CHAPTER 3

FILTERS FOR THE NUCLEAR INDUSTRY

3.1 Introduction

Filters are widely used in nuclear ventilation, air cleanup, and confinement systems to remove particulate matter from air and gas streams. Air filters are defined as porous structures through which air is passed to separate out entrained particulate matter. The word "filter" is derived from a word for the fabric called felt, pieces of which have been used for air and liquid filtration for hundreds of years. The porous structures of a filter may also be composed of granular material such as sand or fibers derived from cotton, minerals (glass, asbestos), metals, or a wide selection of plastic materials. For filtration purposes, the fibers may be woven or felted into a cloth or formed into a paper-like structure. Filters may also be constructed in the form of highly porous fibrous beds of considerable depth. Other kinds of air cleaning devices (e.g., adsorbers, liquid scrubbers, electrostatic precipitators) are sometimes referred to as "filters" because they are capable of removing particles from an airstream. For clarity, the strict definition of a filter (given above) will be used in this chapter.

High-efficiency particulate air (HEPA) filters are components of a nuclear treatment system that degrade with service. The user/owner of the facility shall incorporate written specifications on the service life of the HEPA filters for change-out criteria. Appendix C provides guidance on determining the acceptable service life for each application pf HEPA filters.

Air Filter Types

Air filters of many types and materials of construction have been designed, manufactured, and applied to meet a wide variety of industrial and commercial requirements for clean air (e.g., the nuclear industry makes full use of all filter types). Commercially available filters are divided into three distinct categories based on how they operate to remove suspended particulate matter from the air passing through them. The largest category, often referred to as ventilation or heating, ventilation, and air conditioning (HVAC) filters, is composed of highly porous beds of resin-bonded glass or plastic fibers with diameters ranging from 1 to 40 micrometers (μm). The fibers act as targets for collecting airborne dust. As their name indicates, HVAC filters are widely used for air cleaning in mechanical ventilation systems. They are almost all single-use, disposable items, and are used in all sectors of the nuclear industry, including as prefilters that reduce the amount of coarse dust reaching more efficient filters located downstream.

A second category also is comprised of single-use, disposable filters called HEPA filters. By definition, a HEPA filter is a throwaway, extended-medium, dry-type filter with: (1) a minimum particle removal efficiency of no less than 99.97 percent for 0.3-μm particles, (2) a maximum resistance, when clean, of 1.0 inches water gauge (in.wg) when operated at 1,000 cfm, and (3) a rigid casing that extends the full depth of the medium[1] (**Figure 3.1**). [Note: Filters of different flows and resistances are allowable by the AG-1 Code.] [2] A filter of identical construction and appearance, but having a filtering medium with a retention of 99.9995 percent for 0.1 μm particles, is referred to as an ultra-low penetration aerosol filter (ULPA). The filtering medium of HEPA filters is thinner and more compressed, and contains smaller diameter fibers than HVAC filters. HEPA filters are widely used throughout all phases of the nuclear industry.

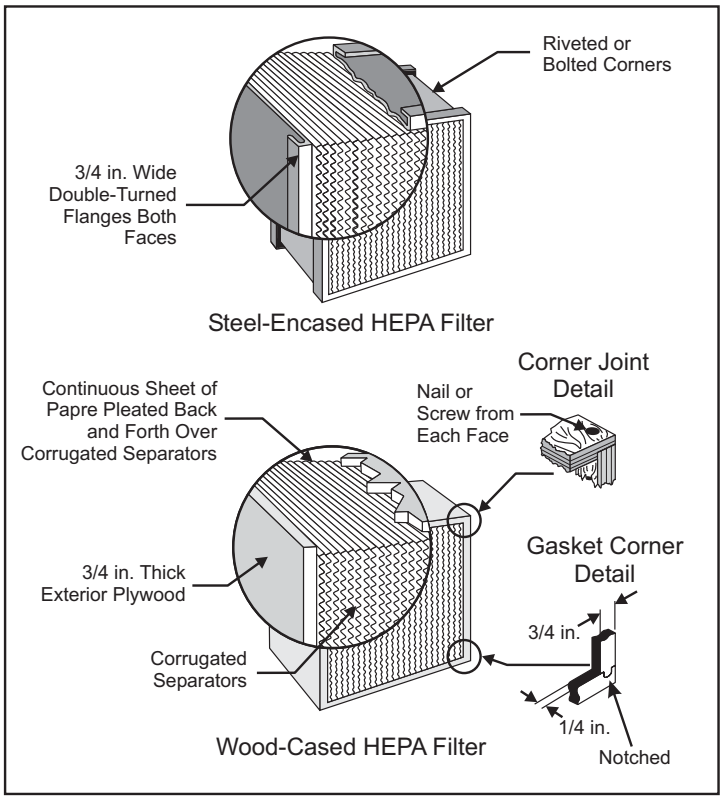

Figure 3.1 – Filter Casing

A third category of commercial air filters is known as industrial cleanable cloth filters. As the designation indicates, these filters have built-in mechanisms for periodically cleaning the filtering surfaces of accumulated dust. Unlike the first two types, industrial cleanable cloth filters rely on building a thick layer of dust on the surface of the cloth to provide a high-efficiency filtering medium. This type of filter is used in the nuclear industry for ore processing and refining and for similar tasks involving high concentrations of coarse mineral dusts.

Further, this third category includes special types of particulate filters for chemical and combustion operations. These include deep beds of sand in graded granular sizes, deep beds of glass fibers, and stainless steel membranes formed from compressed and sintered granules or fibers. Stainless steel membrane filters operate like industrial cleanable cloth filters in that they depend on a dust layer for high-efficiency particle removal and must be cleaned periodically, usually by reverse compressed air jets.

3.2 Filtration

The porosity of air filters has been noted. High porosity is associated with low resistance to airflow (e.g., low-resistance HVAC filters contain approximately 97 percent voids). In a uniformly dispersed filter medium, the individual fibers are relatively far apart—so far apart that the gaps between them are larger than the particles removed from the air. This means that sieving (particle removal via openings that are smaller than the particle dimensions) is not an important filtration mechanism. In fact, a sieve would make a poor air filter, even one containing submicrometer openings, because each collected particle closes up a sieve opening so that very soon no air can pass through. In contrast, filters collect particles from air and gas streams in a number of well-defined ways that are associated with the dynamic properties of airborne particles. The filters respond to the physical forces present as an aerosol passes through a porous medium composed of small granules, fibers, or other shapes.

3.2.1 Particle Collection by Filters

Figure 3.2 shows the streamlines around a spherical granule or a single filter fiber lying normal to the flow direction. A particle entering the flow field surrounding the fibers must follow the curved path of the streamlines so it can pass around the obstacle. When particles possess sufficient inertia, they resist following the curvature of the airstream and come in contact with the fiber because of their higher momentum relative to that of the conveying gas molecules. The capturing effect of *inertial impaction* (see I in Figure 3.2) becomes greater as both aerodynamic equivalent diameter and the velocity of the air approaching the fiber increase.

When suspended particles are very small, however, they tend to follow the curved streamlines closely; that is, they have little inertia, but are in vigorous, random motion (*Brownian motion*—see II drawing in Figure 3.2). Therefore, when a streamline passes close to the fiber surface, the random movements around the streamline may result in some of the particles contacting the fiber and adhering to it. This sets up a concentration gradient between the zone close to the fiber and the bulk of the aerosol which, in turn, results in particle diffusion in the direction of the fiber surface. The smaller the particles, the more vigorous their Brownian motion and the more effective their filtration by *diffusion*. Because the rate at which small particles cross streamlines under the influence of diffusional forces is slow compared to rate of the effects of inertial force on large particles, separation of small particles by diffusion is enhanced by slower velocities through a filter.

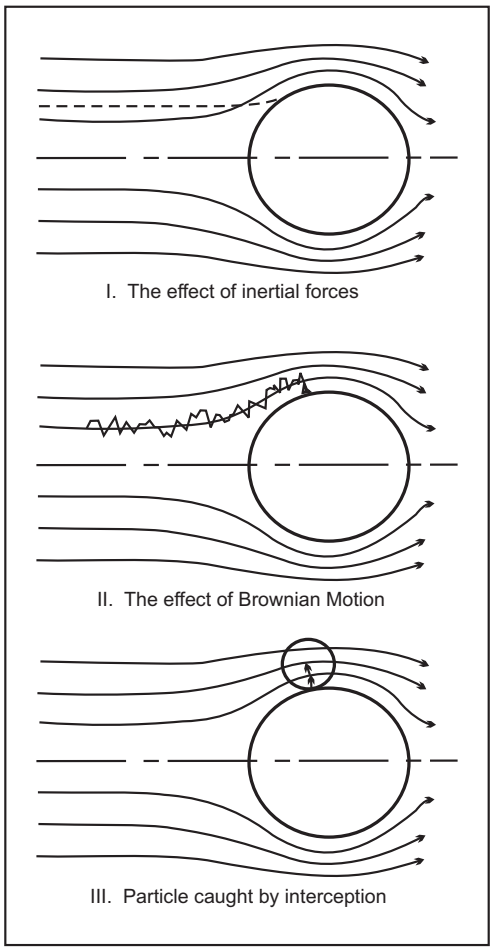

Figure 3.2 – Streamlines Around a Filter Fiber

Particle collection by *interception* (III in Figure 3.2) occurs when a particle traveling in a streamline that approaches a fiber within one particle radius makes contact with the fiber and adheres to it. Interception is independent of flow velocity and is enhanced when the diameter of the collecting fiber or granule approaches the geometric diameter of the particle.

The several filtration mechanisms of importance are shown together in **Figure 3.3**, where penetration (equal to 100 minus collection efficiency) is plotted against particle size. The penetration lines are not cumulative, as particles can be collected but once; however, the net effect can be approximated by the "dashed" summation curve. Figure 3.3 makes it clear there is a particle size where both inertial and diffusional forces are minimal and only interception is unaffected. This explains the concept of a minimum filterable particle size. The exact minimum size depends on fiber diameter, filter construction, and flow velocity. The minimum filterable particle size for currently manufactured nuclear grade HEPA filter papers is close to 0.1 μm when operated at the design flow rate of 1 foot per second. The effect of flow velocity on particle penetration for HEPA filter paper also shows a minimum efficiency point.

3.2.2 Particle Retention in Filters

After an airborne particle contacts a filter element, retention forces prevent re-entrainment under the influence of the drag of the air. For small particles, the principal retentive force is a surface phenomenon called the Van der Waals force, which is proportional to the total area of contact. For small spherical particles, the fraction of the total surface area in contact with a filter fiber will be relatively large, resulting in a retention force that exceeds the re-entrainment force of the air drag.

3.2.3 Airflow Resistance of Filters

Filter resistance is directly related to airflow rate and filter construction details. Decreasing the diameter of filter fibers or granules produces higher resistance for the same overall unit volume of the solid fraction of the filter medium. Greater filter depth at the same porosity increases resistance in proportion to the increase in depth. Within limits, compressing a highly porous filter medium decreases porosity and increases flow

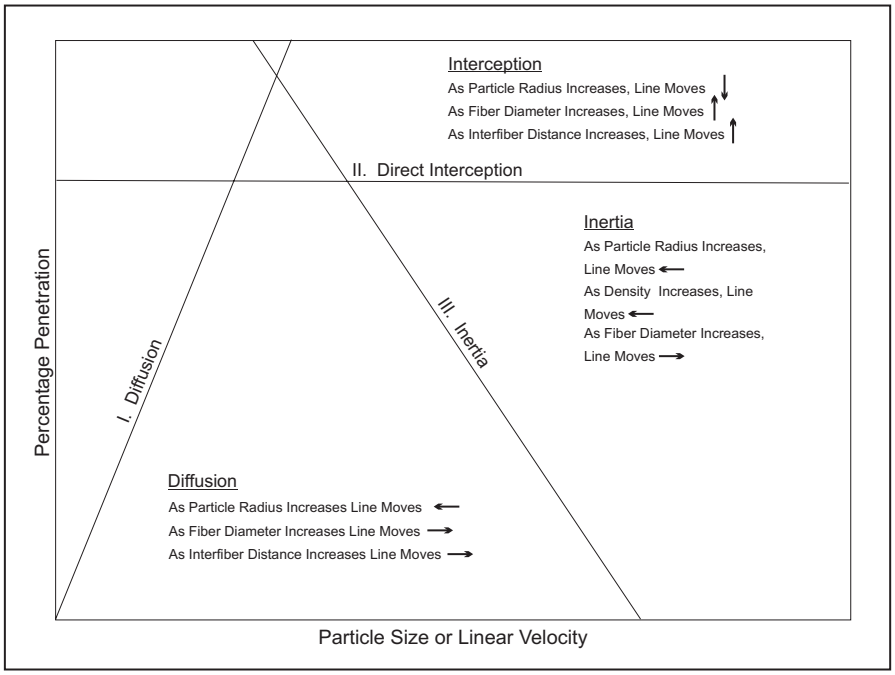

Figure 3.3 – The Effects of Inertia, Diffusion, and Interception on the Penetration-Velocity Curve

resistance, but it does not have much influence on particle removal efficiency until the medium becomes highly compressed.

The text in Section 3.2.1 that describes how fine particles are collected by filter elements applies to new clean filters. As particles collect on the surfaces of fibers or granules, or become entrapped in the interstices between upstream elements of the filter, the collected particles tend to form a coherent dust layer known as a filter cake. When this occurs, particle collection gradually shifts from media filtration (i.e., particle removal by individual filter fibers or granules) to cake filtration, and the filter shares the characteristics of the industrial cloth filter because the original structure now has the sole function of providing support for the filter cake and the filter cake completely takes over the particle separation function. This transformation produces two important changes: (1) efficiency increases in proportion to the increase in thickness of the cake; and (2) after formation of a coherent filter cake, resistance of the filter to airflow, which initially increased at a slow, steady rate as particles accumulated, now increases at an accelerating rate in response to additional particle deposition and narrowing of the pathways. When cake filtration begins, the filter rapidly reaches its terminal design airflow resistance. **Figure 3.4** shows typical pressure rise curves for two HEPA filters exposed to atmospheric dust. As shown, the long, slow pressure rise is clearly followed by a rapidly accelerating increase. The reason for the abrupt change is the onset of sieving, which takes over when the collected particles form a structure containing less space between the particles than the characteristic diameter of the particles being collected. When HEPA filters reach this stage, they must be replaced.

3.3 HEPA Filters

The original specifications for HEPA filter media and cased filters were concealed under a veil of military secrecy because of their use for chemical, biological, and radiological defense purposes. Following World War II, the Atomic Energy Commission (AEC) chose the military's HEPA filters as their principal device for particle removal in all exhaust air systems of nuclear facilities. Eventual expansion of the use of HEPA filters for nonmilitary applications required declassification and release of information about HEPA filter components and manufacturing methods (see Chapter 1). For this reason, military standards MIL-F-51068[3], MIL-F-51079[4] (filter construction and filter medium preparation), and MIL-STD-282[5] (filter testing) were issued in an unclassified format.

MIL-F-51068[3] and MIL-F-51079[4] have now been withdrawn by the Department of Defense and replaced by the American Society of Mechanical Engineers (ASME) *Code On Nuclear Air and Gas Treatment*, AG-1[2] and U.S. Department of Energy (DOE) Standard (DOE-STD-3020-97).[6] While MIL-F-51068[3] and MIL-F-51079[4] were active, the Edgewood Arsenal in Maryland prepared a procurement guide for military and

nuclear agencies, the *Qualified Products List* (QPL), which is based on exhaustive tests of manufacturers' filter media and filters. The QPL referenced available American Society for Testing and Materials (ASTM), Technical Association of the Pulp and Paper Industry (TAPPI), and other standard test procedures and equipment in its documentation of products. Edgewood no longer maintains the QPL, and only issues letters to manufacturers after qualification testing. Standards incorporating the major provisions of these military specification and qualification standards have been issued. Besides AG-1,[2] those most relevant to nuclear service applications include two standards administered by the ASME Committee on Nuclear Air and Gas Treatment (CONAGT), with participation from DOE and the U.S. Nuclear Regulatory Commission (NRC). These standards relate directly to HEPA filter applications in the nuclear industry (i.e., ASME N509, *Nuclear Power Plant Air Cleaning Units and Components*,[1] and ASME N510, *Testing of Nuclear Air Cleaning Systems*.[7]) The requirements of Nuclear Regulatory Guide 1.52 have been incorporated into these standards.[8] DOE prepared a series of filter standards to establish the performance and physical requirements for the filter media and cased filters used in DOE environmental protection applications and to set policy and quality assurance procedures for DOE filter test facilities (FTF).[6, 9, 10, 11]

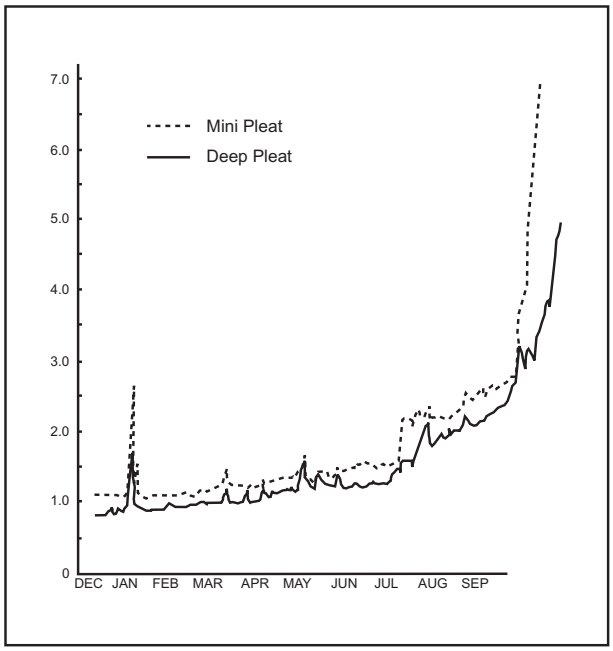

Figure 3.4 – Pressure Rise With Operating Time for Deep-Pleat and Mini-Pleat HEPA Filters

While HEPA filters and their properties are discussed in this section, the same facts apply to ULPA filters (except for differences in penetration, resistance, and media test velocity).

3.3.1 Filter Medium

Filtration theory implies that filter fibers must have diameters that are approximately the same as the aerosol particles to be removed. Therefore, the standard HEPA filter medium must have fiber diameters of 0.2 to 0.5 μm to remove submicrometer particles, and even smaller fiber diameters are necessary for the ULPA filter medium. All high-efficiency filters are now made from a mixture of glass fibers with carefully graduated diameters that provide the required particle retention efficiency without exceeding the maximum airflow resistance criterion and meet a wide variety of physical and environmental requirements. Typical glass fiber sizes used to manufacture HEPA filter media are shown in **Table 3.1**. Small amounts of chemicals are usually added to the glass fibers at the finish stage or after the medium is formed to impart desirable properties to the product (e.g., mildew resistance, water repellency, increased tensile strength of the glass paper). Plastic fibers in amounts less than 7 percent are sometimes added to the glass fibers to increase acid resistance. The ASME AG-1[2] Code for the HEPA filter medium is now a universal standard. This is primarily a performance standard, and the mixture of fiber sizes and specific additives and concentrations vary among manufacturers. Each filter manufacturer has a proprietary formula that qualifies the product for nuclear applications. Other nations have well-established criteria for HEPA filter paper that differ only to a minor degree from the current U.S. standard. Microfibers of plastic materials such as polystyrene, polycarbonate, and polyvinyl chloride also have been used for manufacturing HEPA filter media. Claims have been made that triboelectric charge effects, which are induced on these plastic materials during manufacturing, enhance filtration performance and save energy. Filters from these materials have found

some acceptance in European markets, but have been rejected by the nuclear industry because of flammability, high cost, and loss of performance under conditions such as high humidity, ionizing radiation, and exposure to atmospheric contaminants. A HEPA filter medium made from polyvinyl chloride fibers has been used in East European installations, but has been found unacceptable elsewhere for the reasons noted above.

Table 3.1 – Sizes of Glass Fibers for HEPA Medium

Glass Fiber Industry Code	*Average Fiber Diameter (micrometers)*
112	2.60 - 3.80
110	2.50 - 4.00
108B	1.20 - 2.40
108A	0.69 - 1.10
106	0.54 - 0.63
104	0.39 - 0.53
102	0.33 - 0.38
100	0.29 - 0.32

[Note: Glass Fiber Industry Code Numbers 100-110 were determined by the William Freeness Test. Code 112 was determined by the Manville Micronaire Test FG-436-202 and calibrated by the Brunauer, Emmett, and Teller Test (BET) Surface area.]

In addition to a limit on the organic material content of these filter papers (for fire and smoke control), other qualification criteria include:

- Not less than 99.97 percent retention of 0.3-μm test aerosol particles at a flow rate of 32 liters per minute through a paper area of 100 square centimeters;
- Clean airflow resistance not exceeding 40 millimeters of water at a filtration velocity of 320 centimeters per minute (0.053 meters per second);
- Average tensile strength of not less than 179 g/cm of width in either direction after exposure to 6.0 to 6.5×10^7 rads;
- Resistance to excessive strength degradation after exposure to high temperature [698 ± 82.4 degrees Fahrenheit (370 ± 28 degrees Celsius)] for 5 minutes and to wetting by immersion in water for 15 minutes; and
- Paper thickness of approximately 0.38 millimeters.

HEPA filter papers used for nuclear service currently provide collection efficiencies greater than 99.99 percent when tested with a 0.3-μm-diameter aerosol by the official U.S. test method contained in MIL-STD-282.[5] By increasing the fraction of fine glass fibers in the paper that are less than 0.25 μm in diameter, it is possible to obtain efficiencies in excess of 99.999 percent for 0.1- to 0.3-μm particles with a modest increase in filter resistance—typically about 25 percent. Performance standards for filter papers that are acceptable for use in nuclear-grade HEPA filters (as distinguished from performance standards for fabricated filter units that contain such materials) have not been considered important by some nuclear authorities. This view is based on the assumption that, unless the glass fiber filter paper has the required characteristics, the completed filter unit will not meet the acceptance criteria. This approach is reasonable, provided the filter paper is subjected to equivalent stresses after fabrication (e.g., shock, ionizing radiation, heat, fire).

The filter media production usually constitutes the definition of a batch for HEPA filter manufacturing. Typically, a batch of media can be used to make a lot of only 6 to ten 24- × 24- × 11 1/2-inch HEPA filters. Any selective filter testing (as opposed to 100 percent testing at the manufacturers' or FTF) should be done in accordance with ASQC-Z 1.4-1993, with the batch size set by the media batch production capability of the manufacturer. To utilize this standard, the user must also select the appropriate reliability. A value of 90 percent or greater is appropriate for nonsafety class HEPA use.[12]

3.3.2 HEPA Filter Construction

Most HEPA filter units are constructed the same way—a continuous length of filter paper is folded back and forth into pleats and corrugated separators are inserted between each fold. The assembly is then sealed into a rigid, open-faced rectangle. The components of a fabricated HEPA filter include: (1) extensively pleated filter medium, (2) separators that provide air passages and keep adjacent pleats apart, (3) a rigid filter case that encloses and protects the fragile filter medium, (4) sealants used to bond the filter pack (consisting of the assembled pleated medium and separators) to the filter case and to eliminate leak paths between filter pack components, and (5) gaskets attached to the filter case on one or both open faces to provide an airtight seal between the filter and the mounting frame. Some filter construction methods form the filter paper on the papermaking machine using an interval means to keep the adjacent folds apart, thereby eliminating a need for corrugated separators. These filters are called separatorless HEPA filters (see Section 3.3.3). **Figure 3.5** shows the assembled components of an open-face, deep-pleat HEPA filter with corrugated separators.

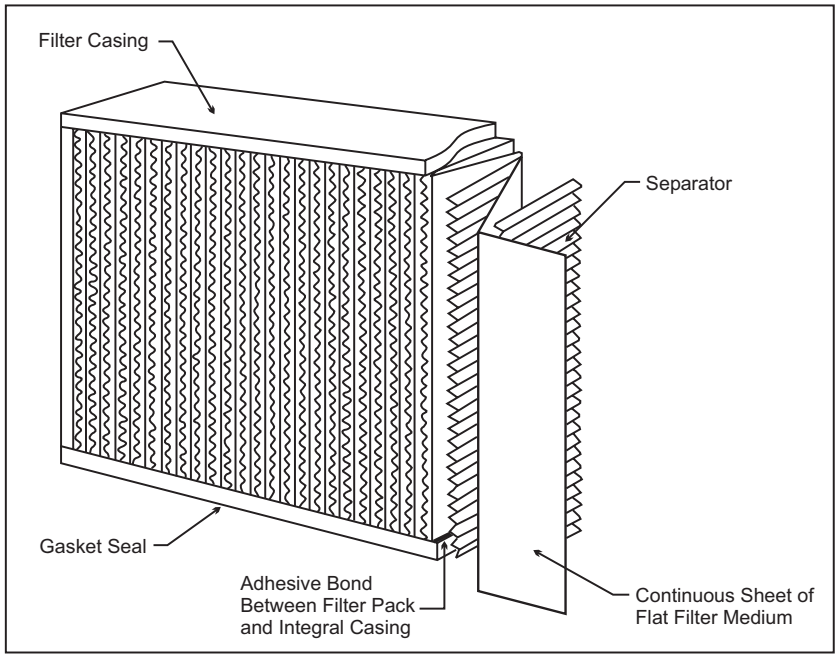

Figure 3.5 – Open-Face Deep-Pleat HEPA Filter-Type A Filter Pack

3.3.2.1 Separators

The most widely used material for the interleaved corrugated separators is tempered aluminum foil. The aluminum foils currently used for separators are identified as ASTM B209, *Standard Specification for Aluminum and Aluminum Alloy Sheet and Plate*,[13] alloys 1145-H19, 3003-H19, or 5052-H39, and are a minimum of 0.035 mm thick. When corrugating the aluminum sheet into separators, edges are often hemmed (turned back on themselves) to prevent the sharp edges from puncturing or tearing the part of the filter medium folded around the separator. Examination of disassembled filters aged up to 10 years showed deterioration of uncoated aluminum spacers to be common to all operating environments. Corrosion leads to adhesion of the spacer to the glass fiber medium. Levels of radioactive contamination on the evaluated filters appeared not to have affected the aging process. When greater chemical resistance is required, a plastic coating of an epoxy, thermo-set vinyl (or a similar compound) is applied to the aluminum sheet. [Note: If significant radiation is a concern, the use of organic materials may not be appropriate.] A dye is usually added to clear coating materials so that defects in the plastic coating can be easily detected. After drying to a film, the coating must be 0.0025- to 0.0050-mm thick, with no cracking, peeling, or delamination after corrugation. Experiments to determine the corrosion-resistance of certain all-plastic separators have been conducted and have generally found them to be

unacceptable because the corrugations tend to reflatten due to "plastic memory," particularly after exposure to moderately high temperatures. ASME AG-1[2] details additional requirements for corrugated aluminum separators.

3.3.2.2 Filter Case

The filter case is constructed of materials that correspond to the specific application, decontamination requirements, and considerations of disposal ease and cost. Commonly used case materials include fire-retardant plywood, chromized carbon steel, and alloys UNS S30400 and UNS S40900 stainless steels. The minimum thicknesses required to maintain rigidity under compressive loads ranging up to 1,400 pounds when the filter is clamped to a mounting frame, are 3/4 inch for wood and manufacturer's standard steel sheet gauge for steel. Grade A-C, American Plywood Association (APA) PS-1 fire-retardant-treated plywood is acceptable, but the "A" face must be on the inside, facing the pack, and should be assembled with this face completely coated with a sealant to close off any leak paths. The outer face should be filled and sanded as smooth as possible (for plywood). This is particularly important for nuclear plant workers whose gloved fingers and hands must not be punctured by splinters from a wooden frame when replacing filters in a contaminated area. For wooden case filters, case panels are to be joined with rabetted joints, which are assembled by gluing with an adhesive and double nailing or doubling screwing with coated box nails, corrosion-resistant plated screw nails, or flat-head wood screws. The end points of the fasteners must not penetrate the inside or outside surfaces of the case. Metal cases should be used in instances of potential wetting or high humidity at elevated temperatures and when the filter will be exposed to corrosive chemicals.

3.3.2.3 Sealants

Sealants used to provide a leak-free bond between the filter pack and case must be resistant to heat and moisture, noncombustible, fire-resistant, or self-extinguishing, as well as capable of maintaining a reliable seal under continuous exposure to design operating conditions. Rubber-based adhesives compounded with chlorine or bromine to ensure self-extinguishing when exposed to ignition are acceptable, but catalytically cured solid and foamed polyurethanes containing additives for combustion suppression are the sealants of choice for most filter manufacturers. Sealants should maintain their integrity over a wide temperature range. Filters designed to operate at temperatures above 392 degrees Fahrenheit (200 degrees Celsius) have been sealed with compression-packed glass fibers and with ceramic cements reinforced with glass fibers, and have been hardened thermally. Compression-packed glass fiber seals are sometimes found to be damaged after shipment. The ceramic seal is often too brittle to withstand commercial shipment. Room temperature vulcanizing silicone rubber sealants have been used successfully at operating temperatures only slightly lower than 392 degrees Fahrenheit (200 degrees Celsius).

3.3.2.4 Gaskets

Filters must be installed so that even the smallest volume of air or gas does not escape filtration; therefore, gaskets and alternative methods of sealing filter units to the mounting frames play a critical role in the satisfactory operation of HEPA filters. The most widely used sealing method is a flexible gasket attached to the open face of the filter case and pressed against the flat face of the mounting framework. The second most popular method is referred to as a "fluid seal." This method uses a channel formed or routed in the peripheral face of the filter case that is filled with a highly viscous, very low volatility, nonflammable (or self-extinguishing), odor-free, non-Newtonian fluid such as a silicone. The fluid flows around and over imperfections, but does not relax or separate from the surfaces it contacts. For installation, the matching framework face is equipped with a continuously protruding knife-edge that mates with the fluid-filled channel in the filter case. The reverse arrangement of a protruding knife-edge on the filter and a fluid-filled channel on the mounting frame also may be employed. These two mounting methods do not have interchangeable parts, so hybrid sealing systems are not feasible.

Gaskets must be oil- and ozone-resistant.[14] Closed-cell sponge gaskets composed of synthetic rubber (neoprene) that conforms to grade 2C3 or 2C4 of ASTM D1056, *Sponge and Cellular Rubber Products*[15] have been widely used. Gaskets should have a minimum thickness of ¼ inch and width of ¾ inch. The gasket face attached to the filter case should be free of any adhesion-resistant mold-release contaminant that may have been acquired when the gasket material was molded. To ensure an absence of residual mold release chemical, only cut surfaces are permitted on both gasket faces. Gaskets may be cut out of a sheet of stock as a single piece or may be made of strips joined at the corners by dovetail or other interlocking arrangement. Joints are sealed against air leakage with a rubber-base adhesive, usually the same adhesive used to attach the gasket to the filter case. Manufacturers of neoprene gaskets recommend a shelf life not to exceed 3 years.

3.3.2.5 Faceguards

To guard against damage from careless handling and faulty installation procedures, a recessed faceguard should be installed across both faces of the filter during fabrication. Woven or expanded metal with square openings approximating 1/3 inch to 1/2 inch on a side have proven satisfactory in largely preventing the inadvertent intrusion of hands or other objects into the filter pack. In addition, a metal mesh faceguard provides added strength to the filter unit, increasing resistance to transportation damage and shock overpressure. Faceguards should conform to either galvanized steel ASTM A740[16] or 304 stainless steel ASTM A580.[17]

3.3.3 Separatorless HEPA Filters

A separatorless HEPA filter design,[18] shown in **Figure 3.6**, is constructed without corrugated spacers inserted between the folds of the filter paper. Instead, a continuous sheet of filter paper is molded on the papermaking machine with corrugations at intervals. When it is folded back and forth upon itself, it becomes a self-supporting pack where the peaks of the interval corrugations of successive layers contact each other to form a honeycomb-like filter pack. For the same filter frame size, a separatorless filter contains more useful filter paper surface than the corrugated separator type, and thus provides greater airflow capacity at equal resistance.

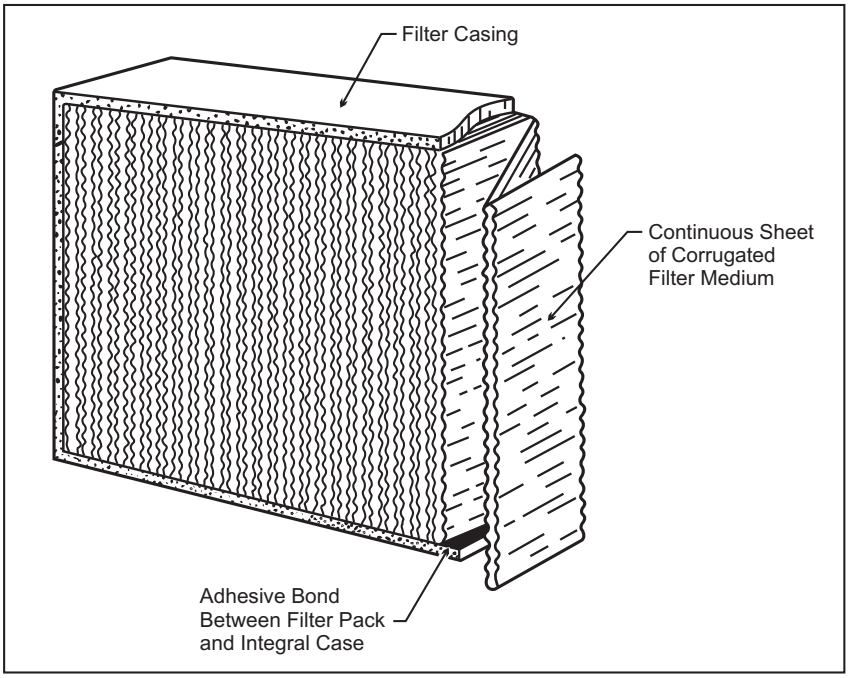

Figure 3.6 – Separatorless Style Filter-Type C Filter Pack

3.3.4 Mini-Pleat HEPA Filters

Mini-pleat filter construction methods utilize 7/8 to 1 1/4-inch-deep pleats with very narrow air spaces (1/8-inch) between, making it possible to pack more filter paper into the standard frame sizes than can be done with deep-pleat, corrugated separators, or even by using separatorless construction methods. Abutting folds are separated by threads, ribbons, tapes, strips of medium, or continuous beads of glass, foam, or

plastic spaced across the width of the medium. Mini-pleat filters contain almost twice as much filter paper as deep-pleat, corrugated separator filters of equal frame size (**Figure 3.7**) (see Section 3.3.2.3). They are rated to have an airflow resistance of 0.25 Kilopascals (kPa) when operated at 3,060 cubic meters per hour (m^3/hr), compared to the same resistance for a flow rate of 1,700 to -2,040 m^3/hr for deep-pleat corrugated separator filters. This gives the user of mini-pleat filters the option of utilizing space-saving higher airflow rates or extending filter life by operating at lower than rated airflow capacity. This is called downrating a filter.

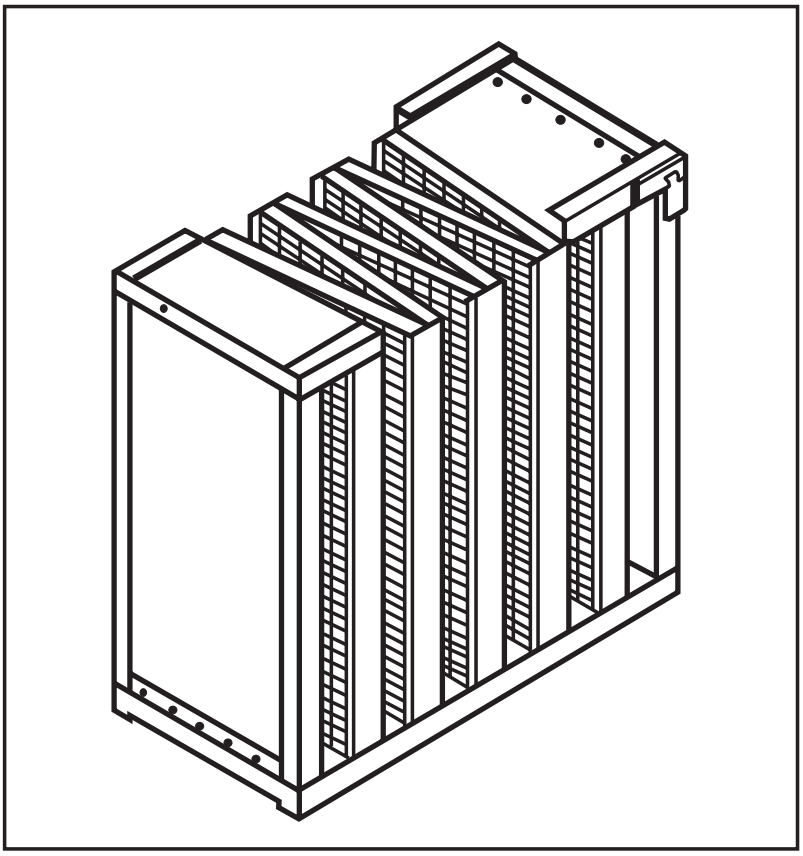

Figure 3.7 – Mini-Pleat (Thread Separator) Filter-Type B Filter Pack

When a mini-pleat filter rated for 3,060 m^3/hr is downrated to service at 1,700 m^3/hr, it theoretically should extend service life more than threefold before it reaches its final permissible resistance increase. In practice, filter life extension was found to be merely 1.6-fold because of dust bridging across the very narrow air passages between the paper pleats to form a filter cake covering the face area. An efficient prefilter might be used to prevent the formation of a surface filter cake and extend the service life of the mini-pleat filter.

Cased mini-pleat HEPA filters are formed from subcomponents assembled in a continuous "V" array. The subcomponents are panels that hold the pleated filter paper in metal frames approximately 23.62 inches wide, 11.81 inches high, and the depth of the paper pleats. A seal is made between framed filter packs and the standard frame using rubber-based adhesives, polyurethane, or some other plastic-based material, all of which are chemically compounded to inhibit their support of combustion.

Another mini-pleat filter design is formed by molding narrow longitudinal ridges into the wet filter paper at approximately 1-inch intervals while the paper is still on the papermaking machine, then folding the paper as it comes off the machine into mini-pleats that may be 2, 4, or 6 inches deep.[18] The filter pack is mounted into the filter case perpendicular to the airflow direction instead of mounting a number of shallow panels arranged inside the filter frame in a series of "V" formations The 6-inch-deep mini-pleat separatorless filter contains the same area of filter paper as the 12-inch-deep separator type. This type of filter has been placed into service, but there is no experience to report for nuclear applications.

3.3.5 HEPA Filter Classes and Sizes

In addition to being the workhorse filter for the nuclear industry, HEPA filters have found many important applications in the industrial, medical, pharmaceutical, and microelectronic sectors. These diverse applications have resulted in a number of industrial and governmental specifications. In general, these

specifications can be grouped into five construction grades and three performance types that provide a range of materials, manufacturing techniques, performance characteristics, and costs for different applications and user preferences. A standard covering the grades and types of HEPA filters has been issued as IEST-RP-CC001.3 by the Institute of Environmental Sciences and Technology.[19] This standard lists the following classifications.

3.3.5.1 Filter Construction Grades

Grade 1 – Fire-Resistant Filters. Filters of this grade must contain fire-resistant materials that may ignite when the filter is exposed to hot air or fire, but will not continue to burn once the ignition source is removed. The filter must exhibit a specified retention efficiency after exposure to no more than 700 ± 50 degrees Fahrenheit (371 ± 10 degrees Celsius). These filters comply with ASME AG-1, Section FC.[2]

Grade 2 – Semicombustible Filters. This grade costs less, but provides a lower level of protection against elevated temperature than Grade 1. For this reason, the user should evaluate application of this filter grade with the individual fire propagation hazards in the area of use. This filter type will fail at temperatures much lower than Grade 1. These filters comply with UL 586.[20]

Grade 3 – Combustible Filters. This grade covers filters required for certain service requirements that permit acceptance of the combustibility hazard. Grade 3 filters are readily combustible and are used only where high-value product recovery by incineration is desirable, disposal of volumes are critical, or exposure to chemical atmospheres might be incompatible with the use of a HEPA filter incorporating a medium of glass fibers. It should be noted that manufacture of a combustible HEPA filter medium formulated from asbestos and cellulose has been discontinued for more than a decade because of the hazards associated with its use and the resulting low demand. Specialty filter media for recovery of precious metals by incineration are still available. These filters comply with UL 900, Class 1.[21]

3.3.5.2 Filter Performance Levels

IEST-RP-CC001.3[19] classifies filter performance levels as:

Type A Filter Performance. Sometimes referred to as industrial types, these filters are tested for overall penetration at rated flow only. The filter retention (inverse of penetration) must exceed 99.97 percent for 0.3-μm particles. ULPA filters greater than this value can be obtained upon agreement between the buyer and seller.

Type B Filter Performance. In addition to the basic requirements for Type A filters, Type B units are certified free of significant pinhole leaks that would cause penetration at low flow rates. This type is tested at 20 percent of rated airflow with the filter encapsulated to disclose casing or gasket leaks. This type is sometimes referred to as "nuclear-type."

Type C Filter Performance. In addition to the performance required of Type A filters, Type C filters, are tested with the use of air-generated test aerosols at 80 to 100 feet per minute (fpm) face velocity. The units are fully face-scanned to detect and eliminate all significant leakage streams greater than 0.01 percent of the upstream test aerosol concentration to which the filter is subjected. This type is infrequently called "laminar-flow type."

Type D Filter Performance. In addition to the testing required for Type C filters, Type D filters should be retested at their rated airflow and penetration, which should be no more than 0.001 percent of the upstream concentration. The filter unit should be encapsulated so that all components, including the filter pack, frame,

and gasket, are subjected to testing. In the U.S., laser spectrometers are used to measure efficiencies of ULPA filters (>99.99999 percent).

Type E Filter Performance. Type E filters are designed, constructed, and tested in strict accordance with military specifications for HEPA filters intended for biological use.[22] This type is for application in air cleaning or filtering systems involving toxic chemical, carcinogenic, radiogenic, or hazardous biological particulates. This type is referred to as a "biological unit."

UL Class 1,[21] Type B filters are recommended for most nuclear applications, particularly in single-pass systems. These units comprise a large part of those manufactured by industry and are used extensively in nonnuclear industries as well. UL Class 1, Type C filters are common in clean room applications where laminar flow requirements are coupled with low particle penetration.[23] UL Class 1, Type D filters presently are used in printed-circuit or microprocessor clean rooms.

Figure 3.8 – Enclosed HEPA Filter

3.3.5.3 Enclosed Filters

Most HEPA units are used in the open-face configuration (Figure 3.1). When used in this manner, the filter is secured firmly to a rigid framework by a pressure device such that a leak-free seal exists between the unit and the framework. The HEPA filter may also be placed completely within an enclosing casing that is equipped with nipples at both ends for attachment to existing ventilation ducts (**Figure 3.8**). Enclosing casings may be metal or plywood, but care must be taken to ensure the casing material is compatible with Underwriters Laboratories, Inc., (UL) requirements for resistance of the filter to heated air and flame.[22] The enclosing casing forms the leak-free pressure boundary in addition to the filter case, and care must be taken to ensure that it is treated as an encapsulated design for both performance and leak-acceptance testing. Enclosed HEPA units have significantly higher resistance to airflow than the open-faced design because of the added restrictions of the duct transitions.

Enclosed filters are sometimes referred to as encapsulated (nipple-connected, closed-face, or self-contained) HEPA filters. They are not recognized by applicable codes (i.e., AG-1[2]) and standards and fail to meet all the requirements contained in DOE Standard DOE-STD-3020-97[6]. The most serious deficiency is failure to meet the requirement for uniform velocity across the filter face. This can invalidate the in-place filter leak test.

The enclosed filter and its casing are often misused as part of a nuclear ventilation system pressure and confinement boundary. Enclosed HEPA filters are not specifically designed, analyzed and tested to meet either the housing or the ventilation ducting containment requirements of nuclear codes. When designing and constructing new nuclear facilities, enclosed HEPA filters should not be used in nuclear ventilation systems. When an installed ventilation system is being modified or upgraded, consideration should be given to replacement of enclosed HEPA filters with nuclear grade housings containing ASME AG-1 certified filters. A technical justification should be developed where the enclosed filter is not replaced with a housing.

Figure 3.9 – Open-Faced Cylindrical Axial Flow HEPA Filter

3.3.5.4 Cylindrical Filters

Cylindrical filters may be either open-faced cylindrical axial (**Figure 3.9**) or radial flow (**Figure 3.10**). Filters fabricated with cylindrical cases appear to offer substantial advantages such as easier mounting in circular ducts, but in practice they have been found to have disadvantages attributable to manufacturing difficulties, escalated costs, and increased susceptibility to leakage. However, cylindrical filters offer significant advantages regarding simplified gasketing and automated filter-changing techniques. In the United Kingdom, a "push-through filter system" has been developed that permits changing of cylindrical filters by loading a clean filter that has gaskets on the top and bottom filter flanges into the filter housing tube from the "clean side," then pushing it through until it ejects the old contaminated filter into the "dirty side" of a cell or glovebox. A cylindrical filter of somewhat different design, but with similar characteristics, has been developed in the United States.

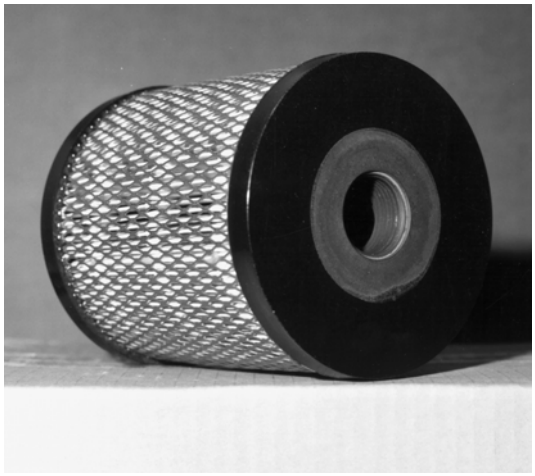

Figure 3.10 – Radial Flow HEPA Filter

3.3.5.5 Filter Sizes

The physical dimensions shown in **Table 3.2** have been standardized for the HEPA filters currently used in nuclear service and by U.S. Government agencies. [Note: DOE STD-3020-97 addresses more sizes than are indicated here, and may be used in addition to the table shown below.] Other sizes can be manufactured and purchased, but are considered "special orders." Nonnuclear applications (clean rooms, biological safety cabinets, medical facilities) generally use the same filter height and depth dimensions shown in Table 3.2, but may have lengths up to 72 inches. Special HEPA filter configurations for computer applications use many different sizes and shapes depending on the volume available within the computer cabinet. As many as 1,000 different configurations exist, each specific for a respective manufacturer, model, type, or size of computer.

Table 3.2 – Nominal Sizes and Ratings

Number Designation	*Size*		*Minimum Rated Airflow*		*Maximum Resistance*	
	Inches	*Millimeters*	*Standard Cubic Feet per Minute (scfm)*	*m^3/hr*	*Inches Water Gauge (in.wg)*	*Pascal (Pa)*
1	8 × 8 × 3 1/16	203 × 203 × 78	25	42	1.3	325
2	8 × 8 × 5 7/8	203 × 203 × 149	50	85	1.3	325
3	12 × 12 × 5 7/8	305 × 305 × 149	125	212	1.3	325
4	24 × 24 × 5 7/8	610 × 610 × 149	500	850	1.0	250
5	24 × 24 × 11 1/2	610 × 610 × 292	1,000	1,700	1.0	250
6	24 × 24 × 11 1/2	610 × 610 × 292	1,250	2,125	1.3	325
7	24 × 24 × 11 1/2	610 × 610 × 292	1,500	2,550	1.3	325
8	24 × 24 × 11 1/2	610 × 610 × 292	2,000	3,400	1.3	325
9	12 × 12 × 11 1/2	305 × 305 × 292	250	424	1.3	325

[Note: AG-1 currently allows for the qualification of the largest size to apply smaller size filters, i.e., a size 5 filter can be used to qualify a size 4 filter. It has been brought to the attention of the CONAGT that the

qualification of the size 4 filter listed above may need to be independent of the size 5 qualification. Readers should check revisions to AG-1 post 2003].

3.3.5.6 Filter Weight

The weight of a filter unit is an important factor in design and maintenance. **Table 3.3** lists the weight of clean, open-faced filters and enclosed filters of rectangular design. For design purposes, the weight of a dirty filter that is ready for change-out is approximately 4 pounds heavier per 1,000 cfm of rate capacity. Because many applications employ multiple filter units in banks that are as many as 6 to 10 units in height, minimal filter weight, without loss of performance, is critical to the ease of original installation and replacement.

Table 3.3 – Weight of Unused HEPA Filters

Filter Size (inches)	*Nominal Airflow Capacity (cfm)*	*Approximate Weight (pounds) of Filters With*	
		Wood Case	*Steel Case*
Open-face			
8 × 8 × 3 1/16	25	2	3
8 × 8 × 5 7/8	50	3.6	5.8
12 × 12 × 5 7/8	125	4.8	7.3
24 × 24 × 5 7/8	500	17	22
24 × 24 × 11 1/2	1000, 1250, 15000	32	40
Enclosed			
8 × 8 cross-section	25	5	9
8 × 8 cross-section	50	7	10.5
12 × 12 cross-section	125	17	20
24 × 24 cross-section	500	64	72
24 × 24 cross-section	1000	78	95

3.3.6 HEPA Filter Performance Characteristics

3.3.6.1 Airflow Resistance

Resistance to airflow (pressure drop) of a nuclear-grade, 1,000 cfm capacity filter should not exceed 1 in.wg when tested at rated airflow (see Table 3.2 for additional filter capacities and pressure drops). The pressure drop for ULPA filters is frequently greater than for standard HEPA filters, and this feature is subject to negotiation between customer and vendor. Resistance increases with particulate loading. A new nuclear-grade filter is qualified by a wet overpressure test up to 10 in.wg for 1 hour; however, this should not be confused with normal in-service operating pressures. Normal in-service pressures should be limited to 3 to 5 in.wg above startup pressure.

3.3.6.2 Dust-Holding Capacity

The dust-holding capacity of a filter is a function of the type, shape, size, and porosity of the filter as well as the aerosol size, shape, and concentration characteristics to which the filter is exposed. As HEPA filters are designed to filter out the smallest particles, they can accommodate only extremely light particulate loadings without experiencing a rapid pressure drop increase. HEPA filters are affected particularly adversely by fibers, lint, and other materials that exhibit a large length-to-diameter ratio because they tend to bridge the air entrance gaps between the adjacent pleats of medium, thereby preventing particles from accessing the full depth of the filter. A HEPA filter can be protected by a prefilter capable of removing the bulk of large particles and fibers, thereby extending its useful lifetime. As noted earlier, a dust-holding capacity of 4 pounds per 1000 cfm of rated airflow capacity may be assumed for design purposes. This is probably a conservative figure for granular dusts, but may overestimate the filter's dust-holding capacity for metal fumes.

An increase in dust accumulation on the filter medium both improves filtration efficiency and increases resistance to airflow. One of the limitations of HEPA filters is their low-dust-holding capacity and their need for frequent replacement when exposed to high aerosol concentrations. The pressure rise curve experienced by HEPA filters also depends on the particulate composition of the atmosphere to which it is exposed. A filter installed in a moderately contaminated urban area will show as much as a six-fold increase in resistance in a year's time, whereas a unit in a clean room application may last ten years or longer before reaching a six-fold pressure increase. The use of a prefilter (described in Section 3.4) increases the service life of HEPA filters and helps make the combined filtration system cost effective.

Tests conducted at the Harvard Air Cleaning Laboratory[24] explored the pressure buildup of filter units under urban conditions. During testing, commercial deep-pleat, aluminum-corrugated separator HEPA filters and mini-pleat HEPA filters, all 24 × 24 × 11.4 inches in size, were exposed side-by-side to an urban atmosphere while being operated continuously at rated and downrated airflow without prefiltration. The downrated mini-pleat HEPA filters did not fulfill the theoretical prediction of three times the service life of a deep-pleat U.S. HEPA filter when both were operated at 1,700 m^3/hr; instead, an extended service life of about 1.6 times was achieved. This shortfall was attributed to dust and lint bridging the narrow openings between the pleats of the mini-pleat unit (the pressure rise curves of the two filter types are illustrated in Figure 3.4). Extremely high concentrations of soot and dense particular matter from fire conditions may overwhelm both the prefilters and the HEPA filters, thereby inactivating the total system. For this reason, some practical means of suppressing smoke before it reaches the filters is required. Water curtains, electrostatic precipitators, inertial separators, or other devices have been utilized for this purpose with varying success.

3.3.6.3 Shock and Blast Resistance

The resistance of HEPA filters to shock and blast is important because these filters are often the final barrier between a highly contaminated enclosure and the environment. Shock stress may occur from disruptive natural phenomena (e.g., earthquakes) or from internal and external explosions.

Early tests at the Harvard Air Cleaning Laboratory showed that filter units of 1950s vintage sustained moderate damage at 6-inch-mercury [2.95 pounds per square inch (psi)] overpressure, and complete destruction at 10-inch-mercury overpressure (4.91 psi). The U.S. Navy determined that filter units subjected to an overpressure simulating an atomic explosion (50-millisecond duration) failed at variable values depending on the face and depth dimensions. The values listed in **Table 3.4** are the maximum shocks that can be tolerated without visible damage or loss of filtration efficiency. Specific conclusions reported from the Harvard study included: (1) filters with faceguards on both faces had about a 40 percent greater resistance to shock than those without faceguards; (2) dirt-loaded filters had 15 percent less shock resistance than clean filters; (3) the smaller the filter face area, the greater the resistance to shock; (4) the greater the filter depth, the greater the resistance to shock. At overpressures exceeding those listed in Table 3.4 by 0.5 to 1.0 psi, the filter medium ruptured or experienced cuts on the downstream face. At pressures 2 psi greater than those listed in Table 3.4, extensive damage occurred. At pressures above 5 psi, the entire filter pack within the frame was dispersed. No significant differences were found between successive tests of increasing shock force on the same filter and a one-shot test of the same force—both procedures produced the same failure modes. Using the data on shock overpressure resistance versus face depth and dimensions, Burchsted[18] produced the chart shown in **Figure 3.11**. Los Alamos National Laboratory (LANL) repeated some of the Navy shock tests and arrived at similar values for loss of structural integrity. In addition, the researchers discovered that, although the break point for the units was similar in value, the specific values for rupture were highly dependent on the filter source. Tests on HEPA filters constructed with a special scrim-backed glass-fiber filter medium showed that this filter retained an efficiency in excess of 99.92 percent for the test aerosol after exposure to a differential pressure of 7.5 kPa and a temperature of 932 degrees Fahrenheit (500 degrees Celsius).

LANL also conducted tests on filter units under simulated tornado pressure loadings (represented by a slower pressure buildup, but sustained for a longer period of time). Damage levels in these tests were identical to those found for shock overpressures of the same level, but shorter duration. Filters of U.S. and European manufacture gave comparable results. LANL found separatorless filters had only two-thirds the structural strength of their separator-containing counterparts when subjected to tornado conditions, and only one-half the strength under shock overpressure exposures. However, another series of seismic simulation tests conducted by Wyle Laboratories found that separatorless filters successfully withstood seismic shocks equivalent to 12 moderate (less than 4.0 Richter scale) earthquakes when correctly mounted in well-designed housings. During these tests, the filters were operated at design flow rate of 1,700 m^3/hr, but under cumulative (multiple earthquake) worst-case conditions. The units were challenged continuously with heterogeneous test aerosol, with no demonstrated resulting loss of efficiency for the filter, housing, or fluid seal between the filter and housing. Current NRC regulations do not require seismic testing for filters, but do allow mathematical analysis of the housing, with the sole consideration being the weight of the filter(s) in the housing.

Table 3.4 – Shock Overpressure Resistance of Open-face HEPA Filters[25]

Filter Dimensions (inches)		*Overpressure (psig)*		
			Recommended Design Limit for Used Filters	
Face	*Depth*	*Overpressure at Failure* [a]	*With Faceguards*	*Without Faceguards*
8 × 8	3 1/16	3.7	[b]	2.0
8 × 8	5 7/8	4.5	[b]	2.5
12 × 12	5 7/8	3.6	[b]	2.0
24 × 24	5 7/8	2.2	1.7	1.2
24 × 24	11 1/2	3.2	1.7	1.8

[a] Clean filter with 4 by 4 mesh faceguards on both faces.
[b] Faceguards not available.

3.3.6.4 Heat from Fire and Explosion

Grade 1, fire-resistant filters are fabricated from a glass medium with flame-inhibited or self-extinguishing adhesive or sealant, aluminum alloy separators, and fire-retardant wood or metal frames. Nevertheless, the material that collects on the filters poses special fire and explosion hazards when it contains substantial amounts of organic or pyrophoric substances. Fires from this source can produce undiluted hot gases that attain temperatures as high as 1,830 degrees Fahrenheit. The softening point of glass fibers used in currently manufactured HEPA filter media is about 1,250 degrees Fahrenheit, and direct impingement of a

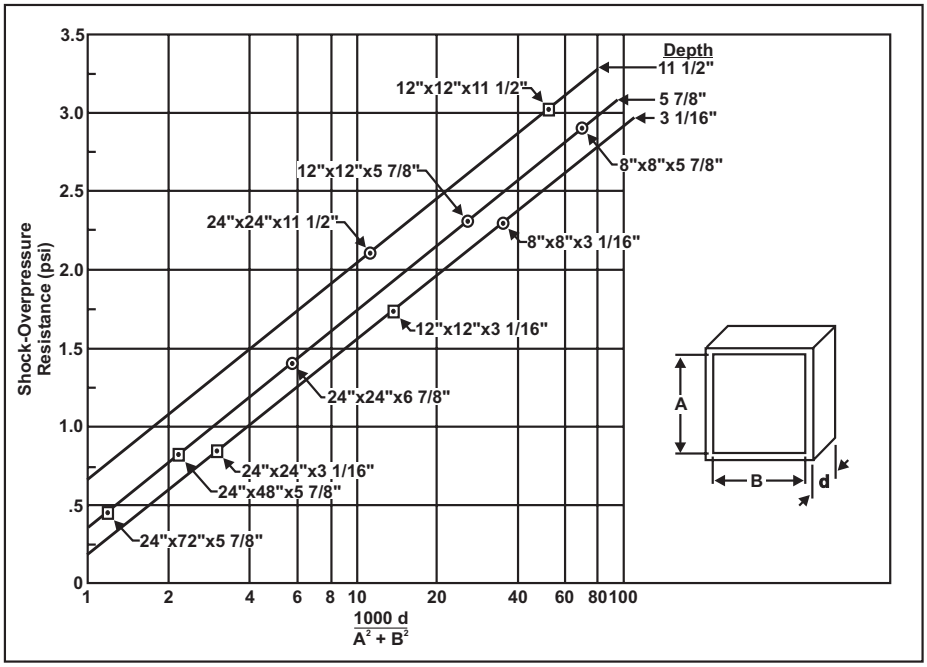

Figure 3.11 – Shock-Overpressure Resistance of Clean HEPA Filters (Separator Type) as a Function of Size

1,700 degrees Fahrenheit flame will cause immediate melting. A glowing solid particle that lands on HEPA filter media will perforate it if it continues to burn. Explosions that could destroy or seriously damage the filter from high pressure, shock waves, or an excessive temperature excursion can also occur from ignition of organic or pyrophoric dusts, vaporized organics, or combustible gas products of combustion. The spark and flame arresters installed upstream of the filters are designed to alleviate this problem. Spark arresters constructed of coarse glass fibers provide reasonable protection at low cost. Spark and flame arresters constructed of grids or heavy wire mesh that provide graduated openings are required to provide a 2-minute delay before flame penetration.

The recommended limitation for filter operating temperature is 250 degrees Fahrenheit.[19] The filter media binder is assumed to be the HEPA filter component that is most susceptible to failure resulting from elevated temperature. The binder begins burning off at 350 degrees Fahrenheit.

Commonly used sealants are also highly susceptible to elevated temperatures. **Tables 3.5 and 3.6** list continuous-service temperatures for wood- and steel-cased filters. At temperatures well below the char point of an elastomeric sealant, the sealant loses its shear strength, resulting in a reduction from approximately 6,000 kPa at room temperature to a low of 100 kPa at 300 degrees Fahrenheit. HEPA filters exposed to thermal stress will begin to release contaminates at temperatures above 300 degrees Fahrenheit.

Table 3.5 – Recommended Limited Service Temperatures for Steel-Framed Fire-Resistant HEPA Filter Units Sealed with Elastomeric Adhesives

Sealant Used	Temperature to Which Filter was Exposed (degrees Fahrenheit)				
	Up to 10 Min [a]	Up to 2 Hours	Up to 48 Hour	Up to 10 Days	> 10 Years
HT-30-FR [b]	750	350	325	300	260
Z-743 [c]	750	325	300	275	200
EC-2155 [d]	750	250	220	200	200
Polyurethane foam	750	325	300	275	230

[a] Some reduction in efficiency may occur after 5 minutes of exposure.
[b] Goodyear.
[c] Pittburgh Plate Glass.
[d] Minnesota Mining and Manufacturing (3M).

Table 3.6 – Recommended Limited Service Temperatures for Wood-Framed Fire-Resistant HEPA Filter Units [a]

Frame Material	Temperature to Which Filter was Exposed (degrees Fahrenheit)				
	Up to 10 Min	Up to 2 Hours	Up to 48 Hours	Up to 10 Days [b]	> 10 Years [b]
3/4-inch-thick plywood [a, c]	750	300	275	200	180

[a] Subject to sealant limitations given in Table 3.5.
[b] Maximum temperature of 120 degrees Fahrenheit where relative humidity is 75 percent or higher.
[c] Exterior grade, fire-retardant-treated.

3.3.6.5 Moisture and Corrosion Resistance

Moisture

Water exposure is unquestionably an important factor leading to the deterioration of HEPA filters and their degradation to 0 percent efficiency when coupled with higher pressure drop. HEPA filters become weak and plug with water. One of the most common events is when people think no detrimental effects occur as a result of repeatedly wetting the filter and drying it. Tests have shown that repeat wetting and drying of a HEPA filter will cause the loss of half its strength. There also are very strong effects of operational time on the behavior of HEPA filters under wet conditions. Tests have shown that the binder starts to get soft and

dissolves at high differential pressures. One of the most serious issues dealing with HEPA filters in DOE facilities is their potential for rupture during accidental fires and the resulting release of radioactive smoke. The water spray systems in the HEPA filter housings used in nearly all DOE facilities for protection against fires were designed under the assumption that the HEPA filters would not be damaged by the water spray. The most likely scenario for filter damage in these systems involves filter plugging by the water spray, followed by fan blowing out of the medium.

Water repellency is important for units that are used in laboratory and industrial applications. Repellency is measured by the height of a water column that does not leak through the paper. A water repellency of 20 in.wg is required for filters that are operated in high-humidity conditions and stream-containing atmospheres. In the absence of adequate water repellency characteristics, liquid contaminants that collect on the filter paper can be carried through it by air pressure or capillary action and become re-entrained into the downstream air.

Humidity

Numerous German studies from the Nuclear Air Cleaning Conferences during the 1970s and 1980s showed that high humidity can result in high pressure drop and a corresponding decrease in media strength, the combination of which can lead to structural damage and a loss of filter efficiency. These tests showed the most frequent failure mode is rupture of the downstream pleat. With particle deposits, the filter would absorb water at a lower relative humidity (RH) and would rupture even with a demister installed to protect the filter. The tests further showed that filter failure under the humid air condition occurred at differential pressures that were one-third to one-fourth the comparable values for filter failure under dry conditions. The tests also showed that the tensile strength of a new filter is reduced by a factor of three due to humidity exposure.

Previous studies have shown serious problems exist with HEPA filter wetting [22, 26, 27, 28] (Bergman, Fretthold). HEPA filters exposed to wetting or high humidity must be removed from service before an accident can happen because the strength of the filter may be seriously compromised (see Appendix C).

Corrosion

For many industrial applications, a moisture- and chemical-resistant filter should be capable of withstanding attack by acids, most gas-phase alkalis, and solvent droplets and vapors. However, fine glass fibers have poor resistance to hydrogen fluoride (HF), only moderate resistance to other concentrated acids, and fair resistance to water and milder chemical corrosive agents. On occasion, corrosive chemicals in the airstream will condense on the filter medium, accelerating the attack on the finest fibers. Airstreams containing some residual HF and droplets of liquid carryover after treatment by an alkali scrubber produce a severe attack on the glass fiber filter medium.

In AEC-sponsored research to develop an HF-resistant filter medium, Johns-Manville Corporation formulated a special glass fiber for the purpose. However, the high costs associated with the finished paper, together with a high shot content, large fiber diameter, and production difficulties, resulted in only marginal benefits and precluded the glass fiber's adoption for industrial use. Media made from ceramic fibers (a combination of silicon dioxide and aluminum oxide) were found to have higher HF resistance than glass, but in this case as well, the fibers have not been produced with diameters small enough to provide the required efficiency characteristics. A U.S. filter manufacturer has developed an HF-resistant, high-efficiency glass fiber paper containing up to 7 percent of a temperature-resistant polyamide (nylon). Filter units incorporating this medium were exposed to 2 to 3 parts per million (ppm) of HF and 100 ppm of nitric acid in a humid atmosphere. The test results were considered successful, and the medium was incorporated into filters used at a nuclear energy plant. The service life of the new filters was three to four times longer than

that of previously used filters that were manufactured with a glass-asbestos filter medium. The adoption of plastic-coated separators has contributed significantly to extending the life of HEPA filters under corrosive service conditions.

A wooden case is more resistant to chemical attack than is a steel case. Exterior-grade material should be specified, however, because interior-grade plywood is unsuitable for outdoor filter operation or for continuous interior operation in very humid (90 to 100 percent RH) environments at temperatures above 131 degrees Fahrenheit (55 degrees Celsius), particularly when operation and shutdown periods alternate and the environment returns to room temperature. During cooling, moisture may condense on the surfaces of the wooden case and infiltrate the structure, causing swelling of the elements and a separation between the seal and frame. Most exterior-grade wood products employ a moisture-impermeable phenolic resin bonding agent, while water-soluble urea-formaldehyde resins are used as bonding chemicals for interior-grade products. Stainless steel is recommended when a metal frame is required. Mildew growth may occur on the sealant and frame interface in high humidity while the filter is in storage, causing filter degradation.

Seepage of particles collected on HEPA filters never occurs unless the filter paper becomes thoroughly wet. For this condition, different entrainment mechanisms are involved.

3.3.6.6 Radiation Resistance

Most applications for HEPA and ULPA filters in the electronics and other industries do not involve exposure to high levels of ionizing radiation. However, post-accident cleanup by nuclear reactor containment systems and some fuel reprocessing applications of facilities can involve exposure of filters to high levels of radiation. One reactor accident scenario estimates an integrated beta-gamma dose to the engineered safety feature (ESF) filters of 3.5×10^7 rads. This radiation level can result in a significant reduction in tensile strength, an increase in penetration, and an impairment of water repellency. Tests of commercial HEPA filter media before and after radiation exposures up to a level of 4.5×10^7 rads were made at the Savannah River Site. The filter papers were tested at a face velocity of 28.2 feet per minute, which is more than five times the design service velocity and greater than any velocity anticipated under post-accident conditions. Test results showed up to 64 percent loss of strength and penetration increases of 4 to 50 percent. When samples were tested for degradation of water repellency as a function of gamma dose, half of the samples showed hydrophilic action in less than 10 seconds and the remainder in 60 to 100 seconds. The current code, ASME AG-1[2], calls for filter papers to support a 6-inch column of water after exposure to an integrated gamma dose of 6.0 to 6.5×10^7 rads. Other tests exposed small HEPA filters to a range of radiation doses, and then exposed them to a flowing steam-air mixture to determine the residual resistance to plugging and rupture. Plugging was found to be inversely proportional to radiation dose (e.g., filters exposed to 6×10^8 rads ruptured in 100 seconds) but a sample irradiated to only 1×10^8 rads withstood the steam-air mixture for 250 seconds before failure. Despite some blinding (water vapor interference with particulate capture), unirradiated samples did not rupture under the same flow regimen. These tests verified the need to provide filter systems with reliable protection from wetting wherever exposure to spray or condensing steam is possible, particularly when water exposure may be coupled with high levels of radiation.

3.3.7 HEPA Filter Performance Testing for Nuclear Service

HEPA filters for nuclear service undergo a qualification procedure and two testing regimens. The first regimen consists of a stringent visual examination and penetration tests at the place of manufacture. The second regimen is an in-place leak test performed at the place of utilization. DOE requires independent inspection and penetration tests at the designated DOE FTF prior to installation at its final destination. [For a detailed discussion of qualification procedures, see Section 8.2, "Proof of Design – HEPA Filter

Qualification for Nuclear Service."] The state of DOE testing and the test facility are discussed in DNFSB Tech-23.[29]

The manufacturer's testing regimen involves two distinct phases: (1) a quality control routine to ensure careful manufacture of the product, and (2) a series of tests to verify filter compliance with standards and performance criteria related to collection efficiency and resistance to airflow. When all factors are within the tolerance limits set by applicable specifications, the manufacturer certifies that each filter unit meets the specification acceptance criteria.[30]

In addition, DOE mandates independent inspection and penetration testing for all filters purchased. Testing is currently required for filters installed in hazard Category 1 and 2 facilities that perform a safety function, and a statistical approach for the balance.[31] The filters are tested for compliance with the requirements for physical characteristics, efficiency, and airflow resistance. This testing is conducted at the DOE-supported FTF before the filters are released to the customer's facility. Filters failing to meet the FTF specification acceptance criteria are rejected and turned over to the purchaser for disposition; typically, they are returned to the manufacturer for credit. Both DOE and the NRC do not permit repairs of HEPA filters intended for nuclear service.

3.3.7.1 Manufacturers' Filter Qualification Test Protocols

Penetration (Efficiency)

For HEPA filters, particle removal is usually expressed as collection penetration (treated air concentration ÷ untreated air concentration × 100) or as penetration (100 - efficiency). Concentration may be expressed by particle count per unit air volume (emphasizing the smallest particles present), particle weight per unit air volume (emphasizing the largest particles present), ionizing radiation intensity per unit volume of air (particle size effect indeterminate), or by light-scattering intensity per unit air volume (emphasizing small particle sizes). Sometimes filter penetration is expressed as a decontamination factor (DF), the ratio of the untreated air concentration to the treated air concentration, (e.g., a 99 percent collection efficiency is the same as a DF of 100, and is equal to a penetration of 1 percent). The DF descriptor is most frequently used when ionizing radiation is the concentration descriptor.

Airflow Resistance

The resistance of a filter to airflow, often expressed as "pressure drop" and "back pressure," is almost always measured as the height of a water column that exerts an equal pressure. This practice probably was borrowed from hydrology, where the unit has a more direct relationship, as well as the use of water-filled manometers to measure air filter resistance. The characteristic flow regime through HEPA filter media is aerodynamically described as laminar. For this reason, the airflow resistance of these filters changes in direct proportion to changes in air volume throughput (expressed as feet per unit area), even though the air approaching the filter may be turbulent. The direct proportionality of resistance to flow rate is not a characteristic of prefilters. For prefilters, resistance is a power function of airflow rate with an exponent larger than 1, but not exceeding 2.

The test protocols used to qualify HEPA filters for nuclear service are described below. Testing of all new filters intended for nuclear service in the United States is conducted with a 0.3-μm test aerosol in a rig called a Q107 penetrometer that was designed by the U.S. Army Chemical Corps during the 1950s. Construction and operation are described in MIL-STD-282, Method 102.9.[5] The complete penetrometer consists of test aerosol generator, an instrument that measures the size and uniformity of the particles formed, a clamping device to seal the filter under test into the test rig, a total scattering photometer to measure test aerosol penetration, and a manometer to measure filter resistance at rated airflow rate.

The Q107 penetrometer, used for filters of 1,700 m^3/hr rated capacity, exceeds 40 feet in length (**Figure 3.12**). The Q76 penetrometer, which tests smaller filters and is based on the same principle of operation, is considerably smaller. When testing a 1,700 m^3/hr filter, about 2,400 m^3/hr of outside air is drawn into the system and divided into 3 parallel ducts that carry approximately 170, 500, and 1,350 m^3/hr, respectively. The remainder, approximately 350 m^3/hr, is exhausted through another path. The 170 m^3/hr duct contains electric heaters that raise the temperature of the air to 374 degrees Fahrenheit (190 degrees Celsius). Other electric heaters keep the liquid test aerosol reservoir heated to approximately 392 degrees Fahrenheit (200 degrees Celsius). The test aerosol is vaporized from the reservoir into the heated airstream as it sweeps across the liquid surface and is mixed with the air in the 500 m^3/hr duct that contains both cooling units and reheaters to provide partial dilution and temperature control of the test aerosol vapor stream. The temperature of the test aerosol liquid reservoir establishes the mass concentration of the aerosol; a liquid temperature of 392 degrees Fahrenheit (200 degrees Celsius) produces 80 to 100 μg/L of test aerosol when diluted with 2,400 m^3/hr of air. The particle size of the aerosol is determined by the temperature differential between the evaporated test aerosol vapor stream and the much cooler diluting stream—the greater the temperature differential, the smaller the resulting particle size. Temperature fluctuations in both airstreams influence particle size distribution; the greater the fluctuation, the wider the size distribution. The combined flows from the 170- and 500-m^3/hr ducts are diluted further with the air in the 1,350-m^3/hr duct to produce the final aerosol concentration used for filter testing. Baffles are placed upstream and downstream to help mix the aerosol entering and leaving the filter being tested.

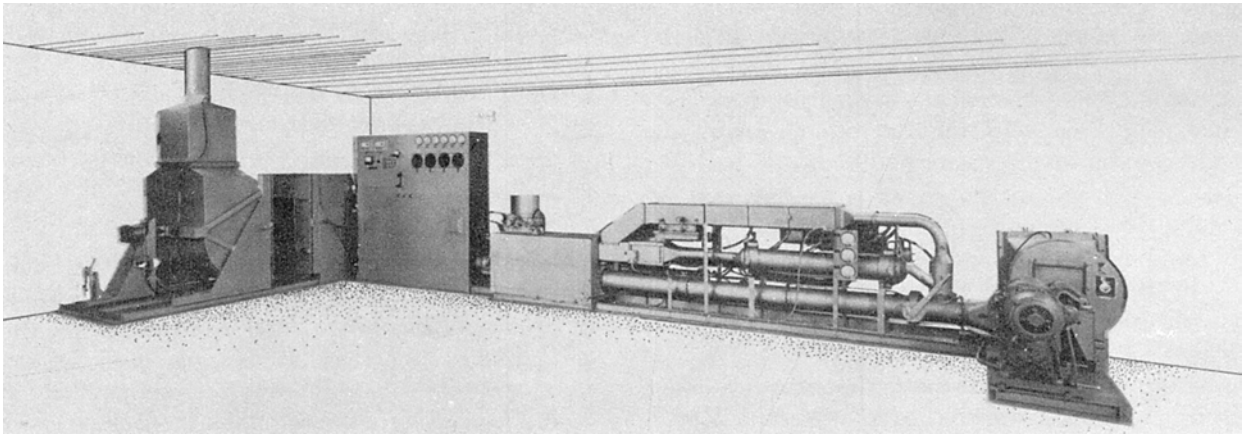

Figure 3.12 – Q107 Penetrometer

The test aerosol particle size is determined by passing a sample through an optical particle-sizing instrument called an OWL[32] and noting the degree of polarization of a light beam. A polarization angle of 29 degrees indicates a particle diameter of 0.3 μm when the aerosol is monodisperse.[33]

The optical device used to measure particle concentration is a forward-angle, light-scattering photometer capable of measuring scattering intensity over a range of at least five orders of magnitude. Current commercial instruments can give a useful signal with a concentration as low as 10 particles/cm^3 when finely tuned and used by a skilled operator. For routine testing, a downstream concentration of 10^{-4} mg/m^3 can be measured with reliability when the upstream concentration is 10 mg/m^3, indicating a filter efficiency of 99.99 percent for the test aerosol. This level of measurement is considered adequate for nuclear applications (in view of the lesser efficiency credit regularly assigned to filters by regulatory authorities), however, manufacturers of microelectronic chips have sought filters with much higher retention efficiency.

ULPA filters have an efficiency of 99.9995 percent for particles in the 0.1-μm range, which is the minimum filterable particle size for currently manufactured HEPA filters operating at their design airflow rate. This

degree of efficiency is beyond the range of the Q107, but a laser spectrometer has been developed that can measure filter performance at much higher efficiencies and for smaller particle diameters. This device measures the sizes of individual particles in an aerosol and displays the particle-size distribution on a screen and a printout. When used with a polydisperse aerosol challenge, it can measure penetration values as low as 1×10^{-9} in a range of particle diameters from 0.07 to 3.0 μm. Use of duplicate instruments upstream and downstream permits the determination of a "particle size-collection efficiency" table or chart for individual filters at a modest cost and within a reasonable period of time. Laser spectrometers can also be used to determine such important filter performance parameters as maximum penetrating size, efficiency of filters in series, and the optimum formulation of filter fibers. The laser spectrometer has been used experimentally for in-place filter testing, but an inability to detect and isolate small leaks in a filter bank at low upstream aerosol concentrations is unresolved. [Note: Lasers are currently being used routinely for high-efficiency filters (HEPA and ULPA) with acceptable results. Operator training is still an important issue, as is recognition that most lasers are calibrated using polystyrene latex (PSL) rather than the test aerosol. The properties of PSL (e.g., refractive index) are not identical to the test aerosol. This can produce inaccurate results unless operators understand the differences and set up the equipment properly. Upstream concentration is also critical because lasers can be blinded by the passage of too many particles to the counter. Most successful applications use calibrated particle diluters to ensure the laser is not overwhelmed.]

An international sampling of laser use for filter efficiency testing was conducted in 1985 by the Institute of Environmental Sciences and Technology (IEST) Working Group RP7 (IEST-RP-CC007.1)[34]. Samples of 14 different high-efficiency filter media were sent to interested parties with recommended protocols for instrument calibration and test performance. Results from eight participants showed wide variation in particle size efficiency results for identical filter papers. Incorrect calibration of laser spectrometers and incomplete knowledge of laser operation were contributing factors.

Based on the 1985 IEST findings, standards-writing groups organized at DOE since 1980 have established rigid procedures for spectrometer calibration and use for filter testing. The operating policy of DOE's filter testing program, contained in DOE-STD-3022-98[9], calls for testing of all HEPA filters intended for environmental protection at a DOE-operated FTF. Delivery of filters to a test facility for quality assurance review is mandatory for all DOE facilities, and the service is also available to the public for a fee. When the filter manufacturer's test data are confirmed, the FTF test results are added to the information on the filter case. The test procedures at the FTFs call for "penetration and resistance tests…visual inspection for damage and visible defects…[and other]…visually verifiable requirements." Except for the smallest filter sizes, penetration tests are required to be conducted at 100 percent and 20 percent of rated airflow capacity, and the maximum penetration of 0.1- to 0.2-μm particles at both airflow rates is 0.03 percent, in accordance with draft DOE-STD-3025-99, *Quality Assurance Testing of HEPA Filters*.[10] Penetration tests may be conducted using a monodispersed aerosol and a total light-scattering photometer, or a polydisperse aerosol with a single particle counting and sizing instrument.[10] A quality assurance program for DOE's FTFs is contained in draft DOE-STD-3026-99,[11] and specifications for HEPA filters to be used by DOE contractors are contained in draft DOE Standard DOE-STD-3020-97.[6] The HEPA filter specifications in DOE-STD-3020-97 are the same as those in the previously cited military specifications, except that the size and size distribution of monodispersed aerosols, when measured by the OWL, must be verified by a single particle counter.[6]

3.3.7.2 Quality Control/Assurance Considerations

Systematic quality control and quality assurance testing are conducted at all stages of the product cycle from development to use. The filter medium receives the most rigorous and extensive control and evaluation, perhaps because its development and manufacture necessarily demand a degree of art as well as science. Performance of the filtration medium is determined by a thermally generated monodispersed aerosol generated by a Q127 penetrometer,[35] a smaller version of the Q107 used to test cased filters. The physical

characteristics of the medium are controlled by a battery of standard test protocols developed by the TAPPI, ASTM, and ASME AG-1.[2] The use of ASME AG-1 requires an ASME NQA-1[36] program. After fabrication, in addition to measuring the efficiency and airflow resistance of the filter assembly with a Q107 or a Q76 penetrometer (depending on the rated airflow capacity and physical size of the filter), a series of physical tests described in ASME AG-1, Section FC,[2] are applied to filter prototypes for qualification. These include tests of dimension tolerances and resistance to rough handling, pressure, heated air, flame, and unfavorable environments (simulated desert, tropical, and Arctic conditions).

Filter Test Facilities were established in the early 1960's (see Chapter 1, Section 1.1.8). The last remaining FTF is at Oak Ridge, Tennessee, and continues to inspect and test HEPA filters destined for safety class or safety significant service at DOE facilities. The FTF continues to routinely find problems with HEPA filters sent by the various manufacturers. Problem HEPAs are returned to the manufacturer at no cost to DOE. Problems encountered occur in two categories: (1) flow/resistance/penetration amounting to approximately 1 to 2 percent per year, and (2) obvious defects in workmanship (which do not get flow tested) such as splinters, protruding nails, improper gaskets, etc.) amounting to an additional 2 to 3 percent per year. There have been major spikes (up to 20 percent) when a media making or packaging process was changed. The FTF serves its function well.

3.3.7.3 Other Historical Methods of Testing New HEPA Filters

Nebulized Paraffin Oil

In Germany, new HEPA filters are tested according to German Standard, DIN 24-184[37] The aerosol used is generated from a distillate oil fraction (paraffin oil) with a viscosity of 3 to 3.8×10^{-5} m^2/sec by heating the oil to 212 degrees Fahrenheit (100 degrees Celsius) and nebulizing it with compressed air. The oil mist concentration is about 10 mg/m^3, with a droplet size median diameter of 0.36 μm and a geometric standard deviation of about 2.0. A 45-degree angle, light-scattering aerosol photometer is used to measure the light-scattering concentration of the aerosol entering and leaving the filter undergoing a penetration test. The DIN 24-184[20] test method differs in details, but is very close in principle to the U.S. test method.

Nebulized Sodium Chloride

The standard test method used in Great Britain for new HEPA filters[38] utilizes a dried sodium chloride aerosol generated from solution with a compressed air nebulizer. An emission-flame photometer is used to measure the quantity of sodium chloride entering and leaving the filter being tested. The dried aerosol particles have a concentration of about 3 mg/m^3, a mass median diameter of 0.65 μm and a geometric standard deviation of 2.1. The test rig and test procedures employed do not differ significantly from those used in the United States, Germany, and a number of other countries.

Nebulized Uranine

The French standard test method, AFNOR NFX 44.011,[39] uses dried particles of uranine, a fluorescent material generated from a solution with a compressed air nebulizer. The aerosol concentration for the test is about 8×10^{-3} mg/m^3. The mass median diameter of the particles is 0.15 μm, with a geometric standard deviation of 1.55.

Aerosol samples are extracted from the test apparatus upstream and downstream of the filter being tested and are collected on filter papers. After the sampling period has expired, the filter papers are extracted in water and analyzed by fluorimetry. Filter efficiency is expressed as the percent by weight of fluorescent particles collected by the filter. Because of the need to collect samples over some averaging period (e.g., 10 minutes) and then to extract the uranine quantitatively from the filters and read the fluorescence intensity in a

fluorimeter, about 30 minutes is required for an analysis. Direct readout of filter efficiency is characteristic of most other standard test procedures.

Interrelationships Between Test Methods

A number of comparative analyses have been conducted for the purpose of establishing ratios between the several standard test methods, with indifferent results. This is understandable because different test methods use different test aerosols, very different analytical processes, and are applied to filters that respond differently to aerosols that have variable fractions of large and small particles. So, it is wise to view a filter's ability to pass the formal test protocols as simple assurance that the filter is constructed of quality components and was assembled in a sufficiently careful manner to make it free of unacceptable defects. In short, passing any one of the tests establishes that the filter is satisfactory for nuclear service—nothing more.

3.3.8 The Impacts of Aging, Wetting, and Environmental Upsets on HEPA Filter Performance

Intuitively, the aging of filters in storage or in use inplace should lead to a higher probability of media or structural failure. At least five experimental studies [22, 40, 41, 42, 43] have shown that with aging, HEPA filters lose strength and water repellency but do not necessarily become less efficient. Logically, it follows that filter efficiency depends on the physical geometry of the filter media, and is not significantly affected when the organic binders and sealants become brittle or degrade with age. Filter strength prevents structural failure during events that produce high stress across filter media, e.g., when particle deposits and water accumulation cause filter plugging. Historical measures of filter strength are: (1) the tensile strength of the paper in combination with a 10-inch overpressure test on the filter, and (2) burst strength. Burst strength (the pressure required to tear open the media) quantitatively measures two-dimensional stretches as compared to the one dimension used to measure the tensile strength. The brittleness of the media, which is measured by flexing it, is a third major strength measurement, although it is not generally measured in aging studies. Several authors have noted that aged HEPA filters are very brittle.

Decreasing water repellency produces filter plugging as accumulated moisture plugs filter media and decreases tensile strength. Critical filter parameters such as media tensile strength and water repellency unfortunately vary widely by manufacturer and types of particulate deposits. These varying parameters frequently mask the effects of aging, often making it difficult to derive an age limit using the available experimental data. M.W. First[43] qualitatively described the deterioration mechanisms involved in HEPA filter aging as:

- Aging and weakening of glass fibers;
- Aeterioration of the resin binder and the organic sealant;
- Corrosion of the aluminum separators;
- Moisture damage; and
- Mechanical stresses caused by handling the filter and airflow pulses.

Johnson, et al.,[41] were unable to measure the tensile strength across the media folds for aged HEPA filters because the brittle media cracked; they also observed that the media had lost most of its water repellency.

Following issuance of the Defense Nuclear Facilities Safety Board's Technical Report 23, *HEPA Filters Used in the Department of Energy's Hazardous Facilities*,[29] DOE initiated efforts to update ERDA 76-21, *The Nuclear Air*

Cleaning Handbook,[44] to present new guidelines for root causes and factors that would dictate replacement of HEPA filters within DOE nuclear facilities. However, as publication of this revision was delayed, increasing risks identified with aging HEPA filters at many DOE sites required the development of interim criteria for replacing safety-related HEPA filters to address wetting and environmental conditions, as well as aging considerations.

Many of these issues have been reviewed throughout the DOE complex in response in part to the Defense Nuclear Facilities Safety Board (DNFSB) Recommendation 2000-2, *Configuration Management, Vital Safety Systems.*[31, 45] DOE reviewed several facilities for their conformance to regulations, Orders, and standards concerning confinement ventilation systems (CVS). These reviews identified both strengths and weaknesses in the sites' filter programs in the following areas: (1) independent quality assurance testing/inspection by the FTF; (2) receiving inspection; (3) storage of HEPA filters; (4) in-place testing; (5) system bypass testing, and (6) service life. They also identified the need for more periodic CVS reviews. These have typically been woven into ongoing periodic assessments.

3.3.8.1 Aging

Bergman[45] stated that, "a conservative interpretation of my experimental results indicates that the maximum total life (storage and in-service) of HEPA filters for consistently removing greater than 0.9997 of 0.3 micron particles from highly hazardous aerosols is 10 years from the date of manufacture for applications in dry systems, and 5 years in applications where the filter can become wet more than once for short periods of time." If a filter gets wet it should be replaced expeditiously. At Oak Ridge National Laboratory (ORNL), Lawrence Livermore National Laboratory (LLNL), Idaho National Engineering and Environmental Laboratory (INEEL), and Savannah River Site (SRS) for "dry service" at normal relative humidity, the 10-year criterion is applicable to HEPA filters for aging. The date of installation is available for most safety-related HEPA filters. Historically, the date of manufacture has not been documented in a readily accessible manner, but will be under the new Standards Based Management System (SBMS). Clearly, however, the date of manufacture may not be retrievable for currently installed filters. If this information is available (without having to remove the filter to retrieve the data on its frame), the filter service life will be determined based on the date of manufacture. If the date of manufacture is not available, the date of installation will be used. If neither is available, the filter will be assumed to be over 10 years old and subject to immediate replacement.

3.3.8.2 Wetting

In his experiments, Fretthold[42] demonstrated that "previous water exposure weakened the filter media irreversibly," and that the "burst strength of the filter media decreased significantly with each wetting and drying." The replacement criteria will be exposure to a single occurrence of filter wetting. Potential sources of filter wetting are entrained droplets from actuation of sprinklers in areas that are upstream of the airflow to the filters, rain or groundwater inleakage into the filter system, or condensation from a leak of steam or hot water.

3.3.8.3 Upset Environmental Conditions

Section 12.05 of the Lawrence Livermore National Laboratory Health and Safety Manual,[47] *High Efficiency Particulate Air (HEPA) Filter System Design Guidelines for LLNL Applications*, stated that continuous exposure to the following operational environments will permanently damage or compromise HEPA filters:

- **Moisture and Hot Air**: 95 to 100 percent RH at temperatures higher than 130 degrees Fahrenheit.
- **Fire**: Direct fire or high concentrations of particulate matter produced by fire.

- **High Pressure**: 6.0 in.wg or more, internal or differential across the filter media. Filters should be changed if the differential pressure [adjusted for rated flow] exceeds 4.0 in.wg.

- **Corrosive Mist**: Dilute moist or moderately dry concentrations of acids and caustics.

- **Shock Pressures**: More than 1.7 psig.

The following criteria were modified for conservatism and simplification for use in an SBMS.

- **Wetting:** A single occurrence of filter exposure to water including entrained droplets from actuation of sprinklers in the area upstream of the filters, rain or groundwater, or condensation from a leak of steam or hot water.

- **Moisture and Hot Air:** HEPA filters may be operated continuously at 180 degrees Fahrenheit and between 5 and 75 percent RH, or at 120 degrees Fahrenheit and between 75 and 95 percent RH. HEPA filters are not to be used for installations where there is a possibility of condensation forming on them. They will provide maximum service life when operated below 100 degrees Fahrenheit and 75 percent RH.

- **Fire:** A single occurrence of direct flame impingement. [Note: Filters subjected to smoke from fires must have an in-place leak test performed on them immediately by the responsible in-place testing group (i.e., within 24 hours) and must be replaced if the filter fails the in-place leak test.]

- **High Differential Pressure:** A single occurrence of a differential pressure across a single filter of 8.0 in.wg or more.

- **Shock Pressure:** A single exposure to more than 1.7 psig.

- **Corrosive Mist:** Prolonged exposure (more than 4 weeks) to dilute moist or moderately dry concentrations of acids and caustics.

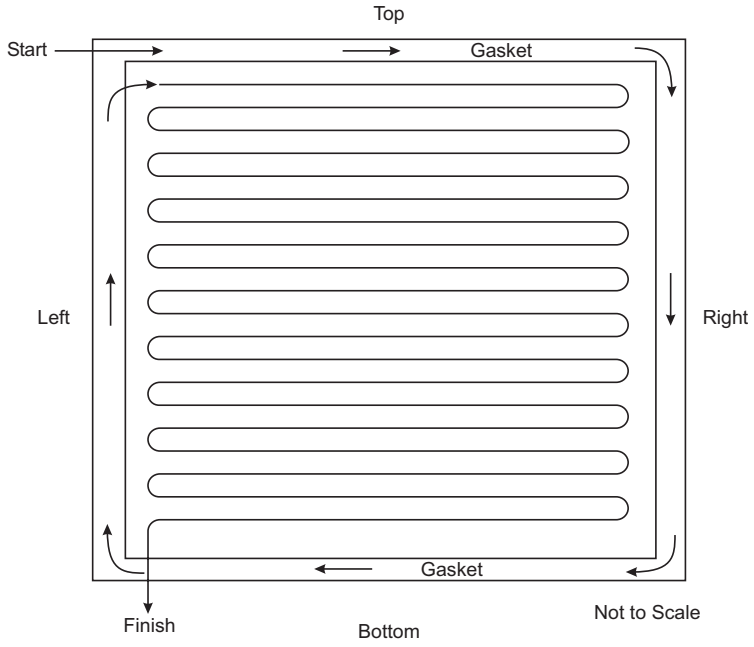

Figure 3.13 – Suggested Filter Probe Traverse Diagram

3.3.8.4 In-Place Testing of Filter Installations

An in-place leak test is done after filters are installed at a DOE nuclear facility to ensure the performance of the confinement ventilation system. The in-place leak test is used both for an acceptance and for surveillance leak testing of the installed HEPA filter bank. An in-place leak test and visual inspection of HEPA filters are performed initially upon installation to detect bypasses and damage to filters and periodically to establish current condition of a nuclear air cleaning system and its components. Specific objectives of in-place filter testing are (1) to test the aggregate performance to filters in a filter bank, (2) to evaluate the effectiveness of seals between the filter gasket and the filter housing, (3) to assess the leak-tightness of the filter housing, and (4) to determine whether bypasses exist around the filter housing. Each time repairs are made, the system

must be retested until it meets the established criteria for leaktightness.[48] Detailed information on in-place filter testing is included in Chapter 8.

3.3.8.5 Packaging, Storage, and Handling of HEPA Filters

The manufacturer should have a quality program for the packaging, shipping, handling, and storage of HEPA filters (e.g., NQA-1). HEPA filters are normally packaged in corrugated cardboard cartons that conform to shipping regulations. Additional internal pieces are inserted to protect the filter faces from damage during handling and transit. Palletizing crating should be constructed for ease of disassembly (see **Figure 3.14**). For multiunit shipments, individual cartons should be crated and palletized to minimize handling, particularly at trans-shipment points when using public carriers. For very large shipments, sealed and dedicated trailers are recommended. [Note: Filters shipped in less-than-truckload amounts using common carriers are often rearranged incorrectly by the carriers, resulting in damaged filters.] Upon delivery at the destination, mechanical warehousing equipment should be used for unloading and transferring the shipment. Cartons should be placed in clean, dry, interior storage until used. They should be positioned as directed on the carton exterior, and no more than three filter cartons should be stacked atop each other.

Figure 3.14 – Filter Crating and Palletizing

When a filter is inserted in the cardboard shipping container, the pleated folds should be oriented in the vertical direction (except Type B filters), and both the filter frame and the enclosing carton should be labeled with a vertical arrow or the notation, "This Side Up" (including Type B filters). When handling a filter inside a carton, the box should be tilted on one corner, picked up, and carried by supporting it at diagonally opposing corners. Removing the filter from its shipping carton without damaging the medium is best accomplished by opening and folding back the top flaps of the carton, inverting the carton onto a clean surface, and lifting the carton off the filter. Then the filter unit can be grasped by the outer frame surfaces without the danger of personnel coming into contact with the filter pack enclosed within the frame. Additional details can be found in Appendix B.

3.4 Prefilters for HEPA Filters

3.4.1 Filter Descriptions

The service life of HEPA filters can often be extended by using less efficient filters that selectively remove the largest particles and fibers from the incoming airstream. In some cases, HEPA filter lifetimes can be increased by as much as four times with multiple prefilter changes during the interval between HEPA filter changes. It is recommended that HEPA filters be protected from: (1) particles larger than 2 μm in diameter, (2) lint, and (3) particle concentrations greater than 2.3 mg/m^3. Selection of an appropriate prefilter includes

consideration of: (1) the rapidity of filter resistance buildup and associated energy costs, (2) the size and complexity of the resulting filtration system, (3) the fact that replacement filters and associated costs generally increase with increasing prefilter efficiency, and (4) the disposal costs for contaminated HEPA filters and potentially uncontaminated prefilters. It has been estimated that, with frequent prefilter replacements, savings in filter system operation could be as much as one-third the cost of operating without prefilters. Assessment of an acceptable combination of prefilters and HEPA filters depends on the dust-loading and efficiency characteristics of the different filter types available for the particular aerosol to be filtered. The clogging susceptibility of HEPA filters will vary with the dust and filtration characteristics of the prefilters.

The types of filters used as prefilters are also widely used for cleaning ventilation supply air in conventional HVAC systems. The important advantage of filtering ventilation supply air for many operations that generate radioactive particles is a reduction in the dust load that reaches the final contaminated filters. This helps extend the service life of the exhaust filters, thereby reducing overall system costs because the supply air filters can be changed without resorting to radiation protection measures—often the most costly aspect of a contaminated exhaust filter change. These filters have a wide range of efficiencies, including 5 to 10 percent for warm air residential heating systems; 35 to 45 percent for ventilation of schools, stores, and restaurants; and 85 to 95 percent for fully air-conditioned modern hotels, hospitals, and office towers.

3.4.2 Classes, Sizes, and Performance Characteristics of Prefilters

For prefilters intended to remove only the largest airborne particles, a reverse relationship between retention and re-entrainment forces occurs, causing collected particles to seep through the filter under prolonged airflow unless the filter fibers are coated with viscous liquids to wet the collected particles and increase the area of contact between them and the filter surfaces.

The most widely used test methods for ventilation air filters are published by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) as Standard 52.1-92,[49] which contains two different protocols. One uses a prepared "test dust" consisting of road dust, carbon black, and cotton fibers. In this procedure, the test dust is aerosolized by compressed air and blown into the filter at a concentration many times that normally found in ambient air. The filter is rated by the weight percent of dust retained. This obsolete test method originated in the days when coal was the only fuel and has little relevance to today's air filter requirements. The second test method uses unaltered atmospheric air as the test medium and rates filter efficiency on the basis of the percent reduction in discoloration of simultaneous samples taken on white filter papers upstream and downstream of the filter being tested. Reductions in discoloration cannot be related to weight percent efficiency. In addition to dust-collecting efficiency, the first test procedure measures filter resistance increase with dust deposition and dust-holding capacity. Ventilation filters in the 35 to 95 percent efficiency range are evaluated by the atmospheric dust discoloration test.

Table 3.7 (from ASHRAE 52.2)[50] shows cross-reference and application guidelines for air cleaners with particulate contaminants. For comparison purposes, the HEPA filter is rated at 100 percent for both the stain-efficiency and artificial dust arrestance tests. Because the atmospheric dust test is based on the staining capacity of the dust that penetrates the filter, compared to the staining capacity of the entering dust, it is not a true measure of particle-removal efficiency for any one particle-size range.

Table 3.7 – Cross-reference/Application Guidelines for Air Cleaners with Particulate Contaminants

Std. 52.2 Minimum Efficiency Reporting Value (MERV)	*Approximate Std. 52.1 Results*		*Application Guidelines*		
	Duct Spot Efficiency	*Arrestance*	*Typical Controlled Contaminant*	*Typical Applications and Limitations*	*Typical Air Filter/Cleaner Type*
			≤0.30 µm Particle Size		**HEPA/ULPA Filters**
20	n/a	n/a	Virus (unattached)	Cleanrooms Radioactive materials	≥99.999% efficiency on 0.1-0.2 µm particles, IEST Type F
19	n/a	n/a	Carbon dust Sea salt	Pharmaceutical manufacturing	≥99.999% efficiency on 0.3 µm particles, IEST Type D
18	n/a	n/a	All combustion smoke	Carcinogenic materials	≥99.99% efficiency on 0.3 µm particles, IEST Type C
17	n/a	n/a	Radon progeny	Orthopedic surgery	≥99.97% efficiency on 0.3 µm particles, IEST Type A
16	n/a	n/a	**0.3-1.0 µm Particle Size** All bacteria	Hospital inpatient care General surgery	**Bag Filters**: Nonsupported (flexible) microfine fiberglass or synthetic media, 12 to 36 inches deep, 6 to 12 pockets **Box Filters:** Rigid style cartridge filters 6 to 12 inches deep may use lofted (air laid) or paper (wet laid) media.
15	>95%	n/a	Most tobacco smoke Droplet nuclei (sneeze)	Smoking lounges Superior commercial buildings	
14	90-95%	>98%	Cooking oil Most smoke		
13	80-90%	>98%	Insecticide dust Copier toner Most face powder Most paint pigments		
12	70-75%	>95%	**1.0-3.0 µm Particle Size** Legionella	Superior residential Better commercial buildings Hospital laboratories	**Bag Filters:** Nonsupported (flexible) microfine fiberglass or synthetic media, 12 to 36 inches deep, 6 to 12 pockets. **Box Filters:** Rigid style cartridge filters 6 to 12 inches deep may use lofted (air laid) or paper (wet laid) media.
11	60-65%	>95%	Humidifier dust Lead dust		
10	50-55%	>95%	Milled flour Coal dust		
9	40-45%	>90%	Auto emissions Nebulizer drops Welding fumes		
8	30-35%	>90%	**3.0-10.0 µm Particle Size** Mold	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	25-30%	>90%	Spores Hair spray		
6	<20%	85-90%	Fabric protector Dusting aids		
5	<20%	80-85%	Cement dust Pudding mix Snuff Powdered milk		
4	<20%	75-80%	**>10.0 µm Particle Size** Pollen	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%	70-75%	Spanish moss Dust mites		
2	<20%	65-70%	Sanding dust Spray paint dust		
1	<20%	<65%	Textile fibers Carpet fibers		

ASHRAE Standard 52.1-92[49] tests have replaced those sanctioned formerly by the Air Filter Institute and the Dill Dust-Spot Test of the National Institute for Standards and Technology. Care must be taken in the interpretation of data from the ASHRAE tests. Arrestance test results depend highly on particles that exceed 1 μm in diameter, but the ambient atmospheric dust test results depend on the nature and concentration of aerosol particles at the testing location. The average particle size of the urban atmosphere is assumed to be 0.5 μm. The results of the various tests are not comparable, and a filter determined to be efficient by one test may be determined to be inefficient by another. Users should examine the test used to evaluate a filter's efficiency to properly understand the results. Efficiency tests are made on prototype filters, and the results are extrapolated to other units of similar design (certification of every prefilter by testing would be too costly).

Values stated in Table 3.7 for dust-holding capacity were determined with resuspended synthetic dust mixtures. Dust-holding capacity varies with the nature and composition of the particles (e.g., carbon black, cotton linters). Dust-holding capacity under service conditions cannot be predicted accurately on the basis of manufacturers' data. Air resistance is the primary factor in prefilter replacement. Although manufacturers recommend specific values of resistance for prefilter replacement, loss of adequate airflow is often a more reliable indicator of system performance and is also more cost effective. Panel filters will plug rapidly under heavy loads of lint and dust. An accumulation of surface lint may increase the efficiency of an extended-medium filter by adding "cake" filtration principles to the existing physical mechanisms. The extended-medium prefilter will plug readily in an airstream carrying profuse smoke and soot from a fire. Operation at airflows below rated capacity will extend the service lives of filters and be more cost effective by reducing the frequency of filter replacement. On the other hand, when airflow exceeds rated values, dust-loading rate and system costs begin to increase exponentially along with proportional increases in airflow. [ASHRAE also publishes Standard 52.2-99,[50] which gives methods for testing filter efficiency by particle size using optical particle counters, including lasers.]

3.4.3 Construction of Prefilters

Prefilters are classified by the American Refrigeration Institute (ARI) 850-93[51] as follows:

- Group I - Unit or panel.
- Group II - Self-cleaning, self-renewable, or any combination thereof.
- Group III - Extended surface.
- Group IV - Electronic air cleaner.
- Group V - Air filter media.

Group I panel filters (viscous impingement filters) are shallow, tray-like assemblies of coarse fibers (glass, wool, vegetable, or plastic) or metal mesh enclosed in a steel or cardboard casing. The medium is usually coated with an inhibited viscous oil or adhesive to improve trapping and retention of particles. Single-use disposable and cleanable-reusable types are available. The latter have metal mesh and generally are not used in nuclear applications for effluent or process air cleaning because of the high labor costs associated with cleaning and disposal of entrapped radioactive materials. A disposable panel filter has a fairly high dust-holding capacity, low airflow resistance, low initial and operating costs, and high removal efficiency for large particles. It is particularly effective against fibrous dust and heavy concentrations of visible particles, but is ineffective for smaller particles. For nuclear service, it is less cost-effective than the more costly Group II or III filters that provide better protection for the HEPA filter.

Group II (moderate-efficiency) and Group III (high-efficiency) filters are usually comprised of extended-medium, dry-type, single-use disposable units. The filter medium is pleated or formed into bags or socks to provide a large filter surface area with minimal face area. They are not coated with adhesive. The particle size efficiency of Group II filters is moderate to poor for submicrometer-sized particles, but often approaches 100 percent for particles greater than 5 μm. In most cases, the pressure drop of extended-media Group II filters varies directly with efficiency. Group II filters are recommended for high lint- and fiber-loading applications. The large filter area relative to face area permits duct velocities equal to or higher than those of panel filters.

Group III filters are preferred when higher efficiency for smaller particles is desired. The dust-holding capacity of Group III filters usually is lower than that of Group II filters.

3.4.4 Electrostatic and Electrified Filters

An electrostatic charge may be induced on filter fibers by triboelectrification and by sandwiching the fiber bed between a high voltage and a grounded electrode. Triboelectrification can be used to induce a high electrostatic charge on suitable high dielectric materials, but under practical-use conditions, the charge is subject to rapid dissipation due to air humidity, oily particles, fiber-binding particles, and other interference. Continuously activated electrodes can induce a more permanent charge.

A program to develop electrofibrous filters, undertaken by DOE at LLNL, has proved them effective in providing greater efficiency and longer service life for the prefilters used to protect HEPA filters. They have been used in gloveboxes and for other applications. Laboratory tests using test and sodium chloride aerosols have shown that an "electrofibrous prefilter increases in efficiency from 40 to 90 percent as 10 kV is applied to the electrode." A comparison of uncharged, triboelectrically charged, and permanently charged fibrous filters demonstrated the higher collection efficiency of the permanently charged filter design for submicrometer particles. When continuously charged electrofibrous filters were applied as prefilters for HEPA filters in exhaust air systems or gloveboxes used to burn uranium turnings, they significantly prolonged the life of the final filters.

3.4.5 Operation and Maintenance of Prefilters

All prefilter construction materials must be compatible with those of the downstream HEPA filters they are designed to protect. Therefore, they must conform to the rigorous physical properties prescribed for HEPA filters (e.g., resistance to shock, vibration, tornado, earthquake, moisture, corrosion, and fire). Survivability under the specific operational conditions and requirements must be addressed when prefilters are selected because moisture or corrosive products in the airstream may limit the choice of filter. Although many filter media will not withstand acid or caustic attack, glass fibers are corrosion-resistant except for fluorides. However, the casing and face screen materials may be less so. Aluminum may deteriorate in marine air, from caustics, or from carbon dioxide. Plastics have poor heat and hot air resistance and generally will not satisfy UL requirements. Condensation from high humidity and sensible water may plug a prefilter and result in more frequent replacement. In general, a prefilter made of construction materials identical to those in the HEPA filter will have equivalent corrosion and moisture resistance. Any increase in resistance from moisture accumulation will be greater for MERV 17-20 filters than for MERV 9-16 filters (ASHRAE 52.2 Table E-1)[50]. UL classifies ventilation air filters in two categories with respect to fire resistance.[50] When clean, UL Class 1 filters do not contribute fuel when attacked by flame and emit a negligible quantity of smoke. UL Class 2 filters are permitted to contain some small amount of combustible material, but they must not contribute significantly to a fire. The collected material on inservice UL-approved Class 1 and 2 filters may burn vigorously and create a fire that is difficult to extinguish. Therefore, use of an UL-rated prefilter should not lead to an unwarranted sense of security on the part of the user. The UL maintains a current listing of filters that meet the requirements of their standards.[21]

Most types of prefilters are suitable for continuous operation at temperatures not exceeding 149 to 248 degrees Fahrenheit (65 to 120 degrees Celsius). Other types with glass-fiber media in steel or mineral board frames may be used at temperatures as high as 392 degrees Fahrenheit (200 degrees Celsius). Users of high-temperature prefilters should take a conservative view of performance claims, particularly claims related to efficiency at operating temperature.

Because of waste disposal requirements, the preferred choice of a prefilter for nuclear applications is the single throwaway cartridge. A replaceable-medium filter offers an advantage over the throwaway because the bulk of material that needs to be discarded is smaller and handling and disposal costs are minimized. However, re-entrainment of contaminants and contamination of the peripheral area are possible because the medium is removed from the system and prepared for disposal. The replaceable-medium type is not recommended for toxic exhaust systems. The cleanable-medium filter is undesirable for nuclear systems because of the extensive downtime of the system that is required for changing and decontaminating areas in proximity to the filter installation.

3.5 Deep-Bed Filters

Deep-bed filters were designed, built, and placed in service early in the development of nuclear technology for treating offgasses from chemical processing operations. The first, a sand filter, was constructed at the Hanford, Washington, nuclear facility in 1948, and deep-bed glass fiber filters were constructed soon after. These were not considered competitive with then-current versions of the HEPA filter (the CWS-Type 6 or AEC-Type 1), but were thought to have a different function. With the thin-bed filters, the intent is usually to replace or clean the filter medium periodically. The deep-bed filter, on the other hand, usually has as its objective the installation of a unit which will have a long life, in the dust capacity sense, of say 5 to 20 years, corresponding to either the life of the process or the mechanical life of the system. Thus, when resistance starts increasing rapidly, instead of replacing or cleaning the filter medium, the entire filter installation would be abandoned and replaced with a new unit. In fact, the life span of some deep-bed filters constructed during the early 1950s has not yet been entirely expended. A partial explanation for this longevity is the original design concept that deep-bed filters would be used where the total aerosol concentration was usually on the order of or less than normal atmospheric dust concentrations. An important reason for selecting sand for the initial bed material was a need to filter large volumes of wet corrosive aerosols for which more usual filter materials would prove unsatisfactory. Deep beds of crushed coke had been used by the chemical manufacturing industry for many years to remove sulfuric acid mist from the effluent gas of sulfuric acid manufacturing plants prior to 1948. Silverman cited efficiencies as high as 99.9 percent by weight for a crushed-coke bed against a sulfuric acid mist of 0.5 to 3.0 μm in diameter.[52] Perhaps a carbon-filled bed was considered unsuitable for filtering an aerosol that might contain fissile material, and sand was selected for the first deep-bed filter for nuclear fuel processing facility ventilation air.

3.5.1 Deep-Bed Sand (DBS) Filters

Some of the following material is taken directly from ERDA 76-21[44]. Although dated, it is still relevant today. It has been updated where appropriate. Initially, sand filters were installed at the Hanford, Washington, nuclear facility and at the Savannah River nuclear plant. Following their success, more were added at Hanford and Savannah River and others were constructed at plants in Morris, Illinois, and Idaho Falls, Idaho. The Argonne National Laboratory compiled a bibliography of DBS filters. These DBS filters had collection efficiencies for particles greater than or equal to 0.5 μm that compared favorably with the HEPA filters of that era. Their advantages for the nuclear programs at these sites included large dust-holding capacity, low maintenance, chemical resistance, high heat tolerance, fire resistance, and a capability to withstand large shock and gross pressure changes without operational failures. They also had disadvantages such as high capital

costs, need for large areas and volumes, inability to maintain the granular fill, and lack of a reasonable means of disposing of the contaminated fill.

DBS filters contain up to 10 feet of rock, gravel, and sand constructed in graded layers that diminish granule size by a factor of 2 as the layers go from bottom to top. Airflow direction is upward so that granules decrease in size in the direction of flow. A top layer of moderately coarse sand is generally added to prevent fluidization of the finest sand layer underneath. The rock, gravel, and sand layers are positioned and sized to provide the desired structural strength, particle collection ability, dirt-holding capacity, and long service life. Ideally, the layers of the largest granules, through which the gas stream passes first, remove all the large airborne particles, whereas the fine sand layers on top retain the finest smallest particles at high efficiency. Below the granular bed there is a layer of hollow tile that forms passages for air distribution. The total bed is enclosed in a concrete-lined pit. The superficial velocity is about 5-feet per minute, and pressure drop across the seven layers, sized 3 1/2-inch average diameter down to 50 mesh, is from 7 to 11 in.wg. Collection efficiencies as high as 99.98 percent for test aerosols have been reported. Some DBS filters have experienced premature plugging at relatively low dust loadings. Another suffered partial collapse from disintegration of grout between the tiles supporting the overhead filter structure. These failures were caused by moisture leaking through voids in the system perimeter or by chemical corrosion and erosion of system components from nitric acid fumes in the effluent air. Disposal of inoperable DBS filters, usually contaminated, is generally accomplished by sealing and abandonment. Replacement systems normally are constructed nearby to accommodate the same air intake duct system.

Currently, there is renewed interest in sand filters for ESF applications (e.g., the plutonium Pit Disassembly and Conversion Facility in Savannah River, South Carolina; emergency confinement venting for light-water reactors). The Swedish confinement venting system, known as FILTRA, features large concrete silos filled with crushed rock. It is designed to condense and filter the stream blown from the confinement and to release to the atmosphere less than 0.01 percent of the core inventory.

3.5.2 Deep-Bed Glass Fiber (DBGF) Filters

The rapidly emerging glass fiber technology of the late 1940s shifted attention to the use of very deep beds (1 or more meters thick) of graded glass fibers as a satisfactory substitute for sand filters when treating gaseous effluents from chemical operations. They proved to be more efficient, less costly, and to have a lower airflow resistance than the DBS filters they replaced. In addition, these DBGF filters employ a medium that has more controllable physical features and more assured availability than the DBS to permit a larger airflow per unit volume at lower pressure drop, lower operating costs, and potentially lower spent-filter disposal costs. DBGF filters have been used at Hanford for several decades on their Purex process effluent streams. However, the DBGF filters do not have the corrosion resistance of the DBS, particularly from HF, and are less fire-resistant. The DBGF is also less of a heat sink and has less capability to resist shock and high-pressure transients.

The intake segment of the DBGF filter system was designed with layered beds of uniform-diameter glass fibers to a total depth of 8 to 84 inches. Each layer in the direction of airflow was compressed to a higher density and enclosed in a stainless steel tray with impermeable walls and a perforated screen above and below. Capacity varied from 200 to 200,000 cfm (350 to 350,000 m^3/hr). Although the first unit constructed at Hanford was small (400 m^3/hr (235.4 cfm), many of the 25 subsequent units were much larger and experienced extensive usage from nuclear fuel processing to hot cell ventilation. The glass fiber of preference for this application was Owens-Corning's 115-K, a 29-μm-diameter, curled glass fiber that resisted clumping, settling, and matting. A system that was designed for downward airflow became inoperative from precipitation of ammonium nitrate at the filter face. Subsequent units were designed with airflowing upward and were equipped with water sprays directed from below to dissolve salt precipitation on the intake face to reduce pressure drop buildup. The design airflow velocity of a typical DBGF was 50 feet per minute, and

clean pressure drop was close to 1.5-in.wg. The final pressure drop, after a total particle loading estimated at 10,500 pounds, was 8-in.wg. The final stage of a second-generation DBGF filter system employed two 12-mm blankets of 3.2-μm- and 1.2-μm-diameter glass fibers fabricated as a twin-layer bag stretched over a stainless steel framework. Airflow from the first stage passed through the filtration blankets from the outside to the inside, then was exhausted from inside the metal framework. The number of bag filters was proportional to the capacity of the intake segment of the DBGF filter. Later designs of the DBGF filter's cleanup stage substituted HEPA filters in a group of manifolded caissons (encapsulating filter holders), and a comparable increase in collection efficiency was realized. The most recent installation of a DBGF filter system required more than 100 HEPA filters downstream of a deep bed containing more than 38,000 pounds of 115-K fiber. By carefully selecting the packing density, bed depth, and airflow velocity, collection efficiencies greater than 99 percent for 0.5 μm particles were attained.

Provision for periodic backflushing will often extend the life of the total filter. Most DBGF filter systems, contained in vaults below ground, are resistant to shock and overpressure from natural phenomena. The dust-holding capacities of DBGF filters are very large, and many units have operated for years without attendance or maintenance. Pressure drop sensors can often predict evolving difficulties and indicate when it is time for backflushing, precipitate dissolution, or other preplanned remedial actions. Just as for DBS filters, decontamination and disposal is difficult for small systems and nearly impossible for the larger systems.

3.5.3 Deep-Bed Metal Filters

Deep beds of metal fibers have a number of applications in the nuclear industry, particularly where maximum resistance to fires, explosions, and overpressure shocks are essential. In offgas systems containing substantial concentrations of HF, use of stainless steel metal fibers has been studied as a substitute for glass.

In most cases, the objective when using metal fiber filters is to obtain particle collection efficiencies that duplicate those obtainable with HEPA filters. However, the unavailability of metal fibers with diameters close to or below 1 μm makes it necessary to provide great filter depth as a substitute for small fiber collection efficiencies. For sodium fire aerosols, high collection efficiency can be obtained with relatively large diameter metal fibers because the combustion products in air, sodium oxide, and carbonate rapidly form large flocs that are easily filtered. The ease of filtration results in the extremely rapid formation of a high-resistance filter cake that severely limits the amount of sodium aerosol particles that can accumulate in the filter before the limit of the fan's suction pressure is reached. Here, the requirement is for a graded-efficiency, deep-bed, metal filter with a large storage capacity in the initial layers of the filter for the fluffy sodium aerosol particles, a high efficiency for small particles in most downstream layers of the filter, and the elimination of abrupt interfaces between graded fiber layers where a filter cake might form. This is a different filtration requirement than obtaining high efficiency for low concentrations of small, nonagglomerating particles—instead, the requirement is for uniform particle storage throughout the depth of the filter. Here also, uniform diameter fibers can be used in great depths, as in the DBGF filters, to substitute for the presence of very small-diameter filter fibers.

Other types of metal filters have been constructed by sintering stainless steel powders or fine fibers into a sieve-like structure that function very much like a conventional pulse-jet-cleaned industrial cloth filter. The metal membrane has an inherent high efficiency for particles greater than a few micrometers, but depends on the formation of a filter cake to obtain high efficiency with submicrometer particles. Clean airflow resistance is high and increases rapidly as cake thickness builds up. It is cleaned periodically by backflow jets of compressed air. Efficiencies are comparable with those of HEPA filters when the sintered metal filters are precoated with filter aids. Because of their high-temperature resistance and ability to handle high concentrations of mineral dusts, these types of filters have been used in nuclear incinerator offgas cleaning systems, particularly when heat recovery from the hot filtered gases is desired. However, care must be exercised to avoid releasing tar-like combustion products to sintered filters that are operated at high

temperatures because the tarry material tends to lodge in the pores and turn to cake that cannot be removed by chemical means or by elevating the temperature to the limit of the metal structure.

Another type of sintered filter construction for high-temperature applications has been prepared from a mixture of stainless steel and quartz fibers. The composite material has the same efficiency and pressure drop as HEPA filter glass paper, but has 4 times the tensile strength and can operate continuously at temperatures up to 932 degrees Fahrenheit (500 degrees Celsius). Applications of the stainless steel and quartz fiber HEPA filter medium have not proceeded beyond the laboratory stage.

3.6 Demisters

Liquid droplet entrainment separators are required in the standby air treatment systems of many water-cooled and -moderated power reactors to protect the HEPA filters and activated-charcoal adsorbers from excessive water deposition should a major high-temperature water or stream release occur as a result of an incident involving the core cooling system. Droplet entrainment separators are also used in fuel processing operations to control acid mists generated during dissolving operations and subsequent separation steps.

Entrainment separators consisting of a series of bent plates are widely used in HVAC applications for controlling water carryover from cooling coils and humidifiers; but for nuclear applications, their droplet removal efficiency is inadequate. Therefore, fiber-constraining demisters with a much greater efficiency for small droplets are standard for nuclear service. Entrainment separators utilizing fiber media remove droplets by the same mechanisms that are effective for dry fibrous filters, but they must have the additional important property of permitting the collected water to drain out of the cell before it becomes clogged. Should clogging occur and the pore spaces fill with water, the pressure drop across the separator will rise and some of the water retained in the pore spaces will be ejected from the air discharge side to create sufficient passages for air to pass through. The ejected water can become airborne again by this mechanism.

Droplets from condensing vapors originate as submicrometer-sized aerosols, but the droplets may grow rapidly to multimicrometer size by acting as condensation centers for additional cooling vapors and by coagulation when the concentration of droplets exceeds 10^6 droplets/ml. Firefighting spray nozzles, confinement sprays, and other devices that mechanically atomize liquid jets yield droplets that predominantly range from 50 to more than 1,000 μm in diameter. This range means that entrainment separators must not only be capable of removing the smallest droplets, but also must resist becoming flooded by the largest droplets and releasing the collected liquid as entrained water.

The NRC recommends the use of entrainment separators for engineered safety systems when the air may be carrying entrained liquid droplets or a cooling and condensing vapor.[8, 31, 45, 50] Although HEPA filter paper is treated for water repellency, high-water loadings rapidly saturate the paper and raise its airflow resistance to a point where gross holes can result. Hot water and steam cause paper to lose its strength and to fail even more rapidly. Therefore, the criteria for entrainment separators used for nuclear service call for: (1) at least 99.9 percent retention by weight of entrained water and condensed steam in the size range 1 to 2,000 μm diameter, at a duct velocity from 250 to 2,500 linear feet per minute, and water delivery rate of 8 gallons per minute (gpm) per 1000 cfm of installed HEPA filter capacity; (2) at least 99 percent retention by count of droplets in the 1- to 10-μm-diameter range, at a duct velocity from 250 to 2,500 linear feet per minute; (3) no flooding or water re-entrainment at a water-steam delivery rate of 8 gpm at a duct velocity of 2,500 linear feet per minute; and (4) a temperature tolerance at least to 320 degrees Fahrenheit (160 degrees Celsius) and gamma radiation exposure up to 10^6 rads integrated dose without visible deterioration or embrittlement of the materials of construction. An entrainment separator with these characteristics will provide long-term protection for a downstream HEPA filter that would be destroyed in a few minutes without it. Entrainment separators are usually constructed of deep layers of high-porosity metal and glass fibers, either packed or

woven into stable batts, and arranged in graded sizes and packing density to give the desired small droplet collection capability with excellent resistance to flooding and re-entrainment.

3.7 Filter Design Selection

Nuclear-grade HEPA filter papers are distinguished from otherwise identical products by their proven resistance to deterioration by radiation. This requirement is spelled out in ASME AG-1,[2] which calls for 50 percent retention of original strength and water repellency after exposure to an integrated dose of 6.0×10^7 to 6.5×10^7 rads at a dosage rate not to exceed 2.5×10^6 rads per hour. Because all fabricated filters destined for nuclear service will contain identical or equivalent paper, selection can be based solely on the type of filter construction.

Deep-pleat filters with corrugated aluminum separators have dominated nuclear service both by numbers and years of use, and therefore have the longest and most thoroughly documented performance record. They appear to be stronger than other filter designs, although mini-pleat and separatorless filters are able to meet existing strength requirements in applicable filter standards. Mini-pleat construction has the desirable advantage of packing twice as much paper into a given volume of filter. A disadvantage of the mini-pleat design is the narrowness of the air passages between adjacent pleats, which make it susceptible to premature clogging of the openings by large particles and fibers. This may not be a difficulty when the air being filtered is exceptionally dust-free or when efficient prefilters are employed. Nuclear service experience is sparse or totally lacking for types of filter construction other than deep-pleat filters with corrugated separators, although there may be equivalent experience in nonnuclear applications.

Special nuclear filters are needed when service conditions involve exceptional physical or chemical stress. Although the usual run of filters for nuclear service must provide resistance to short-term exposure to heated air and flame, they are not designed for long-term operation at temperatures exceeding 250 degrees Fahrenheit (120 degrees Celsius). Because the organic sealant between filter pack and filter frame is the least temperature-resistant component, it is possible to increase temperature resistance by substituting a tightly compressed fine-fiber batt for the organic adhesive. In addition, substituting a metal frame for a plywood or composition board increases temperature resistance to the melting point of the glass fibers in the filter medium [932 degrees Fahrenheit (500 degrees Celsius)]. Before this temperature is reached, the organic binder and water-repellent chemicals in the paper will be lost, but this may not adversely affect filtration efficiency or airflow resistance, but does reduce the filter strength.

The chemical resistance of low-temperature nuclear filters is generally excellent for all dry gases. With high humidity, the presence of HF will cause etching and embrittlement of the glass fibers and ultimate failure of the filter. When droplets of HF or condensed water plus HF gas are present in the airstream, rapid failure of the glass filter paper may be anticipated. Rapid failure (within hrs) also occurs when hydroscopic salts from chemical processing collect on the filter surface and form a moist, slush-like cake that absorbs HF and infiltrates the pores of the filter paper. Special filter papers have been formulated with 7 percent Nomex fibers to provide extra chemical resistance for this type of service.

Aluminum separators are especially susceptible to chemical attack by many substances other than HF. United States requirements call for vinyl-epoxy coatings of 0.2 to 0.3 μm in thickness on both the sides and edges of aluminum separators when the presence of acid is predicted. Stainless steel separators are a more costly alternative.

Deep-bed filters of sand, gravel, and crushed stone do not compete directly with HEPA filters, except at a few installations involved in chemical operations associated with fuel reprocessing, but they have recently come under intense study as a means of mitigating core meltdown events by providing a filtration capacity for venting confinement vessel overpressures and for coping with a possible hydrogen burn inside the

confinement. DBS filters have also been studied extensively for a potential role in mitigating loss of coolant accidents for metal-cooled reactors.

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