, Sep 20, 2010 at 10:00 AM**
To: Ann Gregg <agregg.ksu@gmail.com>

Ann -

Please feel free to use the diagrams and tables so long as they are properly cited. If they could be annotated "Courtesy of Elmarco" that would be great.

See page 39 of this old presentation: http://czech.nsc.gov.tw/public/Data/852916565971.pdf (I can't find the original press release...)

I'm sure you also found this paper: http://www.elmarco.cz/upload/soubory/dokumenty/67-1-2-eu-kones-zakopane-09.pdf which is somewhat related to your topic.

Best of luck and please let us know when the paper is published.

Oh, and if anyone at KSU is interested in producing nanofibers, as opposed to writing about them, please have them contact me.

Tom B I R C H A R D
Product Manager

ELMARCO, Inc.
900 Perimeter Park Dr.
Suite C
Morrisville, NC 27560
USA

Tel: (919) 334 6497
Mob: (919) 830 7885
Fax: (919) 651 0246
Email: tom.birchard@elmarco.com
Web: www.elmarco.com

Ann Gregg <agregg.ksu@gmail.com> **Sun, Sep 19, 2010 at 8:32 PM**
To: tom.birchard@elmarco.com

Tom Birchard,

I am following up from our conversation on Friday, as I am requesting the republication release of the following figures and tables from"Production Nozzle-Less Electrospinning Nanofiber Technology" by Stanislav Petrik and Miroslav Paly:

- Figure 1: The path of an electrospinning jet
- Figure 5: Free liquid surface electrospinning from a rotating electrode (a) and the various types of spinning electrodes (b)
- Table 2: Nanofiber Production Methods

You said there are a couple of companies that are currently using the electrospinning processes to produce air filters, and if you are able to share their information with me that would be greatly appreciated. Thank you for your help, and I will be sure to get you a copy of my final report, when it is completed.

Sincerely,
Ann Gregg
Kansas State University
agregg.ksu@gmail.com
913.669.8526

Darrell Reneker <reneker@uakron.edu> **Mon, Sep 27, 2010 at 10:38 AM**
To: Ann Gregg <agregg.ksu@gmail.com>

Ann Greg--

It is unlikely that any problems will arise from your proposed use of the figure. There will certainly be none from me.

--Darrell Reneker

Ann Gregg <agregg.ksu@gmail.com> **Thu, Sep 23, 2010 at 11:19 AM**
To: Darrell Reneker <reneker@uakron.edu>

Dr. Darrell Reneker,

I am a graduate student at Kansas State University and I received your contact info from Tom Birchard and Stanislav Petrik from Elmarco. I am requesting the republication release of a The Path of an Electrospinning Jet, which was used as Figure 1 in "Production Nozzle-Less Electrospinning Nanofiber Technology" by Petrik and Maly from Elmarco. The document is attached or can be found at http://www.elmarco.com/upload/soubory/dokumenty/66-1-1-mrs-fall-boston-09.pdf.

This request is for educational purposes of completing a Masters of Science report with the potential for publication.

Sincerely,
Ann Gregg
Kansas State University
agregg.ksu@gmail.com
913.669.8526

Alan Veeck <mvainc1@aol.com> **Thu, Sep 23, 2010 at 9:01 AM**
To: Ann Gregg <agregg.ksu@gmail.com>

Good Morning Ann;

Sorry – going backwards on my emails I found your request…everything looks good and you have our permission to reprint.

Please include the reference:

Reprinted with permission from the by the National Air Filtration Association (NAFA) from the text, *Installation, Operation and Maintenance of Air Filtration Systems* 2nd Edition.

Thanks Ann. We would pleased to have a copy of your thesis when completed.

Alan C. Veeck, CAFS, NCT, II

National Air Filtration Association

PH: 757-313-7400

FAX: 757-497-1895

Cell: 757-508-6232

Representing the Interests of the Air Filtration Industry-Worldwide

---

Ann Gregg <agregg.ksu@gmail.com> **Thu, Sep 23, 2010 at 8:57 AM**
To: Alan Veeck <mvainc1@aol.com>

Alan,

I am requesting the republication release of the following figures and tables from NAFA Installation, operation and maintenance of air filtration systems (1997):

- Figure 11.4: Typical filter life curve (pg. 11-4)
- Table comparing pressure drop range to hours of operation (pg. 11-5)
- Table comparing denier to fiber diameter (pg. G-3)

The request is for educational purposes of completing a Masters of Science report with the potential for publication. Thank you for all of your help.

Sincerely,

Ann Gregg
Kansas State University
agregg.ksu@gmail.com
913.669.8526

Babcock, Brian <Brian.Babcock@donaldson.com> **Mon, Nov 1, 2010 at 2:26 PM**
To: Ann Gregg <agregg.ksu@gmail.com>
Cc: "Cahn, Becky A. (U.S.)" <Rebecca.Cahn@donaldson.com>

Hi Ann,

Yes, those figures can be used in your report. Thank you for your patience.

Brian Babcock | Intellectual Property Manager | Phone: 952-887-3850

Brian.Babcock@donaldson.com

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Ann Gregg <agregg.ksu@gmail.com> **Tue, Oct 12, 2010 at 1:09 PM**
To: "Babcock, Brian" <Brian.Babcock@donaldson.com>

Brian,

I am requesting the republication release of the following figures from "Polymeric Nanofibers and Nanofiber Webs: A New Class of Nonwovens":
Figure 3: Cross section view of nanofiber web on spunbond substrate
Figure 5: Various nanofiber web densities are possible through process control.

The request is for education purposes of completing a Masters of Science report with the potential for publication.

Sincerely,
Ann Gregg
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