

Fiberglass Vs. Synthetic Air Filtration Media

By Edward Vaughn, Professor, and Gayetri Ramachandran, Graduate Student, Clemson University, Clemson, SC

Abstract

This paper deals with ASHRAE filters used in air filtration applications and summarizes, on the basis of current research work, some of the reasons for the disagreement that exists among filter manufacturers concerning the properties and performance of various types of air filter media in general, glass and synthetic media in particular. Attention is also drawn to some important items that need to be incorporated in test methods and to some factors that could be affecting filter performance

Introduction

The filtration industry today is a diverse and technically sophisticated business with annual sales reported to be in excess of \$100 billion [1]. Filter producers supply various types of filtration systems and filter media designed to meet a wide variety of liquid, air and gaseous fluid filtration needs. The filtration business has evolved over time to become a complex industry with very specific requirements for each area of use. Performance standards for the media used in virtually every application have become very stringent. Recent studies and ongoing research in the area of air filtration suggest that the present test methods may be inadequate in predicting the most economical choice of media, with specific efficiency levels for different end-use applications. Also, some test methods have been criticized for their inability to reflect the true performance of filters in real-life environment over their full lifetime.

The Filter Spectrum

The filtration spectrum covers a wide size range from ionic particles measured in angstroms to larger solids up to several hundred microns in size. The spectrum is divided into four broad categories as shown in *Figure 1*: Reverse Osmosis,

Ultrafiltration, Microfiltration, and General Particle Filtration [9]. Depending on the requirements, different filtering systems can be used. If surface filters are used, then the contaminants are trapped and held on the surface of the media. On the other hand, if depth filters are used, larger particles are caught on the filter's surface and finer contaminants are trapped in the media's fibers within. Accordingly, the most suitable filter media that is disposable or reusable needs to be selected. A wide variety of filter media are available. Some of them include membranes, microporous plastics, sand, diatomaceous earth, perlite, paper, woven metal wire, woven and nonwoven fibrous media. Nonwoven fibrous media are made of synthetic fibers, fiberglass and paper [1].

Filter Media Classification

The classification of filter media depends on the test method used. As most testing is performed in the laboratory with synthetic dust, the classification does not always provide a reliable basis for the estimation of a filter's life or its performance in actual application. According to the European Classification, particle filters are categorized into four types: Course, Fine, High Efficiency Particulate Air Filters (HEPA), and Ultra Low Particulate Air Filters (ULPA). Filters produced from glass fibers or synthetic fibers like polyester, acrylic and polyamide fibers, which separate particles that are 5mm and larger, are designated as course filters. Fine filters are made mainly from glass fibers with an average diameter of 0.5 - 5.0 mm or from coarse plastic fibers, often in combination with an electrostatic charge. European Test Standards classify filters according to their Arrestance (A_m) and Dust Spot Efficiencies (E_m). *Table 1* gives the classification of filters on this basis. For example, a filter with an average arrestance value between 65% and 80 % is designated as an EU 2 filter by Eurovent Classification and G 2 filter by EN 779 Classification. A filter with an average dust spot efficien-

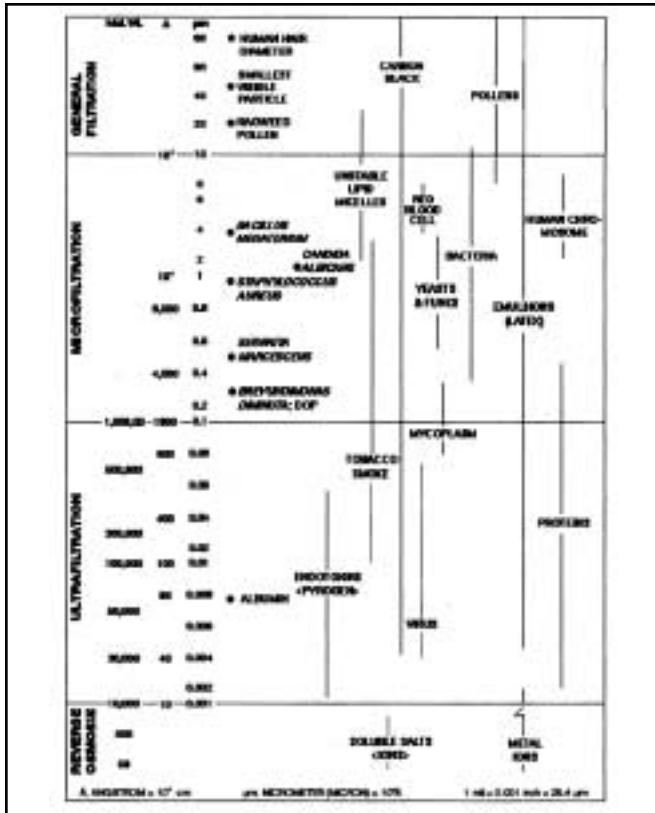


Figure 1

FILTRATION GEOMETRY SCALE AND TYPICAL PARTICLES CAPTURED THEREIN (9)

cy of 95% or less is designated as an EU 9 filter by Eurovent Classification and F 9 filter by EN 779 Classification.

To meet current demands of clean air for specialized applications, such as the military, the nuclear power industry, hospitals and the electronic industry, HEPA and ULPA filters are used. Based on the CEN EN 1822:1998 test method, a filter's efficiency is determined by the Most Penetrating Particle Size (MPPS) value. The Most Penetrating Particle Size is defined as the most frequently occurring particle size that penetrates

through the filter media. Depending on the total level of separation and leakage, a filter is classified as H10, H11, H12, H13 or H14 and U15, U16 or U17.

Chemical filters are adsorption filters impregnated with chemical substances that contain activated carbon. By means of chemical reactions, these filters adsorb and retain gases that are difficult to remove [4].

The Fiberglass Media Versus Synthetic Media Issue

High efficiency fiberglass filter media have been an industry standard for air filtration applications. These media are characterized by a dense structure of fine glass fibers, typically in the one-micron range. More recently, synthetic fiber filter media with a more open structure formed from relatively coarse fibers - mainly electrostatically charged polypropylene fibers - have been introduced.

Short-term tests performed in the laboratory on the basis of ASHRAE and European test procedures show that initial and average efficiencies of these two types of filter media are comparable. But extensive field-testing and real-life tests on the two media show that laboratory tests do not predict the performance of filters over their whole service life. Also, lifetime tests reveal the fact that there is a great difference in the filtration performance of the two types of filtration media. Glass media maintains its efficiency, while synthetic media loses its efficiency over its service life [2].

To understand this disagreement between real-life test results and laboratory results generated from ASHRAE and European test standards, one needs to look keenly into the various factors that affect the filtration capability of filter media. The standard tests do not cover the entire gamut of filtration media types and challenge environments, and their results must be interpreted in light of knowledge of the characteristics and properties of the filter medium in question and the conditions to which it is subjected.

Filtration Mechanisms

A popular misconception regarding how a filter works is that fibrous filters behave like sieves, where particles above a certain size are trapped and smaller particles pass through. While this is the case with some membranes filtering liquids, fibrous air filters defy common sense by actually trapping smaller and larger particles more effectively than mid-sized particles.

Four mechanisms act to separate a particle from a fluid stream and retain it on a filter medium, namely, Interception, Inertial Impaction, Brownian

Table 1
EUROVENT CLASSIFICATION OF FILTERS (4).

Eurovent Filter Class	EN 779 Filter Class	Average Synthetic Dust Weight Arrestance in %	Average Atmospheric Dust Spot Efficiency in %	Final Pa	Filter Classification and Filter Designation
EU 1	G 1	$A_m < 65$	-	250	PRE-FILTER
EU 2	G 2	$65 \leq A_m < 80$	-	250	PRE-FILTER
EU 3	G 3	$80 \leq A_m < 90$	-	250	PRE-FILTER
EU 4	G 4	$90 \leq A_m$	-	250	PRE-FILTER
EU 5	F 5	-	$40 \leq E_m < 60$	450	FINE AIR FILTER
EU 6	F 6	-	$60 \leq E_m < 80$	450	FINE AIR FILTER
EU 7	F 7	-	$80 \leq E_m < 90$	450	VERY FINE AIR FILTER
EU 8	F 8	-	$90 \leq E_m < 95$	450	VERY FINE AIR FILTER
EU 9	F 9	-	$95 \leq E_m$	450	VERY FINE AIR FILTER

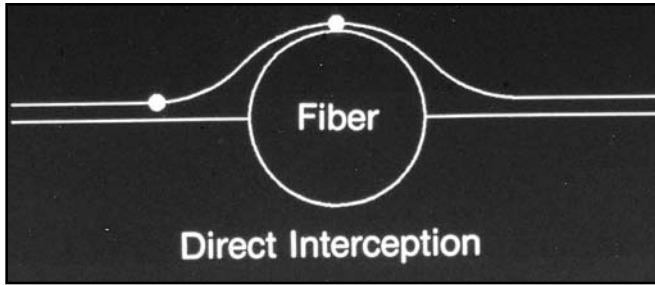


Figure 2
DIRECT INTERCEPTION MECHANISM

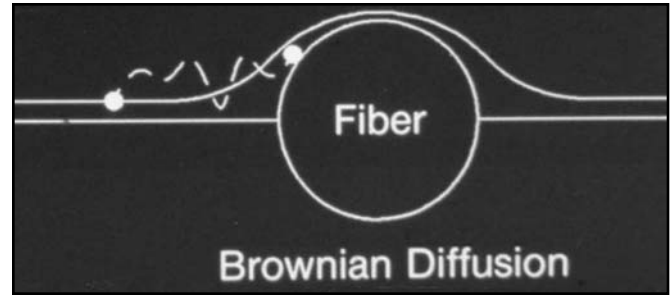


Figure 4
BROWNIAN DIFFUSION

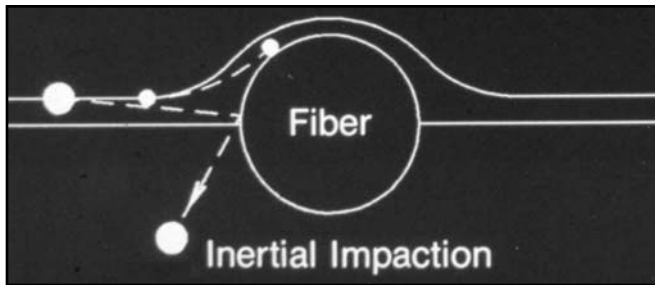


Figure 3
INERTIAL IMPACTION MECHANISM

Diffusion, and Electrostatic Capture.

Interception occurs when a particle following a gas streamline comes within one particle radius of a filter fiber. As shown in *Figure 2*, the particle touches the fiber and is captured, thus being removed from the gas flow. Streamlines farther than one particle radius from the filter fiber will not contribute to the interception mechanism. The size of the particle determines how close it moves to the fiber.

Inertial Impaction generally occurs with larger particles that are unable to quickly adjust to streamline direction near a filter fiber. Due to its inertia, the particle will continue along its original path and hit the filter fiber and fall down in the media, as shown in *Figure 3*.

The very fine particles in the air stream collide with the gas molecules and create a random path through the media. The smaller the particle and the lower the gas velocity, the longer the particle will zigzag around. The resulting random motion, called Brownian Diffusion, will increase the probability of the particle impacting the fiber surface and adhering to it. This is shown in *Figure 4*.

Electrostatic Capture requires imparting an electrostatic charge to a synthetic fiber during its formation. The filter media so formed have charges on the fibers and hence are able to attract dust particles. By this method of particulate capture, the small particles initially adhere to the fibers and form the nucleus for progressive attachment of more dust particles, which finally results in the formation of conglomerate clumps or protuberances on the fibers [8]. This phenomenon is called dendrite formation. Continual attachment of the contaminants onto each other results in the development of dendrite colonies which load the filter, reduce the spacing between adjacent fibers, reduce the size of the voids in the fil-

ter and hence enhance the mechanical filtration capability of the filter medium.

Fiberglass filter media with their finer fibers utilize the first three filtering mechanisms and are enhanced by the number of fibers present per unit volume of the media. With the decrease in fiber diameter, the number of fibers per unit area increases. Also, the path that the contaminate particle must take through the filter media becomes much more intricate, thus dramatically increasing the chances that the particle will be captured on the fiber surface by one of the physical filtering mechanisms.

Because of larger diameter fibers, large voids are present in synthetic media. This characteristic reduces the possibility of a particle colliding with a fiber. Application of electrostatic charge to the fibers in synthetic media results in a greater attraction of dust particles on to the fiber. Atomic forces subsequently hold the particles onto the media [2].

Characteristics of Fiberglass and Synthetic Filter Media

Fibrous filter media made from glass fibers or synthetic fibers are widely used, primarily in disposable filters, due to the favorable characteristics of low cost, depth filtration, good dust holding capacity and variety of constructions. These products are used in industrial as well as consumer applications such as engine air filters, furnace filters, building ventilation filters, cleanroom air filters, and gas cleaning filters in nuclear installations [9].

Porosity: Fibrous filter media can be manufactured with uniform porosity or with a gradient density through the filter depth. A variation in spacing between adjacent fibers results in a non-uniform undefined interconnected porous structure.

Particle Capture through the Filter Depth: In both filter types, particles are collected on the surface, as well as throughout the interior of the filter media, this characteristic results in their being classified as depth filters.

Pressure Drop: Fiberglass filter media are made from flame attenuated glass fibers of about 1.0 - 1.3 mm in diameter. Typical synthetic media consists of one or more layers of fibers depending on the requirements. One of the layers provides particle-capturing efficiency of the product. This layer consists of 3.0 - 4.0 μm diameter fibers that capture particles utilizing electrostatic enhancement.

The fibers in the synthetic filter media, being coarser than

those in the glass media, are not able to pack as closely as the glass media. The fibers are not able to come close together and so, leave large void spaces between them. Hence, synthetic filter media show lower pressure drop than fiberglass media [2]).

Loading: Synthetic media with coarser fibers have a more open structure as compared to the glass media. This characteristic yields a greater void volume per unit area and a higher fluid permeability and dust holding capacity.

Associated Cost: One objective of a filter manufacturer is to provide the most economical solution to a filtration problem. A number of factors influence the total cost associated with using a filter unit. The filter media needs to be designed so that it will achieve its performance requirements satisfactorily while keeping the costs incurred to a minimum. Life cycle analysis and life cycle cost studies are extremely useful tools in assessing the costs of a filter function. Life cycle analysis considers the environmental effect with reference to ecological effects, health effects and consumption of resources. The LCA protocol provides a cost analysis of the effect of a filter on the environment. Cost of raw material, refining, manufacturing and transportation corresponds to approximately 20-30% of the environmental load, while filter operation accounts for up to 80%. Energy returned by burning the filter can reduce the environmental load by 0.5 - 1%. A decrease of 10 Pa in the pressure loss reduces the load by 5%. Life cycle cost takes into account the economic aspects of filter usage. The costs of investment, energy, maintenance and dumping the final waste product throughout the lifetime of the plant are evaluated in LCC. One study shows that the costs of the filter, investment, and maintenance correspond to 20% of the total cost. The energy cost for operation of the filter plant accounts for 80%. Used filter disposal costs account for 0.5%.

Accordingly, it can be concluded that operation and low-pressure loss are absolutely decisive in determining the cost of a filtration system. LCA and LCC are excellent tools that help in designing filters to minimize the cost of filtration [4].

Filter Media Properties

Physical parameters such as fiber diameter, fiber geometry, fiber specific surface, fiber density, filter thickness, packing density, porosity and pore size distribution are major factors, which influence filtration efficiency.

Fiber Diameter: Scanning electron microscopy studies show that fibers used in fiberglass filter media are finer

(about 1.0 μm in diameter) as compared to those used in synthetic media (about 3-4 μm). As fiber diameter decreases, for the same mass of filter media, the number of fibers per unit area increases and hence the surface area increases. Also, the path that a particle must travel through the media becomes more intricate. Accordingly, the capability of particle capture by physical mechanisms of Brownian Diffusion, Inertial Impaction and Interception improves greatly.

Relationship Between Fiber Diameter And Surface Area

The effect of fiber diameter for typical glass and synthetic fiber media is illustrated by an analysis of the data outlined in Table 2 comparing the parameters of competitive glass and meltblown filter media.

The diameter-denier relationship for circular cross-sections is given by,

$$Diameter (\mu m) = 11.87 \sqrt{\frac{Denier}{Density}} \quad (1)$$

From which,

$$Denier = \frac{(Diameter)^2 * (Density)}{(11.87)^2} \quad (2)$$

For the glass media,

$$Denier_G = \frac{(0.9)^2 * (2.5)}{(11.87)^2} = 0.01437 \quad (3)$$

Similarly, for the synthetic media,

$$Denier_s = \frac{(5.4)^2 * (0.92)}{(11.87)^2} = 0.1904 \quad (4)$$

According to the definition of denier and assuming that the fiber media is continuous and laid side by side,

For glass media with a denier of 0.01437, 0.01437 is the weight of a 9000 meter length of fiber.

Therefore, the glass media basis weight of 49.5156 grams is equivalent to a total length of fiber of

$$\frac{(49.5156) * (9000)}{(0.01437)} = 31,011,858.04$$

meters in 1 square meter of glass media.

For synthetic media with a denier of 0.1904,

0.1904 is the weight of 9000 meter length of fiber.

Therefore, the synthetic media basis weight of 77.5027 grams is equivalent to a total length of fiber of

$$\frac{(77.5027) * (9000)}{(0.1904)} = 3,663,467.962$$

Table 2
PARAMETERS OF COMPETITIVE GLASS AND SYNTHETIC FILTER MEDIA

	Diameter (μm)	Specific Gravity	Basis Weight (g/m ²)
Glass	0.9	2.5	49.5156
Synthetic	5.4	0.92	77.5027

meters in 1 square meter of synthetic media.

By definition, the surface area of a cylindrical rod is equal to its circumference times its length, or

$$Surface\ Area = \pi * (Diameter)_{meters} * (Total\ Length)_{meters} \quad (5)$$

Accordingly, for glass media,

$$Surface\ Area_G = [(3.14) * (0.9\mu) * (10^{-6}) * (31,011,858.04)] = 87.6395 \quad (6)$$

Thus, 1 square meter of glass media, with a weight of 49.5156 grams has a surface area of 87.6395 square meters.

And, for synthetic media,

$$Surface\ Area_S = [(3.14) * (5.4\mu) * (10^{-6}) * (3,663,467.962)] = 62.1178\ m^2 \quad (7)$$

Thus, 1 square meter of synthetic media, with a weight of 77.5027 grams has a surface area of 62.1178 square meters.

Defining specific surface area as the surface area per weight of the media,

For the glass media,

$$Specific\ Surface\ Area_G = \frac{Surface\ Area\ of\ 1\ square\ meter\ of\ Media}{Weight\ of\ 1\ square\ meter\ of\ Media} = \frac{(87.6395)}{(49.5156)} \quad (8)$$

For the synthetic media,

$$Specific\ Surface\ Area_S = \frac{Surface\ Area\ of\ 1\ square\ meter\ of\ Media}{Weight\ of\ 1\ square\ meter\ of\ Media} = \frac{(62.1178)}{(77.5027)} \quad (9)$$

The above analysis is summarized in *Table 3*.

The ratio of specific surface areas of glass and synthetic media is

$$\frac{1.7699}{0.8015} = 2.208 \quad (10)$$

This shows that surface area per gram of glass media is more than two times that of synthetic media.

Glass fiber has a higher specific gravity than synthetic fiber, but its smaller diameter more than compensates for this and results in a greater surface area. High surface area enhances the filtration capability of the media.

Initially, for the synthetic media, electrostatic charges

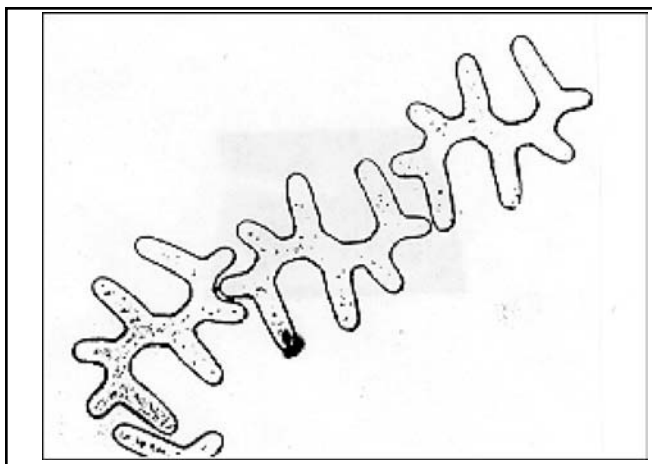


Figure 5

CROSS-SECTIONAL VIEW OF 4DGTM FIBERS
(COURTESY OF FIBER INNOVATION TECHNOLOGY)

enhance particle capture and compensate for smaller surface area. But within a few weeks of service, as electrostatic charges are neutralized, the smaller surface area of synthetic media yields lesser efficient performance, as compared to the glass media.

Fiber Geometry: Fiber geometry as well as surface area can significantly affect the filtration capability of the media. These characteristics have not been fully utilized by the filtration industry. *Figure 5* illustrates a fiber, designated 4DGTM, with both an unusual geometry and high surface area. This fiber was introduced by the Eastman Chemical Company a few years ago.

Earlier studies indicate that existing crenulated fibers had limitations with respect to surface geometry and had insufficient channels for trapping and holding particulates. To respond to this challenge, the Eastman Chemical Company developed a deep-grooved polyester fiber with a very novel eight-legged cross-sectional shape. Expansion of the fiber perimeter results into high surface area of the fiber. The grooves in 4DGTM fibers are large enough to hold many types of substances, whether they accumulate in use or are intentionally placed there for release while being used.

The photomicrograph in *Figure 6* shows that in addition to particulate matter being deposited in the interstices between the fibers, it also collects between the grooves. The grooves provide areas where eddy currents will preferentially deposit particles without blocking the pore of the fabric. This results in longer life and reduced weight of the filter [10]. *Figure 7* shows carbon particles placed in the grooves for odor absorbency.

Surface Area: Specific surface area of a fiber has a direct impact on the filtration performance of a filter. The cross-section illustrations in *Figure 8* show the 4DG geometry compared to that of

Table 3
CALCULATED SURFACE AREA VALUES FOR GLASS AND SYNTHETIC MEDIA

	Denier	Total Filament Length in 1m ² of media (m)	Surface Area) m ²	Specific Surface (m ² /g)
Glass	0.01437	31,011,858.04	87.6395	1.7699
Synthetic	0.1904	3,663,467.962	62.1178	0.8015

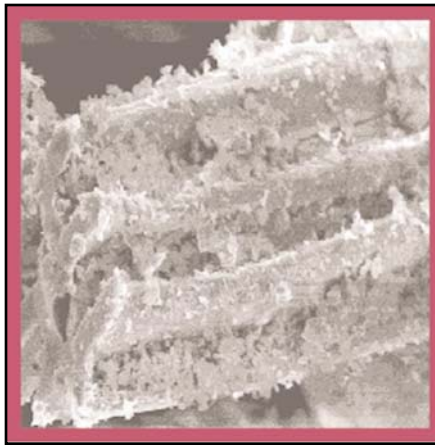


Figure 6
DUST LOADED IN GROOVES
OF 4DG FIBER (10)



Figure 7
4DG FIBERS DEPOSITED WITH
CARBON (10)

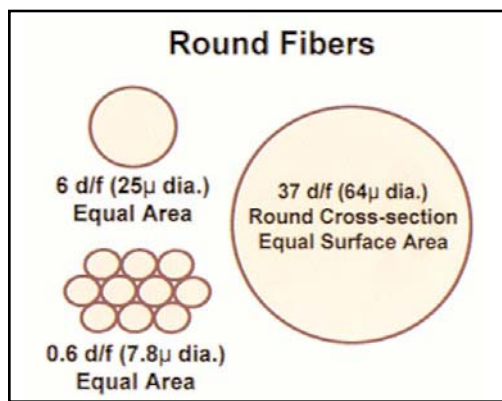
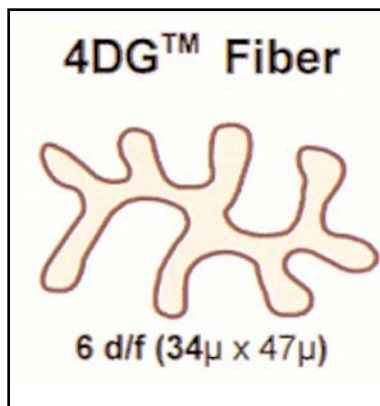


Figure 8
COMPARISON OF SURFACE AREAS OF 4DG™ AND
ROUND FIBERS OF THE SAME DPF (10)

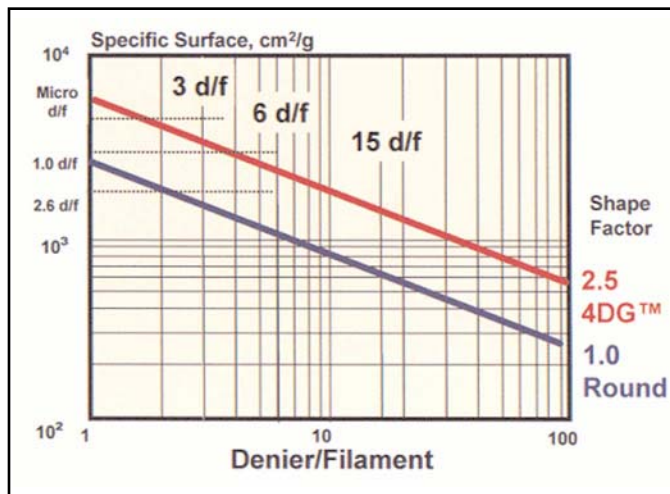


Figure 9
RELATIONSHIP BETWEEN DENIER AND
SPECIFIC SURFACE AREA FOR ROUND AND
SHAPED FIBER CROSS-SECTIONS

round fibers. Both configurations, by definition, have the same cross-sectional area when the polymer type and denier per filament (dpf) are the same. But, the measured surface area of the 4DG fiber is 2.3-2.8 times that of a round cross-sectioned polyester fiber of the same denier. The size of a single round fiber needed to match the perimeter or surface area of the 4DG fiber is also shown. .

As shown in *Figure 9.*, when specific surface areas are compared, 6 d/f 4DG is found to be equivalent to round polyesters of approximately 0.8 d/f [10]. With greater specific surface area of the fibers, the possibility of particles of interest colliding onto the media fibers increases, thereby improving the filtration capability.

Porosity: Filtration performance also depends on the porosity of the medium. If the medium is highly porous, it will allow particles to pass through it easily and not perform the filtration function satisfactorily. In glass media the fine fibers can pack closely, hence the porosity is less. In synthetic media the coarser fibers cannot pack as closely together. The pores in the glass media being smaller can capture the particles better by entrapment. Pore size distribution is an important factor that determines which particles will be allowed to pass through and which particles will be

retained.

Design of Filter Media

Nonwoven filter media are designed to accommodate the environment to be endured and to be functional either from a structural support or effective surface area availability standpoint. Parameters such as media pore size distribution and the relationship between fiber surface area per unit weight or per unit volume can also be used effectively in designing filter media structures.

The design goal for filter media is to maximize the space available for filtration in order to remove large amounts of undesirable contaminants, while not allowing them to pass through the filter, and to keep the operating pressure differential at rated air flow as low as possible to achieve a long service life. The filter design engineer must have an in depth knowledge of the application, type of fluid to be filtered /separated, acceptable power usage allowed to generate flow, and an understanding of the type and nature of contaminant to be removed in order to maximize filter performance at minimum cost [3].

Accordingly, the three design criteria that need to be con-

sidered in a filter product design are: Filtration Efficiency, Dust Holding Capacity, Filter Resistance to Air Flow and Environmental Conditions.

Filtration Efficiency is defined as the efficiency of the filter product in capturing and removing the contaminants of interest. Different applications require different levels of filtration efficiency. In some processes, the specified level of filtration efficiency is vital for normal operation. An understanding of the filtration mechanisms working in the applications and their interaction with the filter media structure selected can lead to creative and marketable solutions to filtration problems.

Dust Holding Capacity characterizes the life of the filter and hence, to a degree, the cost associated with operation. Fiberglass filter media are typically twice as thick as synthetic media. The additional volume gives extra dust holding capacity. Also, the higher stiffness of glass gives greater structural stability to the glass media. Glass filter media retains its three-dimensional structure even as the pressure drop increases during the filter's use. In contrast, the less stiff synthetic fibers are not able to resist the higher-pressure drop; consequently the filter media collapses giving a more two-dimensional structure. These two factors give glass media a greater dust holding capacity and higher service life.

The Filter Resistance to Air Flow is a measure of the energy requirement and cost associated with using the product. Synthetic filter media is more open and the, pressure differential across it is lower when compared to glass media. Initially, synthetic media requires less energy to maintain a particular airflow. Glass media renders greater resistance to the flow of air, and hence the fan consumes greater energy in maintaining equivalent airflow rates [5].

Environmental condition is another important factor to be considered in the design of filter media. The filter must be designed to survive the temperature and chemical conditions it will see in actual use. In most HVAC applications, the filter is not exposed to temperatures much above that of ambient air. But in some installations, when the furnace cycles off, very high temperature air travels out of the furnace's hot heat exchanger by convection and can reach the filter. The filter can melt if this temperature exceeds the melting point of the fibers in the media.

Laboratory and In Situ Testing Of Fiberglass and Synthetic Air Filters

Over the past few decades, a number of laboratory test methods have been developed to measure and characterize air filters using synthetic dust. Initially, different countries tended to develop their own test methods using different measurement principles and synthetic test dusts. Today the tendency is more towards international or worldwide standards.

In the U.S., the American Society for Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) adopted test standards to characterize filter media. ASHRAE test standards have obtained approval from the American National Standards Institute (ANSI) as an American National Standard. Eurovent, the European Association for

Manufacturers of air-handling equipment, is leading the development of new and modern test methods that can meet today's requirements for ventilating air filter installations in indoor environments and other areas. The European Committee for Normalization (CEN) is working to establish common standards in Europe (11).

The ANSI/ASHRAE 52.1-1992 test standard, "Gravimetric and Dust-Spot Procedures for Testing Air-Cleaning Devices used in General Ventilation for Removing Particulate Matter," is a useful method for measuring the dust spot efficiency of filters, the relative arrestance values of low efficiency filters and dirt holding capacities (DHC) of all types of filters. This standard defines Dust Spot Efficiency, Arrestance and Dust Holding Capacity.

The Dust Spot Efficiency of a filter is its capacity to remove smaller diameter particles from the atmosphere. This is measured by comparing the opacity of glass media target paper, upstream and downstream, of the filter under evaluation.

Arrestance is a parameter that measures the ability of a filter to remove synthetic dust from the atmosphere. Arrestance is indicative of the filter's capability of removing coarse particles from the atmosphere. It is measured by feeding a known amount of ASHRAE Test Dust upstream of the target filter and comparing that with the weight gained by a HEPA filter placed downstream of the filter being characterized.

Dust Holding Capacity is a measure of the amount of ASHRAE Test Dust that a filter will capture until a specified pressure drop is reached. The basic test sequence is as follows:

- 1) The pressure drop of a clean filter is measured at 50%, 75%, 100% and 125% of rated airflow.
- 2) Initial atmospheric dust spot efficiency is tested on a clean filter
- 3) The filter is loaded with ASHRAE test dust at various intervals until a final pressure drop is reached or other conditions are met. The dust spot efficiency and arrestance are measured for each level of loading.
- 4) At the end of the test, the average efficiency, arrestance and dust holding capacity are calculated [5].

ASHRAE 52.1 test standard measures dust spot efficiency using atmospheric air, an uncontrolled test aerosol that does not allow accurate repeatable comparisons among different laboratories and different manufacturers. The test also requires prolonged sequences that are influenced by outside weather conditions. This test does not provide information on the filter's capability to remove particles of a particular size range, information that is critical in some applications. This standard measures the average efficiency of an air filter over its service life. In actual working, a filter's performance is lower initially and then the efficiency improves over its service life. This test standard overestimates the performance of a filter when it is new.

ASHRAE 52.2, "Method Of Testing General Ventilation Air Cleaning Devices For Removal Efficiency by Particle Size", is a significant step forward in filter testing and Indoor Air Quality (IAQ) control. It is designed not to replace the

earlier standard but to supplement it. This standard provides a repeatable method for testing and measuring air filter performance under controlled laboratory conditions in terms of its fractional efficiency [6]. This standard introduces the concept of fractional efficiency. Fractional efficiency is defined as the characteristic of a filter to remove known particle size fractions from the atmosphere. Knowledge of fractional efficiency is vital in critical operations, such as the manufacture of microelectronic devices, in order to facilitate the proper selection of filter media. Also, with increasing IAQ requirements, the ability of a filter to remove the respirable particle size portions of atmospheric contaminants is becoming increasingly important.

The ASHRAE 52.2 test method uses laboratory-generated potassium chloride dispersed in air as the challenge aerosol, which yields more consistent results than the atmospheric test dust. After an initial efficiency measurement, the target filter is loaded with the test dust in five different cycles. Particle counters both upstream and downstream of the target filter count particles in 12 different size ranges from 0.3 μm -10 μm for each level of loading to give the fractional efficiencies for different particle size ranges for different loading levels. Pressure drop across the filter is also measured each time. From the above information, fractional efficiency curves for each particle size range are obtained for incremental loading. From these sets of incremental loading fractional efficiency curves, a composite curve is developed that gives the filter's minimum efficiency at each particle size range.

The minimum efficiency composite values are averaged into three size ranges to group filters into three simple efficiency classes: high, medium and low efficiency filters designated as E1, E2 and E3 respectively. To target particles in the 0.3-1.0 μm range, an E1 efficiency filter would be required. To capture particles 1.0-3.0 μm in size, E2 efficiency filter will be needed. An E3 efficiency filter will trap particles 3.0-10 microns in size (5).

The main feature of the new ASHRAE 52.2 performance standard is the Minimum Efficiency Reporting Value (MERV) system. The minimum efficiency composite values averaged into three size ranges are used to determine the MERV, which ranges from MERV 1 (typically a low-efficiency, throw-away filter) to MERV 16 (an over 95% efficiency filter under ASHRAE standard) (6). The MERV system makes it easy to compare filters at a glance and provides a better yardstick in decisions involving choice of filters for different applications.

The ASHRAE 52.2 test procedures and European test procedures conducted in the laboratory have some limitations, which need to be overcome for them to reflect the true performance of filters in real life. The foremost difference is in the test dust used for the testing. The ASHRAE test dust used in the ASHRAE 52.1 test standard is of an entirely different nature from atmospheric dust, the dust that a filter would nor-

Table 4
COMPOSITION AND PARTICLE SIZE DISTRIBUTION
OF VARIOUS DUST PARTICLE TYPES.

Type of Dust	Particle Size Ranges (μm)	Percentage by Weight
Atmospheric Dust	10.0-30.0	28%
	5.0-10.0	52%
	3.0-5.0	11%
	1.0-3.0	6%
	0.0-1.0	3%
Standard Air Cleaner Test Dust	0-5	39%
	5-10	18%
	10-20	16%
	20-40	18%
	40-80	9%
ASHRAE Test Dust	SAE	72%
	Powdered Carbon	23%
	No. 7 Cotton Linters	5%

mally be exposed to in real-life situations. The ASHRAE dust is made up of much larger particles than those present in the atmosphere; hence they load the filters rapidly, enhancing the filter's mechanical filtration capability. This loading is not seen in actual performance in the atmosphere and hence the electrostatic synthetic filter performs poorly. In ASHRAE 52.2 test standard, potassium chloride particles are used which are different in nature from atmospheric particles. A comparison of challenge dust particle distributions is given in *Table 4*.

For the test standards to closely reflect actual performance of a filter, a challenge test dust similar to the particles in atmosphere in terms of particle size distribution, shape and density is needed. Also, the tests need to take account of the fact that atmospheric dust changes with time (season or even time of the day) and location (urban or rural). Thus, the challenge dust must be representative of all conditions.

Another reason for the disagreement between laboratory and real-life results was discovered from a fractional efficiency test performed on a synthetic charged media in the laboratory. The media were loaded independently with a matrix of synthetic dusts of different size ranges with the objective of determining the dependence of contaminant particle sizes on filtration efficiency and to identify the mechanism of dendrite formation. Test results showed that particles 1 to 3 μm in diameter were the major particle size range, which built significant mechanical efficiency due to dendrite formation. SEM analysis of the filter media showed that the one loaded with 1 to 3 μm dust particles had dendrite formation very similar to one seen in real life operational filters [5]. A photomicrograph of ASHRAE test dust used in the laboratory tests is

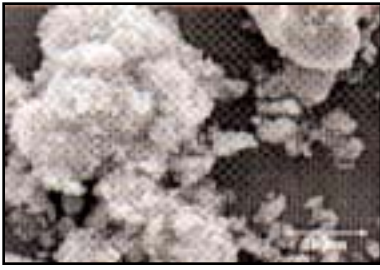


Figure 10

ASHRAE TEST DUST (2)

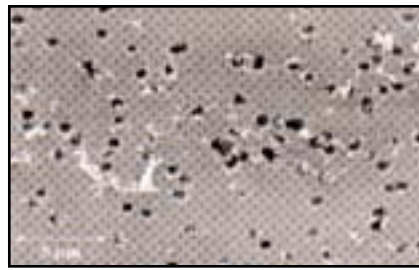


Figure 11

ATMOSPHERIC TEST DUST (2)

shown in *Figure 10*. [2]. As can be seen, this dust has a very large particle size that clogs the media rapidly. In the synthetic media, loss in efficiency due to neutralization of charge is compensated by the large particles that block the voids in the media, thereby giving a misleading picture of performance.

As shown in *Figure 11*, atmospheric dust has a greater number of smaller size particles than the ASHRAE test dust. Since the finer particles in the 1 to 3 μm range are the main contributors to dendrite formation, a period of time is required for mechanical filtration efficiency to be improved by loading. As aerosols neutralize electrostatic charges on the media within a few weeks of service, there is a loss in efficiency in synthetic charged filters in the early part of their service life.

Another factor that must be considered is that test conditions in the laboratory are controlled and are conducted for a reasonably short period of time. They are not subjected to the environmental and temporal conditions that a filter would be subjected to in actual testing conditions.

SINTEF Refrigerating and Air Conditioning, The Research Council of Norway and five filter manufacturers collaborated on a project called "Long Term Tests of Air Filters in Real Environment" [7]. In this work, the tests were done on three types of glass media and two types of synthetic charged media. Two filters were selected from each filter type. So in all, ten filters were selected. All the filters were of EU 7 type. The filters were mounted in a specially built test rig that was mounted on the roof of the laboratory building. The filters were equipped with individual volume regulators to ensure that identical and constant volumes of air flowed through all filters for the entire test period of one year. Pressure drop, filter efficiency, and the amount of dust accumulated were measured for the entire period of the test. Fractional efficiency testing was done in a separate test rig using both atmospheric dust and dioctyl sebacate (DOS) aerosols generated by a Laskin Nozzle aerosol generator.

The long-term test results show that glass fiber filters maintained a more or less constant degree of fractional efficiency throughout the test period. Efficiency of electrostatically charged synthetic media fell significantly right from the start and did not improve much with service. From this work it can be stated that lifetime and in situ testing of filters clearly point out the fact that the challenge dust and testing conditions must correlate more closely to the environment to which a filter would be exposed in actual use.

Health Concerns

In selecting a filter for a particular end-use, one must look not only at performance aspects but also health effects of the product. One concern over the use of glass fibers in filter media is their possible carcinogenic nature. Asbestos-related lung diseases revealed the possible dangers of inhaling foreign matter into the deep lung, resulting in apprehension about using synthetic vitreous fibers, including glass fibers in filter media.

Kern and Harding [12] report that a great deal of scientific research has been done to investigate the injurious effect of glass fibers. A study in the 1940's on 27,000 fiberglass workers exposed to fiberglass for more than 40 years showed no cause and effect relationship between exposure and disease. Since the fiber is inhaled into the lungs, inhalation studies were considered to be more appropriate. Studies on animals exposed to building insulation showed no symptoms of lung-related disease.

The mechanism by which fibers in the lungs might cause disease is complex, but nevertheless, three key factors called the three D's have been identified that strongly influence the process. They are dimension, dose and durability. The fiber needs to be of a minimum diameter to be respirable. A commonly accepted figure is 3 μm . Glass fibers with diameter greater than 3 μm are considered to be harmless. Research has indicated that the longer and finer the fibers, the more difficult it is to remove them out of the lungs by the natural body mechanisms. So, fibers with a higher length-to-diameter ratio are more likely to cause lung disease. Also, the probability of fibers being inhaled into the lungs depends on the concentration of the air being breathed. The greater the number of respirable fibers in the air and the longer a person is exposed to such air, the greater the risk factor. The European Union and the German Government have established standard tests to classify fibers as either carcinogenic or irritants. In North America, control steps and research work are underway to minimize the health risks of synthetic vitreous fibers (SVF's) and fiberglass. Since there could always be respirable fibers in the media, the effort is to have fibers that are less durable in the lung environment. A new biosoluble glass fiber, AF 902, has been introduced. This material has passed the European Union Biopersistence test and German Intratracheal test and has been reported to be performing well in filtration applications.

With regard to health concerns, the phenomenon of fiber shedding from filter media has been studied. A scientifically based method has been developed to give quantitative results on fiber shedding from organic fiber and fiberglass filter media [4]. Early methods had problems with the detection of the shed fibers and with the introduction of variability and contamination in the sample by uncontrolled ambient air. This method overcomes these problems by using very clean air for the test by passing the test air through two 99.9% efficient High Efficiency Particulate Air (HEPA) filters in series, before entering the test chamber. In order to provide for worst

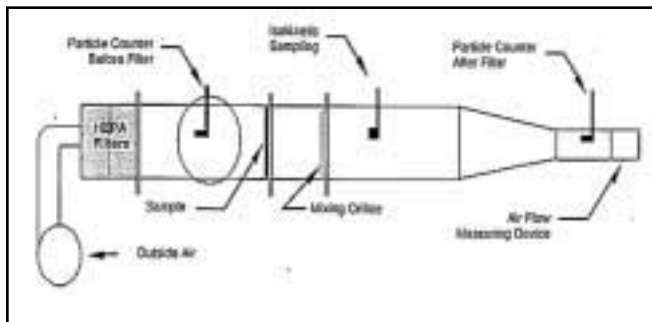


Figure 12

CONFIGURATION OF TEST EQUIPMENT FOR SHEDDING CHARACTERISTICS OF FILTER MEDIA (13)

case release of shed particles, the test is performed under high air flow rates across the test filter, about 35 cubic feet per minute, which is about 50% more than that encountered in commercial systems. A square foot area of the test filter is chosen as sufficient for minimizing the variation within the air filter medium. Scanning Electron Microscopy (SEM) Analysis and Particle Count Method are used to evaluate the system.

As shown in *Figure 12*, air enters the duct and passes through the two HEPA filters, then passes through a sufficient chamber length before it passes through the test filter in order to ensure laminar flow. The blower maintains a constant flow rate of 35 cubic feet per minute throughout the six-hour sampling period. The air then passes through an eight inch mixing orifice to ensure homogenous air for samples collected on a 0.4 μm pore size nucleopore filter for microscopic sampling and subsequent SEM analysis. As the concentration of the fibers in the nucleopore filter is low, the test sample must be concentrated in order to carry out an appropriate analysis. Multi-channel Climet laser based airborne particle counters are used to determine concentrations both in front and behind the filter. *Table 5*. shows the number of particles in unfiltered test air obtained by particle counts.

The HEPA filters removed 99.9% of the particles in the ambient air to provide very clean air for the test as shown in *Table 6*.

SEM Analysis of the Manville fiberglass media (AFS-3B2) and the synthetic (Polycarbonate/polyester) Viledon media (MF95), on the basis of viewing of 200 separate fields, yielded the results tabulated in *Table 7*.

SEM analysis showed that both products shed an extremely small number of fibers. Some of them were respirable fibers with a diameter less than 3 μm and length-to-diameter ratio greater than 3:1. *Tables 8. and 9* summarize data on the average number of fibers shed per cubic foot and cubic centimeter of monitored air for the six-hour test period.

The analyses show that both types of filter shed fibers, with some of them being respirable. Also the difference in fiber shedding between the two filter media is insignificant. The test results also show that fibers shed from the media decrease with time. As compared to the contaminate particles

Table 5
PARTICLE COUNT ANALYSIS FOR AMBIENT AIR (13)

Particle Size	Particles/ft ³	Particles/cm ³
>5	3384	0.12
>3	6961	0.25
>1	19126	0.68
>0.5	152572	5.4
>0.3	437612	15.5
>0.19	1411000	49.8

Table 6
PARTICLE COUNT ANALYSIS FOR HEPA FILTERED AIR (13)

Particle Size	Particles/ft ³	Particles/cm ³
>5	0.03	0.000001
>3	0.1	0.000004
>1	1	0.0004
>0.5	4	0.00015
>0.3	7	0.00025
0.19	17	0.00060

Table 7
SCANNING ELECTRON MICROSCOPY ANALYSIS FOR FIBER CHARACTERIZATION (13)

Product	Manville AFS-3B2	Viledon MF95
Fiber Diameter		
Average (μm)	1.0	2.0
Fiber Diameter Range (μm)	0.2-8.0	0.3-24
Fiber Length		
Average (μm)	25	22
Fiber Length Range (μm)	2-110*	3-65*

* Some fiber lengths were greater than the field of view.

present in ambient air, the number of fibers shed by the filter media is negligible.

Conclusions

Test standards form the basis of selection of filters for different end-use applications. It is important to have standards that will test products under controlled conditions and report on their performance so that both users and specifiers can compare products, predict their performance in operating conditions with reasonable certainty, and determine appropriate air cleaner efficiencies for specific situations. The studies and research work done on filter performance and testing conclude that present standards need to be modified for laboratory-generated test results on filters to predict more closely their real-life, in-use performance. Several factors need to be taken into account, such as variation in the nature of dust in different environments in terms of composition, particle size

Table 8
FIBER SHEDDING EVALUATION BY
SEM ANALYSIS (13)

	Manville AFS-3B2	Viledon MF95
Fibers/ft ³	20	9
Fibers/cm ³	0.0007	0.0003

Table 9
AVERAGE PARTICLE COUNT FOR
AIR FILTRATION MEDIA (13).

Particle size	Manville	Viledon
	AFS-3B2	MF95
	Particles/ft³	Particles/cm³
>5	0.000021	0.0000013
>3	0.000077	0.000033
>1	0.00033	0.00019

and particle density and the effect of differences in testing conditions on performance results of the filter media. Filter media manufacturers should evaluate the use of fibers with high specific surface area and deep-grooved channels. These irregular cross-section fibers have high shape factors and very high capillary surface areas, which provide greater particle capture and accumulation and hence improved filtration properties.

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Glossary of Terms

Absolute Rating (14): A term used to describe or define the degree of filtration. Various methods are used to determine absolute ratings, which are not necessarily interchangeable. Generally absolute means 100% removal of solids above a specified micron size

Absorption (15): The taking up of bulk material by another matter. Absorbent material extracts one or more substances for which it has an affinity, and is altered physically or chemically throughout the process. During absorbency one substance penetrates into another.

Activated Carbon (14): Any form of carbon characterized by high absorptive capacity for gases, vapors or colloidal solids.

The carbon or charcoal is produced by destructive distillation of wood, peat, lignite, nut shells, bones, vegetable or other carbonaceous matter, but must be activated by high temperature steam or carbon dioxide, which creates a porous particulate structure.

Adsorption (14): A natural phenomenon of a gas, liquid, vapor or fine particles being attracted and held on to the molecular surface structure of a material. Not normally a reversible phenomena as absorption is.

Aerosol (15): A quasi-stable dispersion of small solid or liquid particles in air.

American Society for Testing and Materials – ASTM (14): An organization in the United States setting standards for quantitatively testing and measuring.

ANSI (14): American National Standards Institute

Angstrom (14): A unit of length abbreviated as A. Equals one hundred millionth (10⁻⁸) of a centimeter or 0.0001 micron.

Arizona (SAE, ISO) test dust (15): Standardized air cleaner test dusts classified from natural Arizona dust and generally referred to as SAE or ISO test dusts (old A.C. fine and A.C. coarse test dusts)

Arrestance (9): The capacity of the filter to separate synthetic dust. The average value of arrestance of the filter is one of the factors used for filter classification.

Brownian Movement (14): A natural phenomenon caused by small particles of similar mass to fluid molecules that are being bombarded by these molecules. In a liquid stream this causes a random spiraling motion thus enhancing the filter's chances of removing the particle.

Capillary (14): A very thin tube. In filtration, the term is to describe pores in a membrane.

CEN (14): European Committee for Normalization

Chemical filters (9): Chemical filters are mainly adsorption filters based on activated carbon, which, by means of chemical reaction, adsorb and retain gases, which are very difficult to separate.

Coarse filters (9): Filters made out of glass or synthetic plastic fibers like polyester, acrylic and polyamide and used for separating mainly particles 5mm or larger in size with very less influence of outdoor air.

Depth Filtration (14): Filtration of a fluid by passing it through a deep filter material, providing a tortuous path with many points for impingement of particles to occur. Traditionally used in 'Packed Tower' type filters.

Diatomaceous Earth (14): Pre-historic sedimentary deposits of fossilized diatoms. Used as a pre-coat material because diatoms are non-compressible.

Differential Pressure (14): See Pressure Drop. The difference in pressure between the upstream and downstream sides of a filter.

Diffusion (14): A natural phenomena of gas passing through a liquid film in a membrane from the high pressure to the low-pressure side.

Direct Interception (14): The capture of relatively large particles near the surface of a filter material. The particles collide with the filter structure without moving from streamline, laminar flow.

DOS aerosols: Dioctyl Sebacete aerosols.

Downstream (14): Portion of the product stream, which already passed through the system, or the portion of a system located after separator/filter etc.

Dust Spot Efficiency (9): The capacity of a filter to clean normal outdoor air. Average dust spot efficiency of the filter is one of the factors used for filter classification.

Efficiency (14): Degree to which a filter will perform in removing solids and/or liquids.

Extractables (14): Substances that can and will leak out of a cartridge during filtration.

Fiber shedding (9): Particulate matter, which is flushed from the filter during the filtration process, which contaminates the filtered fluid.

Filter (14): A term generally applied to a device used to remove solid contaminate from a liquid or gas, or separate one liquid from another liquid or gas. A filter, as referred to in the industry today, is limited to a device which removes solid contaminants only. A filter may be one of a number of such types as replaceable cartridge, cyclone, edge, leaf, baffle, plate and frame, precoat, centrifuge. The term filter is sometimes erroneously used to describe the media used inside the vessel or filter case, but the correct use should be filter element, cartridge etc.

Filtration (14): Removal of particles, normally solids, from a fluid. These can be contaminants or valuable products.

Fine Filter (9): Filters that are made mainly from glass fibers with an average diameter of 0.5-5.0 μm or of coarse plastic fibers, often in combination with an electrostatic charge. Fine filters are defined according to the EN 779 as filters which, when new, have a dust spot efficiency greater than 20%.

Fractional Efficiency (15): The ability of a filter to remove particles of a specified size, expressed as a percentage. Fractional efficiency is expressed as $E_{Fi} = [(C_{1i} - C_{2i})/C_{1i}] * 100$, where C_{1i} = number of particles of the specified size i in the upstream and C_{2i} = the number of particles of the specified size i in the downstream.

HEPA (high efficiency particulate air) filter (15): High efficiency normally refers to air filters that will remove more

than 99% of airborne particles that are in the size range of 0.1–0.3 µm in diameter. These particles are known as the most penetrating contaminants. HEPA filters are sometimes described as HESPA (High efficiency submicron particulate air) filters.

HVAC (14): Heating, Ventilation and Air Conditioning.

HVACR (14): Heating, Ventilation, Air Conditioning and Refrigeration.

IAQ (4): Indoor Air Quality.

IARC (12): International Agency for Research on Cancer.

Inertial Impaction (14): The capture of medium sized particles within the structure of a filter material. The particles collide with the filter structure because they fail to negotiate the tortuous path and move out of laminar flow.

Interception (15): Dust particle deposition on a fiber or other collecting surface due to the size of the particles. This filtration mechanism is characterized by a dimensionless parameter: particle size/fiber diameter.

IPCS (12): International Program on Chemical Safety.

Isokinetic Sampling (15): Any technique for collecting airborne particulate matter in which the velocity of the air stream entering the sampling probe is equal to that of the air passing around and outside that sampling probe.

LCA (9): An LCA of a filter analyses the environmental effect with reference to ecological effects, health effects and consumption of resources.

Mechanisms of Filtration (14): The physical methods of removing particles from a fluid. They are Direct Interception, Inertial Impaction and Diffusion.

Medium (14): A term used to generally describe a filter material.

Microfiltration (14): Filtration of particles between approximately 10 and 0.1 micron.

MPPS (9): Most Penetrating Particle Size. This statistic is used as a measure of filtration efficiency in the CEN EN 1822:1998 test method. MPPS is the particle that most frequently penetrates a filter medium.

Particle Size (15): The magnitude of some physical dimension of the particle. Unless the particle is a sphere it is not possible to give its size uniquely by a unit of length. For non-spherical particles the method of measurement must be specified.

Particle Size Distribution (14): The size range and quantity of particles, which are measurable in a fluid sample. Used to determine the micron rating of filters for a specific process.

Perlite (14): A siliceous volcanic glass, containing 2-5% combined water, which allows for shattering by heat or pressure into a fine powder suitable for a pre-coat.

Pores (14): A term used to describe the openings in a filter material normally a membrane.

Pore size distribution (15): This is a measure of number of pores in various groups of sizes.

Porosity (14), (15): A term used to describe a filter material's structure - sometimes known as a void volume. The ratio of voids to the total volume of material, for example, the ratio of void volume to total cake volume. Also given as the ratio of the apparent to the true density and expressed as a percentage.

Pressure Drop (14): Loss in applied pressure across a filter system or process.

Re-entrainment (15): The process of rendering particles airborne again after they have been deposited from an air stream. For example, particles captured in a filter may be re-entrained if the velocity through the filter is increased slightly or if the filter is subjected to increased vibration.

Retention (15): The ability of a filter medium to retain particles of a given size.

Surface Filtration (14): Removal of particles on the outside surface of a filter material.

SVF: Synthetic Vitreous Fiber.

ULPA (ultra efficiency particulate) (15): HEPA filters with an efficiency greater than 99.997% are termed as ULPA (ultra efficiency particulate) or UHESPA (ultra high efficiency submicron particulate air) filters

Ultrafiltration – UF (14): A pressure driven membrane filtration system operating in crossflow mode. Used to separate macromolecules such as proteins and organic compounds of molecular weight of 300 and over. UF operates at pressures between 1 and 8 atmospheres and generally separates coarser materials than those removed by a Reverse Osmosis system.

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