

CHAPTER 28

AIR CLEANERS FOR PARTICULATE CONTAMINANTS

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THIS chapter discusses cleaning particulate contaminants from both ventilation and recirculated air for conditioning building interiors. Complete air cleaning may also require removing of airborne particles, microorganisms, and gaseous contaminants, but this chapter only covers removal of airborne particles and briefly discusses bioaerosols.

The total suspended particulate concentration in applications discussed in the chapter seldom exceeds 2 mg/m³ and is usually less than 0.2 mg/m³ of air. This contrasts with flue gas or exhaust gas from processes, where dust concentration typically ranges from 200 to 40,000 mg/m³. Chapter 45 of the 2007 *ASHRAE Handbook—HVAC Applications* covers the removal of gaseous contaminants; Chapter 25 of this volume discusses exhaust-gas control.

Most air cleaners discussed in this chapter are not used in exhaust gas streams, mainly because of the extreme dust concentration and temperature. However, the principles of air cleaning do apply to exhaust streams, and air cleaners discussed in the chapter are used extensively in supplying gases of low particulate concentration to industrial processes.

ATMOSPHERIC DUST

Atmospheric dust is a complex mixture of smokes, mists, fumes, dry granular particles, bioaerosols, and natural and synthetic fibers. When suspended in a gas, this mixture is called an **aerosol**. A sample of atmospheric dust usually contains soot and smoke, silica, clay, decayed animal and vegetable matter, organic materials in the form of lint and plant fibers, and metallic fragments. It may also contain living organisms, such as mold spores, bacteria, and plant pollens, which may cause diseases or allergic responses. (Chapter 12 of the 2005 *ASHRAE Handbook—Fundamentals* contains further information on atmospheric contaminants.) A sample of atmospheric dust gathered at any point generally contains materials common to that locality, together with other components that originated at a distance but were transported by air currents or diffusion. These components and their concentrations vary with the geography of the locality (urban or rural), season of the year, weather, direction and strength of the wind, and proximity of dust sources.

Aerosol sizes range from 0.01 μm and smaller for freshly formed combustion particles and radon progeny; to 0.1 μm for aged cooking and cigarette smokes; to 0.1 to 10 μm for airborne dust, microorganisms, and allergens; and up to 100 μm and larger for airborne soil, pollens, and allergens.

Concentrations of atmospheric aerosols generally peak at sub-micrometre sizes and decrease rapidly as the particulate size increases above 1 μm. For a given size, the concentration can vary by several orders of magnitude over time and space, particularly near an aerosol source, such as human activities, equipment, furnishings, and pets (McCrone et al. 1967). This wide range of particulate size

and concentration makes it impossible to design one cleaner for all applications.

AEROSOL CHARACTERISTICS

The characteristics of aerosols that most affect air filter performance include particle size and shape, mass, concentration, and electrical properties. The most important of these is particle size. Figure 3 in Chapter 12 of the 2005 *ASHRAE Handbook—Fundamentals* gives data on the sizes and characteristics of a wide range of airborne particles that may be encountered.

Particle size in this discussion refers to aerodynamic particle size. Therefore, larger particles with lower densities may be found in the alveolar region of the lungs. Also note that fibers are different from particles in that the fiber’s shape, diameter, and density affect where a fiber settles in the body (NIOSH 1973).

Particles less than 2.5 μm in diameter are generally referred to as **fine mode**, and those larger than 2.5 μm as **coarse mode**. Fine- and coarse-mode particles typically originate by separate mechanisms, are transformed separately, have different chemical compositions, and require different control strategies. Fine-mode particles generally originate from condensation or are directly emitted as combustion products. Many microorganisms (bacteria and fungi) either are in this size range or produce components this size. These particles are less likely to be removed by gravitational settling and are just as likely to deposit on vertical surfaces as on horizontal surfaces. Coarse-mode particles are typically produced by mechanical actions such as erosion and friction. Coarse particles are more easily removed by gravitational settling, and thus have a shorter airborne lifetime.

For industrial hygiene, particles ≤5 μm in diameter are considered **respirable particles (RSPs)** because a large percentage of them may reach the alveolar region of the lungs. Willeke and Baron (1993) describe a detailed aerosol sampling technique. They discuss the need for an impactor with a 2.5 μm cutoff for RSPs that can be deposited in the alveolar region. The cutoff for particles affecting respiratory function is considered to be 2.0 or 2.5 μm. See the discussion in the section on Sizes of Airborne Particles in Chapter 12 of the 2005 *ASHRAE Handbook—Fundamentals*. A cutoff of 5.0 μm includes 80 to 90% of the particles that can reach the functional pulmonary region of the lungs (James et al. 1991; Phalen et al. 1991).

Bioaerosols are a diverse class of particulates of biological origin. They are of particular concern in indoor air because of their association with allergies and asthma and their ability to cause disease. Chapters 9 and 12 of the 2005 *ASHRAE Handbook—Fundamentals* contains more detailed descriptions of these contaminants.

Airborne viral and bacterial aerosols are generally transmitted by droplet nuclei, which average about 3 μm in diameter. Fungal spores are generally 2 to 5 μm in diameter (Wheeler 1994). Combinations of proper ventilation and filtration can be used to control indoor bioaerosols. Morey (1994) recommends providing a ventilation rate of

The preparation of this chapter is assigned to TC 2.4, Particulate Air Contaminants and Particulate Contaminant Removal Equipment.

15 to 35 cfm per person to control human-shed bacteria. ACGIH (1989) recommends dilution with a minimum of 15 cfm per person. It also reports 50 to 70% ASHRAE atmospheric dust-spot efficiency filters can remove most microbial agents 1 to 2 μm in diameter. Wheeler (1994) states that 60% ASHRAE atmospheric dust-spot efficiency filters remove 85% or more of particles 2.5 μm in diameter, and 80 to 85% efficiency filters remove 96% of 2.5 μm particles.

AIR-CLEANING APPLICATIONS

Different fields of application require different degrees of air cleaning effectiveness. In industrial ventilation, only removing the larger dust particles from the airstream may be necessary for cleanliness of the structure, protection of mechanical equipment, and employee health. In other applications, surface discoloration must be prevented. Unfortunately, the smaller components of atmospheric dust are the worst offenders in smudging and discoloring building interiors. Electronic air cleaners or medium- to high-efficiency filters are required to remove smaller particles, especially the respirable fraction, which often must be controlled for health reasons. In cleanrooms or when radioactive or other dangerous particles are present, high- or ultrahigh-efficiency filters should be selected. For more information on cleanrooms, see Chapter 16 of the 2007 *ASHRAE Handbook—HVAC Applications*.

Major factors influencing filter design and selection include (1) degree of air cleanliness required, (2) specific particle size range or aerosols that require filtration, (3) aerosol concentration, (4) resistance to airflow through the filter and (5) design face velocity to achieve published performance.

MECHANISMS OF PARTICLE COLLECTION

In particle collection, air cleaners made of fibrous media rely on the following five main principles or mechanisms:

Straining. The coarsest kind of filtration strains particles through an opening smaller than the particle being removed. It is most often observed as the collection of large particles and lint on the filter surface. The mechanism is not adequate to explain the filtration of submicrometre aerosols through fibrous matrices, which occurs through other physical mechanisms, as follows.

Inertial Impingement. When particles are large or dense enough that they cannot follow the airstream around a fiber, they cross over streamlines, hit the fiber, and remain there if the attraction is strong enough. With flat-panel and other minimal-media-area filters having high air velocities (where the effect of inertia is most pronounced), the particle may not adhere to the fiber because drag and bounce forces are so high. In this case, a viscous coating (preferably odorless and nonmigrating) is applied to the fiber to enhance retention of the particles. This adhesive coating is critical to metal mesh impingement filter performance.

Interception. Particles follow the airstream close enough to a fiber that the particle contacts the fiber and remains there mainly because of van der Waals forces (i.e., weak intermolecular attractions between temporary dipoles). The process depends on air velocity through the media being low enough not to dislodge the particles, and is therefore the predominant capture mechanism in extended-media filters such as bag and deep-pleated rigid cartridge types.

Diffusion. The path of very small particles is not smooth but erratic and random within the airstream. This is caused by gas molecules in the air bombarding them (Brownian motion), producing an erratic path that brings the particles close enough to a media fiber to be captured by interception. As more particles are captured, a concentration gradient forms in the region of the fiber, further enhancing filtration by diffusion and interception. The effects of diffusion increase with decreasing particle size and media velocity.

Electrostatic Effects. Particle or media electrostatic charge can produce changes in dust collection affected by the electrical

properties of the airstream. Some particles may carry a natural charge. Passive electrostatic (without a power source) filter fibers may be electrostatically charged during their manufacture or (in some materials) by mainly dry air blowing through the media. Charges on the particle and media fibers can produce a strong attracting force if opposite. Efficiency is generally considered to be highest when the media is new and clean, decreasing rapidly as the filter loads.

Some progress has been made in calculating theoretical filter media efficiency from the physical constants of the media by considering the effects of the collection mechanisms (Lee and Liu 1982a, 1982b; Liu and Rubow 1986).

EVALUATING AIR CLEANERS

In addition to criteria affecting the degree of air cleanliness, factors such as cost (initial investment and maintenance), space requirements, and airflow resistance have led to the development of a wide variety of air cleaners. Accurate comparisons of different air cleaners can be made only from data obtained by standardized test methods.

The three distinguishing operating characteristics are efficiency, resistance to airflow, and dust-holding capacity. **Efficiency** measures the ability of the air cleaner to remove particles from an airstream. Minimum efficiency during the life of the filter is the most meaningful characteristic for most filters and applications. **Resistance to airflow** (or simply resistance) is the static pressure drop differential across the filter at a given face velocity. The term *static pressure differential* is interchangeable with pressure drop and resistance if the difference of height in the filtering system is negligible. **Dust-holding capacity** defines the amount of a particular type of dust that an air cleaner can hold when it operates at a specified airflow rate to some maximum resistance value (ASHRAE *Standard 52.1*).

Complete evaluation of air cleaners therefore requires data on efficiency, resistance, dust-holding capacity, and the effect of dust loading on efficiency and resistance. When applied to automatic renewable media devices (roll filters, for example), the evaluation must include the rate at which the media is supplied to maintain constant resistance when standardized test dust is fed at a specified rate.

Air filter testing is complex and no individual test adequately describes all filters. Ideally, performance testing of equipment should simulate operation under actual conditions and evaluate the characteristics important to the equipment user. Wide variations in the amount and type of particles in the air being cleaned make evaluation difficult. Another complication is the difficulty of closely relating measurable performance to the specific requirements of users. Recirculated air tends to have a larger proportion of lint than does outside air. However, performance tests should strive to simulate actual use as closely as possible. In general, five types of tests, together with certain variations, determine air cleaner performance:

Arrestance. A standardized ASHRAE synthetic dust consisting of various particle sizes and types is fed into the test air stream to the air cleaner and the weight fraction of the dust removed is determined. In the ASHRAE *Standard 52.1* test, summarized in the segment on Air Cleaner Test Methods in this chapter, this measurement is called **synthetic dust weight arrestance** to distinguish it from other efficiency values.

The indicated weight arrestance of air filters, as determined in the arrestance test, depends greatly on the particle size distribution of the test dust, which, in turn, is affected by its state of agglomeration. Therefore, this filter test requires a high degree of standardization of the test dust, the dust dispersion apparatus, and other elements of test equipment and procedures. This test is particularly suited to distinguish between the many types of low- to medium-efficiency air filters that are common in recirculating systems with

air handlers and fan-coil units having minimal external static pressure capability. It does not adequately distinguish between higher-efficiency filters.

ASHRAE Atmospheric Dust-Spot Efficiency. Unconditioned atmospheric air is passed into the air cleaner under test and the discoloration level of the cleaned air (downstream of the test filter) on filter paper targets is compared with that of the unfiltered outside air (upstream of the test filter). The dust-spot test measures the ability of a filter to reduce soiling of fabrics and building interior surfaces. Because these effects depend mostly on fine particles, this test is most useful for higher-efficiency filters. The variety and variability of atmospheric dust (Horvath 1967; McCrone et al. 1967; Whitby et al. 1958) may cause the same filter to test at different dust-spot efficiencies at different locations (or even at the same location at different times). Accuracy diminishes on lower-efficiency filters.

Fractional Efficiency or Penetration. Uniform-sized particles are fed into the air cleaner and the percentage removed by the cleaner is determined, typically by a photometer, optical particle counter, or condensation nuclei counter. In fractional efficiency tests, the use of uniform-particle-size aerosols has resulted in accurate measure of the particle size versus efficiency characteristic of filters over a wide atmospheric size spectrum. The method is time-consuming and has been used primarily in research. However, the dioctyl phthalate (DOP) or Emery 3000 test for HEPA filters is widely used for production testing at a narrow particle size range. For more information on the DOP test, see the DOP Penetration Test section.

Efficiency by Particle Size. A polydispersed challenge aerosol such as potassium chloride is metered into the test airstream to the air cleaner. Air samples taken upstream and downstream are drawn through an optical particle counter or similar measurement device to obtain removal efficiency versus particle size at a specific airflow rate.

Dust-Holding Capacity. The true dust-holding capacity of similar air cleaners is a function of environmental conditions as well as the variability of atmospheric dust (size, shape and concentration) and is therefore impossible to duplicate in a laboratory test. For testing purposes, measured amounts of standardized dust are used to artificially load the filters. This procedure shortens the dust-loading cycle from weeks or years to hours. Artificial dusts are not the same as atmospheric dusts, so dust-holding capacity as measured by these accelerated tests is different from that achieved by "life" tests using atmospheric dust. The exact life of a filter in field use is impossible to determine by laboratory testing. However, filter testing under standardized conditions does provide a rough guide to the relative effect of dust loading on the performance of similar units, and is one means used to compare them.

Laboratory filter tests are accurate and reproducible within acceptable tolerances. Differences in reported values generally derive from the variability of test aerosols, measurement devices, and dusts. Because most media are made of random air- or water-laid fibrous materials, the inherent media variations affect filter performance. Awareness of these variations prevents misunderstanding and specification of impossibly close performance tolerances. Caution must be used in interpreting published efficiency data, because two identical air cleaners tested by the same procedure may not give exactly the same results, and the result will not necessarily be exactly duplicated in a later test. Test values from different procedures generally cannot be compared. A performance test value of air cleaner efficiency is only a guide to the rate of soiling of a space or of mechanical equipment.

AIR CLEANER TEST METHODS

Air cleaner test methods have been developed by the heating and air-conditioning industry, the automotive industry, the atomic energy industry, and government and military agencies. Several tests have become standard in general ventilation applications in the

United States. In 1968, the test techniques developed by the U.S. National Bureau of Standards [now the National Institute of Standards and Technology (NIST)] and the Air Filter Institute (AFI) were unified (with minor changes) into a single test procedure, ASHRAE *Standard* 52-1968. Dill (1938), Nutting and Logsdon (1953), and Whitby et al. (1956) give details of the original codes. ASHRAE *Standard* 52-1968 was revised and is currently ASHRAE *Standard* 52.1-1992.

In general, the ASHRAE weight arrestance test parallels that of the AFI, making use of a similar test dust. The ASHRAE atmospheric dust-spot efficiency test parallels the AFI and NBS atmospheric dust-spot efficiency tests and specifies a dust-loading technique.

ASHRAE *Standard* 52.1 includes both a weight test and a dust-spot test and requires that values for both be reported. The results may be used for comparisons among air cleaners. ASHRAE *Standard* 52.2 develops **minimum efficiency reporting values (MERVs)** for air cleaner particle size efficiency. [Table 3](#) (from ASHRAE *Standard* 52.2) provides an approximate cross-reference for air cleaners tested under ASHRAE *Standards* 52.1 and 52.2. Currently there is no ASHRAE Standard for testing electronic air cleaners.

Arrestance Test

ASHRAE *Standard* 52.1 defines synthetic test dust as a compounded test dust consisting of (by weight) 72% ISO 12 103-A2 fine test dust, 23% powdered carbon, and 5% No. 7 cotton linters. A known amount of the prepared test dust is fed into the test unit at a known and controlled concentration. The amount of dust in the air leaving the filter is determined by passing the entire airflow through a high-efficiency after-filter and measuring the gain in filter weight. The **arrestance** is calculated using the weights of the dust captured on the final high efficiency filter and the total dust fed.

Atmospheric dust particles range from a small fraction of a micrometre to tens of micrometres in diameter. The artificially generated dust cloud used in the ASHRAE arrestance method is considerably coarser than typical atmospheric dust. It tests the ability of a filter to remove the largest atmospheric dust particles and gives little indication of filter performance in removing the smallest particles. However, where the mass of dust in the air is the primary concern, this is a valid test because most of the mass is contained in the larger, visible particles. Where extremely small particles (such as respirable sizes) are involved, arrestance rating does not differentiate between filters.

Atmospheric Dust-Spot Efficiency Test

One objectionable characteristic of finer airborne dust particles is their capacity to soil walls and other interior surfaces. The discoloring rate of white, filter-paper targets (microfine glass-fiber HEPA filter media) filtering samples of air is an accelerated simulation of this effect. By measuring the change in light transmitted by these targets, the filter efficiency in reducing surface soiling may be computed.

ASHRAE *Standard* 52.1 specifies two equivalent atmospheric dust-spot test procedures, each taking a different approach to correct for the nonlinear relation between the discoloration of target papers and their dust load. In the first procedure, called the **intermittent-flow method**, samples of conditioned atmospheric air are drawn upstream and downstream of the tested filter. These samples are drawn at equal flow rates through identical targets of glass-fiber filter paper. The downstream sample is drawn continuously; the upstream sample is interrupted in a timed cycle so that the average rate of discoloration of the upstream and downstream targets is approximately equal. The percentage of *off*-time approximates the filter efficiency. (See ASHRAE *Standard* 52.1 for details.)

In the alternative procedure, called the **constant-flow method**, conditioned atmospheric air samples are also drawn at equal flow

rates through equal-area glass-fiber filter paper targets upstream and downstream, but without interrupting either sample. Discoloration of the upstream target is therefore greater than for the downstream target. Sampling is halted when the upstream target light transmission has dropped by at least 10% but no more than 40%. The **opacities** (percent change in light transmission) are then calculated for the targets as defined for the intermittent flow method. These opacities are next converted into **opacity indices** to correct for nonlinearity.

The advantage of the constant-flow method is that it takes the same length of time to run regardless of the efficiency of the filter, whereas the intermittent-flow method takes longer for higher-efficiency filters. For example, a test on a 90% efficient filter using intermittent flow requires ten times as long as one using constant flow.

The standard allows dust-spot efficiencies to be taken at intervals during an artificial dust-loading procedure. This characterizes the change of dust-spot efficiency as dust builds up on the filter in service.

Dust-Holding Capacity Test

Synthetic test dust is fed to the filter in accordance with ASHRAE *Standard* 52.1 procedures. The pressure drop across the filter (its resistance) rises as dust is fed. The test normally ends when resistance reaches the maximum operating resistance set by the manufacturer. However, not all filters of the same type retain collected dust equally well. The test, therefore, requires that arrestance be measured at least four times during dust loading and that the test be terminated when two consecutive arrestance values of less than 85%, or one value equal to or less than 75% of the maximum arrestance, have been measured. The ASHRAE **dust-holding capacity** is, then, the integrated amount of dust held by the filter up to the time the dust-loading test is terminated. (See ASHRAE *Standard* 52.1 for more detail.)

A typical set of curves for an ASHRAE air filter test report on a fixed cartridge-type filter is shown in [Figure 1](#). Both synthetic dust weight arrestance and atmospheric dust-spot efficiencies are shown. The standard also specifies how self-renewable devices are to be loaded with dust to establish their performance under standard conditions. [Figure 2](#) shows the results of such a test on an automatic roll media filter.

Particle Size Removal Efficiency Test

ASHRAE *Standard* 52.2 prescribes a way to test air-cleaning devices for removal efficiency by particle size while addressing two air cleaner performance characteristics important to users: the ability of the device to remove particles from the airstream and its resistance to airflow. In this method, air cleaner testing is conducted at a specific airflow based on the upper limit of the air cleaner’s application range. Airflow must be between 470 and 2990 cfm in the 24 by 24 in. test section (face velocity between 120 and 750 fpm). The test aerosol consists of laboratory-generated potassium chloride particles dispersed in the airstream. An optical particle counter(s) measures and counts the particles in 12 geometric logarithmic-scale, equally distributed particle size ranges both upstream and downstream for efficiency determinations. The size range encompassed by the test is 0.3 to 10 µm polystyrene latex equivalent optical particle size. A method of loading the air cleaner with synthetic dust to simulate field conditions is also specified. The synthetic loading dust is the same as in ASHRAE *Standard* 52.1.

A set of particle size removal efficiency performance curves is developed from the test and, together with an initial clean performance curve, is the basis of a composite curve representing performance in the range of sizes. Points on the composite curve are averaged and these averages are used to determine the MERV of the air cleaner. A complete test report includes (1) a summary section, (2) removal efficiency curves of the clean devices at each of the

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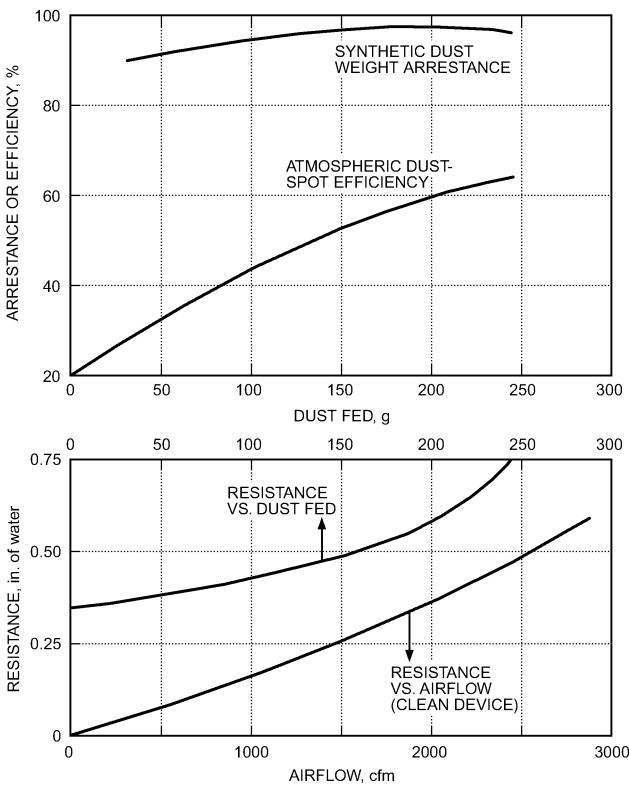
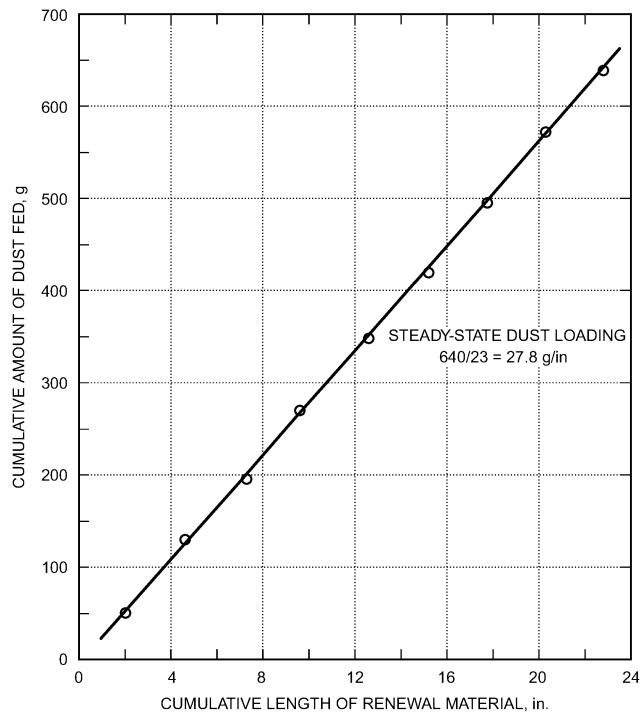


Fig. 1 Typical Performance Curves for Fixed Cartridge-Type Filter According to ASHRAE Standard 52.1



Note: Calculate loading per unit by multiplying steady-state dust loading by 144 and dividing by media width, normally 24 in. For example, $27.8 \times 144/24 = 167 \text{ g/ft}^2$.

Fig. 2 Typical Dust-Loading Graph for Self-Renewable Air Filter

loading steps, and (3) a composite minimum removal efficiency curve.

DOP Penetration Test

For high-efficiency filters of the type used in cleanrooms and nuclear applications (HEPA filters), the normal test in the United States is the thermal DOP method, outlined in U.S. Military Standard MIL-STD-282 (1956) and U.S. Army document 136-300-175A (1965). DOP is dioctyl phthalate or bis-[2-ethylhexyl] phthalate, which is an oily liquid with a high boiling point. In this method, a smoke cloud of DOP droplets condenses from DOP vapor.

The count median diameter for DOP aerosols is about 0.18 μm , and the mass median diameter is about 0.27 μm with a cloud concentration of approximately 80 mg/m^3 under properly controlled conditions. The procedure is sensitive to the mass median diameter, and DOP test results are commonly referred to as efficiency on 0.30 μm particles.

The DOP smoke cloud is fed to the filter, which is held in a special test fixture. Any smoke that penetrates the body of the filter or leaks through gasket cracks passes into the region downstream from the filter, where it is thoroughly mixed. Air leaving the fixture thus contains the average concentration of penetrating smoke. This concentration, as well as the upstream concentration, is measured by a light-scattering photometer. **Filter penetration P (%)** is

$$P = 100 \left(\frac{\text{Downstream concentration}}{\text{Upstream concentration}} \right) \quad (1)$$

Penetration, not efficiency, is usually specified in the test procedure because HEPA filters have efficiencies so near 100% (e.g., 99.97% or 99.99% on 0.30 μm particles). The two terms are related by the equation $E = 100 - P$.

U.S. specifications frequently call for testing HEPA filters at both rated flow and 20% of rated flow. This procedure helps detect gasket leaks and pinholes that would otherwise escape notice. Such defects, however, are not located by the DOP penetration test.

The Institute of Environmental Sciences and Technology has published two recommend practices: IEST RP-CC 001.3, HEPA and ULPA Filters, and IEST RP-CC 007.1, Testing ULPA Filters.

Leakage (Scan) Tests

For HEPA filters, leakage tests are sometimes desirable to show that no small "pinhole" leaks exist or to locate any that may exist so they may be patched. Essentially, this is the same technique as used in the DOP penetration test, except that the downstream concentration is measured by scanning the face of the filter and its gasketed perimeter with a moving probe. The exact point of smoke penetration can then be located and repaired. This same test (described in IEST RP-CC 001.3) can be performed after the filter is installed; in this case, a portable but less precise Laskin nozzle aspirator-type DOP generator is used instead of the much larger thermal generator. Smoke produced by a portable generator is not uniform in size, but its average diameter can be approximated as 0.6 μm . Particle diameter is less critical for leak location than for penetration measurement.

Specialized Performance Test

American Home Appliance Manufacturers Association (AHAM) *Standard AC-1* describes a method for measuring the ability of portable household air cleaners to reduce generated particles suspended in the air in a room-size test chamber. The procedure compares the natural decay of three contaminants (dust, smoke, and pollen) with the reduction in particles by the air cleaner.

Other Performance Tests

The European Standardization Institute (Comité Européen de Normalisation, or CEN) developed EN 779, "Particulate air filters for general ventilation—Requirements, testing, marking" (CEN 1993). Its revision, "Particulate air filters for general ventilation—Determination of the filtration performance" (CEN 2000), was in the formal vote phase as of January, 2001. Eurovent working group 4B (Air Filters) developed Eurovent Document 4/9 (1996), "Method of testing air filters used in general ventilation for determination of fractional efficiency" and is working on the revision of Document 4/10, "In situ determination of fractional efficiency of general ventilation filters." CEN also developed EN 1822 (CEN 1998, 2000), according to which HEPA and ULPA filters must be tested. Also, special test standards have been developed in the United States for respirator air filters (NIOSH/MSHA 1977) and ULPA filters (IEST RP-CC 007.1). [Editor's note: See issuing organizations for latest editions of publications listed in this section.]

Environmental Tests

Air cleaners may be subjected to fire, high humidity, a wide range of temperatures, mechanical shock, vibration, and other environmental stress. Several standardized tests exist for evaluating these environmental effects on air cleaners. U.S. Military Standard MIL-STD-282 includes shock tests (shipment rough handling) and filter media water-resistance tests. Several U.S. Atomic Energy Commission agencies (now part of the U.S. Department of Energy) specify humidity and temperature-resistance tests (Peters 1962, 1965).

Underwriters Laboratories has two major standards for air cleaner flammability. The first, for commercial applications, determines flammability and smoke production. UL *Standard 900* Class 1 filters, when clean, do not contribute fuel when attacked by flame and emit negligible amounts of smoke. UL *Standard 900* Class 2 filters, when clean, burn moderately when attacked by flame or emit moderate amounts of smoke, or both. In addition, UL *Standard 586* for flammability of HEPA filters has been established. The UL tests do not evaluate the effect of collected dust on filter flammability; depending on the dust, this effect may be severe. UL *Standard 867* applies to electronic air cleaners.

ARI Standards

The Air-Conditioning and Refrigeration Institute published ARI *Standards 680* (residential) and *850* (commercial/industrial) for air filter equipment. These standards establish (1) definitions and classification; (2) requirements for testing and rating (performance test methods are per ASHRAE *Standard 52.1*); (3) specification of standard equipment; (4) performance and safety requirements; (5) proper marking; (6) conformance conditions; and (7) literature and advertising requirements. However, certification of air cleaners is not a part of these standards.

TYPES OF AIR CLEANERS

Common air cleaners are broadly grouped as follows:

In **fibrous media unit filters**, the accumulating dust load causes pressure drop to increase up to some maximum recommended value. During this period, efficiency normally increases. However, at high dust loads, dust may adhere poorly to filter fibers and efficiency drops because of offloading. Filters in this condition should be replaced or reconditioned, as should filters that have reached their final (maximum recommended) pressure drop. This category includes viscous impingement and dry air filters, available in low-efficiency to ultrahigh-efficiency construction.

In **renewable media filters**, fresh media is introduced into the airstream as needed to maintain essentially constant resistance and, consequently, constant average efficiency.

Electronic air cleaners, if maintained properly by regular cleaning, have relatively constant pressure drop and efficiency.

Combination air cleaners combine the other types. For example, an electronic air cleaner may be used as an agglomerator with a fibrous media downstream to catch the agglomerated particles blown off the plates. Electrode assemblies have been installed in air-handling systems, making the filtration system more effective (Frey 1985, 1986). Also, low-efficiency pads, throwaway panels and automatically renewable media roll filters, or low- to medium-efficiency pleated prefilters may be used upstream of a high-efficiency filter to extend the life of the better and more costly final filter. Charged media filters are also available that increase particle deposition on media fibers by an induced electrostatic field. With these filters, pressure loss increases as it does on a non-charged fibrous media filter. The benefits of combining different air cleaning processes vary. ASHRAE *Standard* 52.1 and 52.2 test methods may be used to compare the performance of combination air cleaners.

FILTER TYPES AND PERFORMANCE

Panel Filters

Viscous impingement panel filters are made up of coarse, highly porous fibers. Filter media are generally coated with an odorless, nonmigrating adhesive or other viscous substance, such as oil, which causes particles that impinge on the fibers to stick to them. Design air velocity through the media usually ranges from 200 to 800 fpm. These filters are characterized by low pressure drop, low cost, and good efficiency on lint and larger particles (5 μm and larger), but low efficiency on normal atmospheric dust. They are commonly made 0.5 to 4 in. thick. Unit panels are available in standard and special sizes up to about 24 by 24 in. This type of filter is commonly used in residential furnaces and air conditioning and is often used as a prefilter for higher-efficiency filters.

Filter media materials include metallic wools, expanded metals and foils, crimped screens, random matted wire, coarse (15 to 60 μm diameter) glass fibers, coated animal hair, vegetable or synthetic fibers, and synthetic open-cell foams.

Although viscous impingement filters usually operate at around 300 to 600 fpm, they may be operated at higher velocities. The limiting factor, other than increased flow resistance, is the danger of blowing off agglomerates of collected dust and the viscous coating on the filter.

The loading rate of a filter depends on the type and concentration of dirt in the air being handled and the operating cycle of the system. Manometers, static pressure differential gages, or pressure transducers are often installed to measure pressure drop across the filter bank. This measurement can identify when the filter requires servicing. The final allowable pressure differential may vary from one installation to another; but, in general, viscous impingement filters are serviced when their operating resistance reaches 0.5 in. of water. Life cycle cost (LCC), including energy necessary to overcome the filter resistance, should be calculated to evaluate the overall cost of the filtering system. The decline in filter efficiency caused by dust coating the adhesive, rather than by the increased resistance because of dust load, may be the limiting factor in operating life.

The manner of servicing unit filters depends on their construction and use. Disposable viscous impingement panel filters are constructed of inexpensive materials and are discarded after one period of use. The cell sides of this design are usually a combination of cardboard and metal stiffeners. Permanent unit filters are generally constructed of metal to withstand repeated handling. Various cleaning methods have been recommended for permanent filters; the most widely used involves washing the filter with steam or water (frequently with detergent) and then recoating it with its recommended adhesive by dipping or spraying. Unit viscous filters are also sometimes arranged for in-place washing and recoating.

The adhesive used on a viscous impingement filter requires careful engineering. Filter efficiency and dust-holding capacity depend on the specific type and quantity of adhesive used; this information

is an essential part of test data and filter specifications. Desirable adhesive characteristics, in addition to efficiency and dust-holding capacity, are (1) a low percentage of volatiles to prevent excessive evaporation; (2) a viscosity that varies only slightly within the service temperature range; (3) the ability to inhibit growth of bacteria and mold spores; (4) a high capillarity or the ability to wet and retain the dust particles; (5) a high flash point and fire point; and (6) freedom from odorants or irritants.

Typical performance of viscous impingement unit filters operating within typical resistance limits is shown as MERV 1 through 6 in [Table 3](#).

Dry extended-surface filters use media of random fiber mats or blankets of varying thicknesses, fiber sizes, and densities. Bonded glass fiber, cellulose fibers, wool felt, polymers, synthetics, and other materials have been used commercially. Media in these filters are frequently supported by a wire frame in the form of pockets, or V-shaped or radial pleats. In other designs, the media may be self-supporting because of inherent rigidity or because air-flow inflates it into extended form (e.g., bag filters). Pleating media provides a high ratio of media area to face area, thus allowing reasonable pressure drop and low media velocities.

In some designs, the filter media is replaceable and is held in position in permanent wire baskets. In most designs, the entire cell is discarded after it has accumulated its maximum dust load.

Efficiency is usually higher than that of panel filters, and the variety of media available makes it possible to furnish almost any degree of cleaning efficiency desired. The dust-holding capacities of modern dry filter media and filter configurations are generally higher than those of panel filters.

Using coarse prefilters upstream of extended-surface filters is sometimes justified economically by the longer life of the main filters. Economic considerations include the prefilter material cost, changeout labor, and increased fan power. Generally, prefilters should be considered only if they can substantially reduce the part of the dust that may plug the protected filter. A prefilter usually has an arrestance of at least 70% (MERV 3) but is commonly rated up to 92% (MERV 6). Temporary prefilters protecting higher-efficiency filters are worthwhile during building construction to capture heavy loads of coarse dust. Filters of 95% DOP efficiency and greater should always be protected by prefilters of 80 to 85% or greater ASHRAE average atmospheric dust-spot efficiency (MERV 13). A single filter gage may be installed when a panel prefilter is placed adjacent to a final filter. Because the prefilter is frequently changed on a schedule, the final filter pressure drop can be read without the prefilter in place every time the prefilter is changed. For maximum accuracy and economy of prefilter use, two gages can be used. Some air filter housings are available with pressure taps between the pre- and final filter tracks to accommodate this arrangement.

Typical performance of some types of filters in this group, when operated within typical rated resistance limits and over the life of the filters, is shown as MERV 7 through 16 in [Table 3](#).

Initial resistance of an extended-surface filter varies with the choice of media and filter geometry. Commercial designs typically have an initial resistance from 0.1 to 1.0 in. of water. It is customary to replace the media when the final resistance of 0.5 in. of water is reached for low-resistance units and 2.0 in. of water for the highest-resistance units. Dry media providing higher orders of cleaning efficiency have a higher average resistance to airflow. The operating resistance of the fully dust-loaded filter must be considered in design, because that is the maximum resistance against which the fan operates. Variable-air-volume and constant-air-volume system controls prevent abnormally high airflows or possible fan motor overloading from occurring when filters are clean.

Flat panel filters with media velocity equal to duct velocity are made only with the lowest-efficiency dry-type media (open-cell foams and textile denier nonwoven media). Initial resistance of this

group, at rated airflow, is generally between 0.05 and 0.25 in. of water. They are usually operated to a final resistance of 0.50 to 0.70 in. of water.

In intermediate-efficiency extended-surface filters, the filter media area is much greater than the face area of the filter; hence, velocity through the filter media is substantially lower than the velocity approaching the filter face. Media velocities range from 6 to 90 fpm, although approach velocities run to 750 fpm. Depth in direction of airflow varies from 2 to 36 in.

Intermediate-efficiency filter media include (1) fine glass or synthetic fibers, 0.7 to 10 μm in diameter, in mats up to 0.5 in. thick; (2) wet laid paper or thin nonwoven mats of fine glass fibers, cellulose, or cotton wadding; and (3) nonwoven mats of comparatively large-diameter fibers (more than 30 μm) in greater thicknesses (up to 2 in.).

Electret filters are composed of electrostatically charged fibers. The charges on the fibers augment collection of smaller particles by interception and diffusion (Brownian motion) with Coulomb forces caused by the charges. There are three types of these filters: resin wool, electret, and an electrostatically sprayed polymer. The charge on resin wool fibers is produced by friction during the carding process. During production of the electret, a corona discharge injects positive charges on one side of a thin polypropylene film and negative charges on the other side. These thin sheets are then shredded into fibers of rectangular cross section. The third process spins a liquid polymer into fibers in the presence of a strong electric field, which produces the charge separation. Efficiency of charged-fiber filters is determined by both the normal collection mechanisms of a media filter (related to fiber diameter) and the strong local electrostatic effects (related to the amount of electrostatic charge). The effects induce efficient preliminary loading of the filter to enhance the caking process. However, dust collected on the media can reduce the efficiency of electret filters.

Very high-efficiency dry filters, HEPA (high-efficiency particulate air) filters, and ULPA (ultralow-penetration air) filters are made in an extended-surface configuration of deep space folds of submicrometre glass fiber paper. These filters operate at duct velocities near 250 fpm, with resistance rising from 0.5 to more than 2.0 in. of water over their service life. These filters are the standard for cleanroom, nuclear, and toxic particulate applications.

Membrane filters are used mainly for air sampling and specialized small-scale applications where their particular characteristics compensate for their fragility, high resistance, and high cost. They are available in many pore diameters and resistances and in flat-sheet and pleated forms.

Renewable-media filters may be one of two types: (1) moving-curtain viscous impingement filters or (2) moving-curtain dry-media roll filter.

In one viscous type, random-fiber (nonwoven) media is furnished in roll form. Fresh media is fed manually or automatically across the face of the filter, while the dirty media is rewound onto a roll at the bottom. When the roll is exhausted, the tail of the media is wound onto the take-up roll, and the entire roll is thrown away. A new roll is then installed, and the cycle repeats.

Moving-curtain filters may have the media automatically advanced by motor drives on command from a pressure switch, timer, or media light-transmission control. A pressure switch control measures the pressure drop across the media and switches on and off at chosen upper and lower set points. This saves media, but only if the static pressure probes are located properly and unaffected by modulating outside and return air dampers. Most pressure drop controls do not work well in practice. Timers and media light-transmission controls help avoid these problems; their duty cycles can usually be adjusted to provide satisfactory operation with acceptable media consumption.

Filters of this replaceable roll design generally have a signal indicating when the roll is nearly exhausted. At the same time, the drive motor is deenergized so that the filter cannot run out of media. Normal service requirements involve inserting a clean roll of media at the top of the filter and disposing of the loaded dirty roll. Automatic filters of this design are not, however, limited to the vertical position; horizontal arrangements are available for makeup air and air-conditioning units. Adhesives must have qualities similar to those for panel viscous impingement filters, and they must withstand media compression and endure long storage.

The second type of automatic viscous impingement filter consists of linked metal mesh media panels installed on a traveling curtain that intermittently passes through an adhesive reservoir. In the reservoir, the panels give up their dust load and, at the same time, take on a new coating of adhesive. The panels thus form a continuous curtain that moves up one face and down the other face. The media curtain, continually cleaned and renewed with fresh adhesive, lasts the life of the filter mechanism. The precipitated captured dirt must be removed periodically from the adhesive reservoir. New installations of this type of filter are rare in North America, but are often found in Europe and Asia.

The resistance of both types of viscous impingement automatically renewable filters remains approximately constant as long as proper operation is maintained. A resistance of 0.4 to 0.5 in. of water at a face velocity of 500 fpm is typical of this class.

Moving-curtain dry-media roll filters use random-fiber (nonwoven) dry media of relatively high porosity for general ventilation service. Operating duct velocities near 200 fpm are generally lower than those of viscous impingement filters.

Special automatic dry filters are also available, designed for removing lint in textile mills, laundries, and dry-cleaning establishments and for collecting lint and ink mist in printing press rooms. The medium used is extremely thin and serves only as a base for the buildup of lint, which then acts as a filter medium. The dirt-laden media is discarded when the supply roll is used up.

Another form of filter designed specifically for dry lint removal consists of a moving curtain of wire screen, which is vacuum cleaned automatically at a position out of the airstream. Recovery of the collected lint is sometimes possible with these devices.

ASHRAE arrestance, efficiency, and dust-holding capacities for typical viscous impingement and dry renewable-media filters are listed in [Table 1](#).

Electronic Air Cleaners

Electronic air cleaners can be highly efficient filters using electrostatic precipitation to remove and collect particulate contaminants such as dust, smoke, and pollen. The term *electronic air cleaner* denotes a precipitator for HVAC air filtration. The filter consists of an ionization section and a collecting plate section.

In the ionization section, small-diameter wires with a positive direct current potential between 6 and 25 kV are suspended equidistant between grounded plates. The high voltage on the wires creates an ionizing field for charging particles. The positive ions created in the field flow across the airstream and strike and adhere to the particles, imparting a charge to them. The charged particles then pass into the collecting plate section.

The collecting plate section consists of a series of parallel plates equally spaced with a positive direct current voltage of 4 to 10 kV applied to alternate plates. Plates that are not charged are at ground potential. As the particles pass into this section, they are attracted to the plates by the electric field on the charges they carry; thus, they are removed from the airstream and collected by the plates. Particle retention is a combination of electrical and intermolecular adhesion forces and may be augmented by special oils or adhesives on the plates. [Figure 3](#) shows a typical electronic air cleaner cell.

In lieu of positive direct current, a negative potential also functions on the same principle, but generates more ozone. With voltages

Table 1 Performance of Renewable Media Filters (Steady-State Values)

Description	Type of Media	ASHRAE Weight Arrestance, %	ASHRAE Atmospheric Dust-Spot Efficiency, %	ASHRAE Dust-Holding Capacity, g/ft ²	Approach Velocity, fpm
20 to 40 μm glass and synthetic fibers, 2 to 2 1/2 in. thick	Viscous impingement	70 to 82	<20	60 to 180	500
Permanent metal media cells or overlapping elements	Viscous impingement	70 to 80	<20	NA (permanent media)	500
Coarse textile denier nonwoven mat, 1/2 to 1 in. thick	Dry	60 to 80	<20	15 to 70	500
Fine textile denier nonwoven mat, 1/2 to 1 in. thick	Dry	80 to 90	<20	10 to 50	200

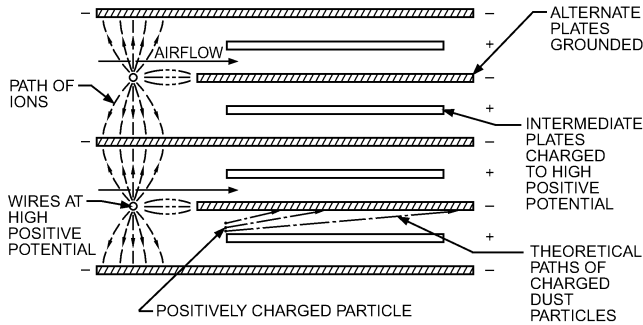


Fig. 3 Cross Section of Ionizing Electronic Air Cleaner

of 4 to 25 kV (dc), safety measures are required. A typical arrangement makes the air cleaner inoperative when the doors are removed for cleaning the cells or servicing the power pack. Electronic air cleaners typically operate from a 120 or 240 V (ac) single-phase electrical service. The high voltage supplied to the air cleaner cells is normally created with solid-state power supplies. The electric power consumption ranges from 20 to 40 W per 1000 cfm of air cleaner capacity.

This type of air filter can remove and collect airborne contaminants with an initial efficiency of up to 98% at low airflow velocities (150 to 350 fpm) when tested according to ASHRAE *Standard* 52.1. Efficiency decreases (1) as collecting plates become loaded with particulates, (2) with higher velocities, or (3) with nonuniform velocity.

As with most air filtration devices, duct approaches to and from the air cleaner housing should be arranged so that airflow is distributed uniformly over the face area. Panel prefilters should also be used to help distribute airflow and to trap large particles that might short out or cause excessive arcing in the high-voltage section of the air cleaner cell. Electronic air cleaner design parameters of air velocity, ionizer field strength, cell plate spacing, depth, and plate voltage must match the application requirements (e.g., contaminant type, particle size, volume of air, required efficiency). Many units are designed for installation into central heating and cooling systems for total air filtration. Other self-contained units are furnished complete with air movers for source control of contaminants in specific applications that need an independent air cleaner.

Electronic air cleaner cells must be cleaned periodically with detergent and hot water. Some designs incorporate automatic wash systems that clean the cells in place; in others, the cells are removed for cleaning. The frequency of cleaning (washing) the cell depends on the contaminant and the concentration. Industrial applications may require cleaning every 8 h, but a residential unit may only require cleaning every one to three months. The timing of the cleaning schedule is important to keep the unit performing at peak efficiency. For some contaminants, special attention must be given to cleaning the ionizing wires.

Optional features are often available for electronic air cleaners. Afterfilters such as roll filters collect particulates that agglomerate and blow off the cell plates. These are used mainly where heavy contaminant loading occurs and extension of the cleaning cycle is desired. Cell collector plates may be coated with special oils, adhesives, or detergents to improve both particle retention and particle removal during cleaning. High-efficiency dry extended-media area filters are also used as afterfilters in special designs. The electronic air cleaner used in this system improves the service life of the dry filter and collects small particles such as smoke.

A **negative ionizer** uses the principle of particle charging but does not use a collecting section. Particles enter the ionizer of the unit, receive an electrical charge, and then migrate to a grounded surface closest to the travel path.

Space Charge. Particulates that pass through an ionizer and are charged, but not removed, carry the electrical charge into the space. If continued on a large scale, a space charge builds up, which tends to drive these charged particles to walls and interior surfaces. Thus, a low-efficiency electronic air cleaner used in areas of high ambient dirt concentrations (or a malfunctioning unit), can blacken walls faster than if no cleaning device were used (Penney and Hewitt 1949; Sutton et al. 1964).

Ozone. All high-voltage devices can produce ozone, which is toxic and damaging not only to human lungs, but to paper, rubber, and other materials. When properly designed and maintained, an electronic air cleaner produces an ozone concentration that only reaches a fraction of the limit acceptable for continuous human exposure and is less than that prevalent in many American cities (EPA 1996). Continuous arcing and brush discharge in an electronic air cleaner may yield an ozone level that is annoying or mildly toxic; this is indicated by a strong ozone odor. Although the nose is sensitive to ozone, only actual measurement of the concentration can determine whether a hazardous condition exists.

ASHRAE *Standard* 62.1 defines acceptable concentrations of oxidants, of which ozone is a major contributor. The U.S. Environmental Protection Agency (EPA) specifies a 1 h average maximum allowable exposure to ozone of 0.12 ppm for outside ambient air. The U.S. Department of Health and Human Services specifies a maximum allowable continuous exposure to ozone of 0.05 ppm for contaminants of indoor origin. Sutton et al. (1976) showed that indoor ozone levels are only 30% of the outdoor level with ionizing air cleaners operating, although Weschler et al. (1989) found that this level increases when outdoor airflow is increased during an outdoor event that creates ozone.

SELECTION AND MAINTENANCE

To evaluate filters and air cleaners properly for a particular application, the following factors should be considered:

1. Types of contaminants present indoors and outdoors
2. Sizes and concentrations of contaminants
3. Air cleanliness levels required in the space
4. Air filter efficiency needed to achieve cleanliness

5. Space available to install and access equipment
6. Life cycle costing, including
 - Operating resistance to airflow (static pressure differential)
 - Disposal or cleaning requirements of spent filters
 - Initial cost of selected system
 - Cost of replacement filters or cleaning
 - Cost of warehousing filter stock and change-out labor

Savings (from reduced housekeeping expenses, protection of valuable property and equipment, dust-free environments for manufacturing processes, improved working conditions, and even health benefits) should be credited against the cost of installing and operating an adequate system. The capacity and physical size of the required unit may emphasize the need for low maintenance cost. Operating cost, predicted life, and efficiency are as important as initial cost because air cleaning is a continuing process.

Panel filters do not have efficiencies as high as can be expected from extended-surface filters, but their initial cost and upkeep are generally low. Compared to moving-curtain filters, panel filters of comparable efficiencies require more attention to maintain the resistance within reasonable limits. However, single-stage, face- or side-access, low- to medium-efficiency filters (25 to 50% dust spot and MERV 6 to 10), from a 2 in. pleat to a 12 in. deep cube, bag, or deep pleated cartridge, require less space with lower initial cost, and have better efficiency. The bag and cartridges generally have a similar service life to that of a roll filter.

If efficiency of 60 to 65% dust spot (MERV 11) or higher is required, extended-surface filters or electronic air cleaners should be considered. The use of very fine glass fiber mats or other materials in extended-surface filters has made these available at the highest efficiency.

Initial cost of an extended-surface filter is lower than for an electronic unit, but higher than for a panel type. Operating and maintenance costs of some extended-surface filters may be higher than for panel types and electronic air cleaners, but efficiencies are always higher than for panel types; the cost/benefit ratio must be considered. Pressure drop of media-type filters is greater than that of electronic-type and slowly increases during their useful life. Advantages include the fact that no mechanical or electrical services are required. Choice should be based on both initial and operating costs (life-cycle costs) as well as on the degree of cleaning efficiency and maintenance requirements.

Although electronic air cleaners have a higher initial cost and maintenance cost, they have high initial efficiencies in cleaning atmospheric air, largely because of their ability to remove fine particulate contaminants. System resistance remains unchanged as particles are collected, and efficiency is reduced until the resulting residue is removed from the collection plates to prepare the equipment for further duty. The manufacturer must supply information on maintenance or cleaning. Also, note that electronic air cleaners may not collect particles greater than 10 μm in diameter.

[Table 2](#) lists some applications of filters classified according to their efficiencies and type, and [Table 3](#) provides an approximate cross-reference between the ASHRAE *Standard* 52.1 and 52.2 reporting methods. A corollary purpose is to provide application guidance for the user and the HVAC designer. HEPA filters are tested by non-ASHRAE standards, but they have been included in the table by arbitrarily assigning minimum efficiency reporting values (MERVs) to Institute of Environmental Sciences and Technology (IEST) test standard ratings. [Table 3](#) combines all the parameters into a single reference covering most types of air cleaners and applications. However, a single performance measurement cannot be applied precisely to all types and styles of air cleaners. Each air cleaner has unique characteristics that change during its useful life.

The typical contaminants listed in [Table 3](#) appear in the general reporting group that removes the smallest known size of that specific contaminant. The order in which they are listed has no signif-

icance nor is the list complete. The typical applications and typical air cleaners listed are intended to show where and what type of air cleaner has been traditionally used. Traditional usage may not represent the optimum choice, so using the table as a selection guide is not appropriate when a specific performance requirement is needed. An air cleaner application specialist should then be consulted and manufacturers' performance curves should be reviewed.

Common sense and some knowledge of how air cleaners work help the user achieve satisfactory results. Air cleaner performance varies from the time it is first installed until the end of its service life. Generally, the longer a media-type filter is in service, the higher the efficiency. The accumulation of contaminants begins to close the porous openings, and, therefore, the filter is able to intercept smaller particles. However, there are exceptions that vary with different styles of media-type filters. Electronic air cleaners and charged-fiber media filters start at high efficiency when new (or after proper service, in the case of electronic air cleaners) but their efficiency decreases as contaminants accumulate. Some air cleaners, particularly low-efficiency devices, may begin to shed some collected contaminants after being in service. Testing with standardized synthetic loading dust attempts to predict this, but such testing rarely, if ever, duplicates the air cleaner's performance on atmospheric dust.

Residential Air Cleaners

Filters used for residential applications are often of spun glass and only filter out the largest of particles. These filters may prevent damage to downstream equipment, but they do little to improve air quality in the residence. Offermann (1992) describes a series of tests used to rate residential air cleaners. The tests were run in a test house with environmental tobacco smoke (ETS) as the test particulate (mass mean diameter = 0.5 μm). The typical residential air filter is not effective on these very small respirable-sized particles.

Console-type air cleaners can be used when an air cleaning system cannot be a part of the ducted HVAC equipment. For whole-house applications, in-line units ducted to the central heating and air-conditioning equipment are recommended.

VAV Systems

ASHRAE *Standard* 52.1 tests on numerous different media-type air cleaners under both constant and variable airflow showed no significant performance differences under the different flow conditions, and the air cleaners were not damaged by VAV flow. Low-efficiency air cleaners did show substantial reentrainment for both constant and VAV flow (Rivers and Murphy 2000).

Antimicrobial Treatment of Filter Media

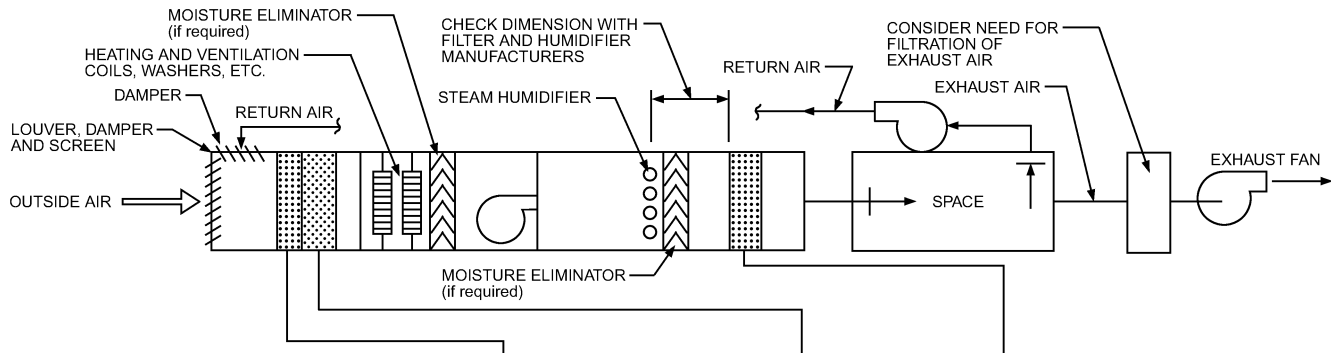
One key factor influencing the ability of a filter to support fungal growth is the filter media itself; using antimicrobials successfully on air cleaners is very complex. Effective assessment of antimicrobial efficacy should include an "as-used" type test, not a test of the antimicrobial alone.

In laboratory and field testing, microbial growth has been seen on both treated and untreated dust-loaded samples for certain media types. Under normal use, fibrous air cleaners are unlikely to become a source of microbial contamination to the space, and antimicrobial treatment does not increase the filtration efficiency for bioaerosols (Foarde et al. 2000).

AIR CLEANER INSTALLATION

Many air cleaners are available in units of convenient size for manual installation, cleaning, and replacement. A typical unit filter may be 20 to 24 in. square, from 1 to 40 in. thick, and of either the dry or viscous impingement type. In large systems, the frames in which these units are installed are bolted or riveted together to form a filter bank. Automatic filters are constructed in sections offering

Table 2 Typical Filter Applications Classified by Filter Efficiency and Type^a



Application	System Designator ^b	Prefilter	Prefilter/Filter	Final Filter	Application Notes
Warehouse, storage, shop and process areas, mechanical equipment rooms, electrical control rooms, protection for heating and cooling coils	A1	None	70 to 85% arrestance	None	Reduces larger particle settling. Protects coils from dirt and lint.
	A2	None	85 to 92% arrestance, 25 to 50% dust spot	None	
Special process areas, electrical shops, paint shops, average general offices and laboratories	B1	None	50 to 65% dust spot	None	Average housecleaning. Reduces lint in airstream. Reduces ragweed pollen >85% at 35%. Removes all pollens at 60%, somewhat effective on particles causing smudge and stain.
Analytical laboratories, electronics shops, drafting areas, conference rooms, above-average general offices	C1	75 to 85% arrestance, 25 to 40% dust spot	80 to 85% dust spot	None	Above-average housecleaning. No settling particles of dust. Cartridge and bag types very effective on particles causing smudge and stain, partially effective on tobacco smoke. Electronic types quite effective on smoke.
	C2	None	80 to 85% dust spot	None	
Hospitals, pharmaceutical R&D and manufacturing (nonaseptic areas only), some clean ("gray") rooms	D1	75 to 85% arrestance, 25 to 40% dust spot	80 to 85% dust spot	95% DOP disposable cell	Excellent housecleaning. Very effective on particles causing smudge and stain, smoke and fumes. Highly effective on bacteria.
	D2	None	80 to 95% dust spot	None	
Aseptic areas in hospital and pharmaceutical R&D and manufacturing. Cleanrooms in film and electronics manufacturing, radioactive areas, etc. ^c	E1	75 to 85% arrestance, 25 to 40% dust spot	80 to 95% dust spot	≥99.97% DOP disposable cell	Protects against bacteria, radioactive dusts, toxic dusts, smoke, and fumes.

^aAdapted from a similar table courtesy of E.I. du Pont de Nemours & Company.
^bSystem designators have no significance other than their use in this table.

^cElectronic agglomerators and air cleaners are not usually recommended for cleanroom applications.

several choices of width up to 70 ft and generally range in height from 40 to 200 in., in 4 to 6 in. increments. Several sections may be bolted together to form a filter bank.

Several manufacturers provide side-loading filter sections for various types of filters. Filters are changed from outside the duct, making service areas in the duct unnecessary, thus saving cost and space.

Of course, in-service efficiency of an air filter is sharply reduced if air leaks through the bypass dampers or poorly designed frames. The higher the filter efficiency, the more attention that must be paid to the rigidity and sealing effectiveness of the frame. In addition,

high-efficiency filters must be handled and installed with care. The National Air Filtration Association (NAFA) (1997) suggests some precautions needed for HEPA filters.

Air cleaners may be installed in the outside-air intake ducts of buildings and residences and in the recirculation and bypass air ducts, but prefilters and intermediate filters (in a three-stage system) should be placed upstream of heating or cooling coils and other air-conditioning equipment in the system to protect that equipment from dust. Dust captured in an outside-air intake duct is likely to be mostly greasy particles, whereas lint may predominate in dust from within the building.

Table 3 Cross-Reference and Application Guidelines (Table E-1, ASHRAE Standard 52.2)

Std. 52.2 Minimum Efficiency Reporting Value (MERV)	Approx. Std. 52.1 Results		Application Guidelines		
	Dust-Spot Efficiency	Arrestance	Typical Controlled Contaminant	Typical Applications and Limitations	Typical Air Filter/Cleaner Type
20	n/a	n/a	≤0.30 µm Particles Virus (unattached) Carbon dust Sea salt All combustion smoke Radon progeny	Cleanrooms Radioactive materials Pharmaceutical manufacturing Carcinogenic materials Orthopedic surgery	HEPA/ULPA Filters ≥99.999% efficiency on 0.1 to 0.2 µm particles, IEST Type F ≥99.999% efficiency on 0.3 µm particles, IEST Type D ≥99.99% efficiency on 0.3 µm particles, IEST Type C ≥99.97% efficiency on 0.3 µm particles, IEST Type A
19	n/a	n/a			
18	n/a	n/a			
17	n/a	n/a			
16	n/a	n/a	0.3 to 1.0 µm Particles All bacteria Most tobacco smoke Droplet nuclei (sneeze) Cooking oil Most smoke Insecticide dust Copier toner Most face powder Most paint pigments	Hospital inpatient care General surgery Smoking lounges Superior commercial buildings	Bag Filters Nonsupported (flexible) microfine fiberglass or synthetic media. 12 to 36 in. deep, 6 to 12 pockets. Box Filters Rigid style cartridge filters 6 to 12 in. deep may use lofted (air-laid) or paper (wet-laid) media.
15	>95%	n/a			
14	90 to 95%	>98%			
13	80 to 90%	>98%			
12	70 to 75%	>95%	1.0 to 3.0 µm Particles Legionella Humidifier dust Lead dust Milled flour Coal dust Auto emissions Nebulizer drops Welding fumes	Superior residential Better commercial buildings Hospital laboratories	Bag Filters Nonsupported (flexible) microfine fiberglass or synthetic media. 12 to 36 in. deep, 6 to 12 pockets. Box Filters Rigid style cartridge filters 6 to 12 in. deep may use lofted (air-laid) or paper (wet-laid) media.
11	60 to 65%	>95%			
10	50 to 55%	>95%			
9	40 to 45%	>90%			
8	30 to 35%	>90%	3.0 to 10.0 µm Particles Mold Spores Hair spray Fabric protector Dusting aids Cement dust Pudding mix Snuff Powdered milk	Commercial buildings Better residential Industrial workplaces Paint booth inlet air	Pleated Filters Disposable, extended-surface, 1 to 5 in. thick with cotton/polyester blend media, cardboard frame. Cartridge Filters Graded-density viscous-coated cube or pocket filters, synthetic media Throwaway Disposable synthetic media panel filters
7	25 to 30%	>90%			
6	<20%	85 to 90%			
5	<20%	80 to 85%			
4	<20%	75 to 80%	>10.0 µm Particles Pollen Spanish moss Dust mites Sanding dust Spray paint dust Textile fibers Carpet fibers	Minimum filtration Residential Window air conditioners	Throwaway Disposable fiberglass or synthetic panel filters Washable Aluminum mesh, latex coated animal hair, or foam rubber panel filters Electrostatic Self-charging (passive) woven polycarbonate panel filter
3	<20%	70 to 75%			
2	<20%	65 to 70%			
1	<20%	<65%			

Note: MERV for non-HEPA/ULPA filters also includes test airflow rate, but it is not shown here because it is of no significance for the purposes of this table.

Where high-efficiency filters protect critical areas such as cleanrooms, it is important that the filters be installed as close to the room as possible to prevent pickup of particles between the filters and the outlet. The ultimate is the unidirectional flow room, in which the entire ceiling or one entire wall becomes the final filter bank.

Published performance data for all air filters are based on straight-through unrestricted airflow. Filters should be installed so that the face area is at right angles to the airflow whenever possible. Eddy currents and dead air spaces should be avoided; air should be distributed uniformly over the entire filter surface using baffles, diffusers, or air blenders, if necessary. Filters are sometimes damaged if higher-than-normal air velocities impinge directly on the face of the filter.

Failure of air filter installations to give satisfactory results can, in most cases, be traced to faulty installation, improper maintenance, or both. The most important requirements of a satisfactory and efficiently operating air filter installation are as follows:

- The filter must be of ample capacity for the amount of air and dust load it is expected to handle. An overload of 10 to 15% is regarded as the maximum allowable. When air volume is subject to future increase, a larger filter bank should be installed initially.
- The filter must be suited to the operating conditions, such as degree of air cleanliness required, amount of dust in the entering air, type of duty, allowable pressure drop, operating temperature, and maintenance facilities.

The following recommendations apply to filters installed with central fan systems:

- Duct connections to and from the filter should change size or shape gradually to ensure even air distribution over the entire filter area.
- The filter should be placed far enough from the fan to prevent or reduce reentrainment of particles, especially during start/stop cycles.

- Sufficient space should be provided in front of or behind the filter, or both, depending on its type, to make it accessible for inspection and service. A distance of 20 to 40 in. is required, depending on the filter chosen.
- Access doors of convenient size must be provided to the filter service areas.
- All doors on the clean-air side should be gasketed to prevent infiltration of unclean air. All connections and seams of the sheet-metal ducts on the clean-air side should be airtight. The filter bank must be caulked to prevent bypass of unfiltered air, especially when high-efficiency filters are used.
- Lights should be installed in the plenum in front of and behind the air filter bank.
- Filters installed close to an air inlet should be protected from the weather by suitable louvers or inlet hood. In areas with extreme rainfall or where water can drip over or bounce up in front of the inlet, use drainable track moisture separator sections upstream of the first filter bank. A large-mesh wire bird screen should be placed in front of the louvers or in the hood.
- Filters, other than electronic air cleaners, should have permanent indicators to give notice when the filter reaches its final pressure drop or is exhausted, as with automatic roll media filters.
- Electronic air cleaners should have an indicator or alarm to indicate when high voltage is off or shorted out.

SAFETY CONSIDERATIONS

Safety ordinances should be investigated when the installation of an air cleaner is contemplated. Combustible filtering media may not be permitted by some local regulations. Combustion of dust and lint on filtering media is possible, although the media itself may not burn. This may cause a substantial increase in filter combustibility. Smoke detectors and fire sprinkler systems may be considered for filter bank locations. In some cases, depending on the contaminant, hazardous material procedures must be followed during removal and disposal of the spent filter. Bag-in/bag-out (BI/BO) filter housings should be considered in those cases.

Many air filters are efficient collectors of bioaerosols. When provided moisture and nutrients, the microorganisms can multiply and may become a health hazard for maintenance personnel. Moisture in filters can be minimized by preventing (1) entrance of rain, snow, and fog; (2) carryover of water droplets from coils, drain pans, and humidifiers; and (3) prolonged exposure to elevated humidity. Changing or cleaning filters regularly is important for controlling microbial growth. Good health-safety practices for personnel handling dirty filters include using face masks, thorough washing upon completion of the work, and placing used filters in plastic bags or other containers for disposal.

[Editor's note: Consult the publishers of sources listed in the References and Bibliography for the latest editions.]

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