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DOE HANDBOOK

HANDBOOK FOR USE WITH DOE-STD-1269-2022, “AIR CLEANING SYSTEMS IN DOE NUCLEAR FACILITIES”

U.S. Department of Energy
Washington, D.C. 20585

FOREWORD

This handbook is approved for use by all Department of Energy (DOE) components and their contractors. It provides advice and recommended good practices for implementing DOE-Standard (STD)-1269-2022, *Air Cleaning Systems in DOE Nuclear Facilities*. It does not add any new requirements to those stated in DOE-STD-1269-2022, nor does it alter in any respect that standard's requirements or recommended practices. Taken together, DOE-STD-1269-2022 and this handbook replace DOE-HDBK-1169-2003, *Nuclear Air Cleaning Handbook*, which is now archived and may be viewed at https://www.standards.doe.gov/.

Comments (recommendations, additions, and deletions), as well as any pertinent data that may be of use in improving this document, should be emailed to: nuclearsafety@hq.doe.gov or sent to:

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1.0 Introduction

1.1 Purpose

This handbook is a companion document to DOE-STD-1269-2022, *Air Cleaning Systems in DOE Nuclear Facilities* (referred to hereafter as "the Standard"). It identifies good practices drawn from operational experience at DOE components and commercial nuclear facilities, industry input, and the advice of technical experts that can be used to meet the Standard's requirements and guidance. It also offers general technical advice on topics related to air cleaning systems needed for nuclear and worker safety. The handbook provides clarification of the rationale for some provisions in the Standard and cites references to assist all DOE components and their contractors in applying the Standard. With respect to the Standard's requirement statements, the handbook should be viewed as an implementation aid, not as an interpretation of the requirements.

1.2 Applicability

The handbook applies to new and existing Category 1, 2, and 3 nuclear facilities.

1.3 Organization

The handbook follows the format and organization of the Standard.

2.0 Terminology

2.1 Acronyms & Abbreviations

This document uses a large number of acronyms and abbreviations. Some are well-known in the nuclear industry at large (such as DOE, NRC, and ASTM) while others such as HEPA and ASHRAE are familiar to any engineer working on air cleaning systems. In each case where a less familiar acronym or abbreviation is used (e.g., DAC for derived air concentration), an explanation is provided on first use.

3.0 System Design

3.1 Introduction

Design of an air cleaning system in a nuclear facility is a complex task that requires the careful integration of numerous primary and support systems. The system should be capable of providing a clean, healthy working environment for personnel in the facility, contain radioactive and chemical hazards in both normal and accident conditions, and remain operational when challenged by events such as earthquakes or fires. This section of the handbook provides a wide range of guidance on system design, based upon many decades of DOE experience dating back to the Manhattan project.

3.2 Contaminants

Intake air cleaning systems or supply systems filter the atmospheric dust and other contaminants brought into the facility. Recirculating systems, if used, clean the air in a building or location and return the air to that location. Other sources of particulate and gaseous contamination are infiltration and “people-generated” particulates (e.g., lint, skin, hair) and off-gassing of materials such as paint, solvents, carpets, and furniture. All of these factors should be considered in determining the parameters for proper system design. These contaminants may become radioactive when exposed to certain environments (e.g., by adsorption of radioactive vapors or gases or by agglomeration with already radioactive particles). Because particles in the size range of 0.05 to 5 micrometers (µm) tend to be retained by the lungs when inhaled, they are of primary concern in operations that involve radioactive material. They are also recognized as among the health hazards of nonradioactive air pollution. As shown in Table 3.1, over 99 percent, by count, of typical urban air samples have a mean particle size of 0.05 µm.

Reports of dust concentrations in air are generally based on the masses of the particulate matter present. As shown **in Table 3.1,** mass accounts for only a negligible portion of the total number of particles in the air. This is important in filter selection because it indicates that some filters with a high efficiency based on weight may be inefficient on a true count basis. That is, the filters are efficient for large particles, but inefficient for small (less than 0.75 µm) particles. This is true of most common air filters used as medium efficiency filters. On the other hand, the High-Efficiency Particulate Air (HEPA) filter is highly efficient for all particle sizes down to and including the smallest shown in Table 3.1. The 99.97 percent minimum efficiency for these filters is actually for the most penetrating size particles, i.e., those ranging in size from 0.07 to 0.3 µm. Dust concentrations vary widely from place to place and, for the same location, from season to season and from time to time during the same day. Concentrations in the atmosphere may vary from as low as 20 micrograms per cubic meters (µg/m^3) in rural areas to more than 20 mg/m^3 in heavily industrialized areas.

Table 3.1: Distribution of Particles in Typical Urban Air Sample

Mean Particle Size (µm)	Particle Size Range (µm)	Approximate Particles Count per Cubic Foot of Air	Percent by Weight	Percent by Count
20.0	50-10	12.5×10^{3}	28	1×10^{-10}
7.5	10-5	10×10^{4}	63	8×10^{-10}
2.5	5-1	12.5×10^{6}	6	1×10^{-7}
0.75	1-0.5	10×10^{7}	2	8×10^{-7}
0.25	0.5-0.1	12.5×10^{9}	1	1×10^{-4}
0.05	0.1-0.001	12.5×10^{15}	<1	99.9999

Dust-producing operations may generate concentrations as great as several thousand g/m^3 at the workplace. Because the weight percent determinations on which these concentrations are based account for only a small fraction of the number of particles present, the true count of particles smaller than 5 µm may number in the billions per 1000/ft^3. Atmospheric dust concentrations can vary significantly through the year. Filter selection, particularly medium efficiency filter and building supply filter selection, should be based on the atmospheric dust concentrations that can be encountered at a particular site at any time of the year.

Figure 3.1 below, "Distribution of Particles," shows the distribution of particles (by weight percent) in atmospheric air as a function of particle shape. Variations in particle shape, mean particle size, particle size range, and concentration affect filter life, maintenance costs, and operational effectiveness. The size range of various types of particles, the technical nomenclature of various types of aerosols, and the applicability of various types of air cleaning devices as a function of particle size are shown in **Figure 3.2**. A major source of the lint often found on filters is derived from the operations, which generate droplets and solid abrasion of clothing as people move about. In addition, a person at rest gives off more than 2.5 million particles (e.g., skin, hair) and moisture droplets/minute in the size range of 0.3 to 1 mm^3.

Description	Appearance	Kinds	Percent Present by Weight	
			Range	Average
Spherical		Smokes	0-20	10
		Pollens		
		Fly Ash		
Irregular		Minerals	10-90	40
Cubic		Cinder		
Flakes		Minerals	0-10	5
		Epidermis		
Fibrous		Lint	3-35	10
		Plant Fibers		
Condensation		Carbon	0-40	15
Flocs		Smokes		
		Fumes		

Figure 3.1: Distribution of Particles

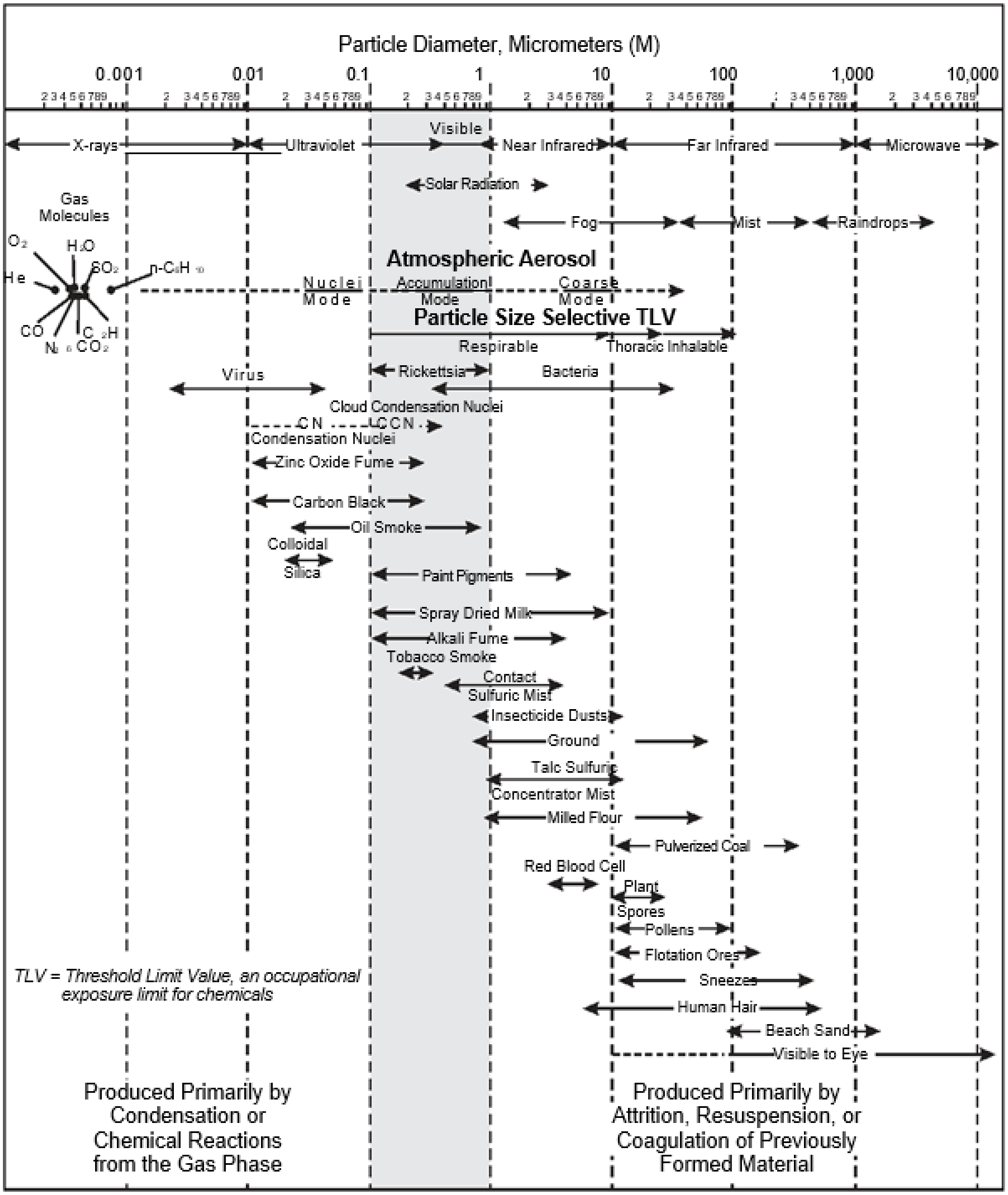

Figure 3.2: Characteristics of Atmospheric and Process-Generated Particulates, Fumes, and Mists and Effective Range of Air

Process-generated airborne contaminants fall into two general size ranges. Those produced by machining, grinding, polishing, and other mechanical operations are generally large, (from one to several hundred µm), based on the process. Particles less than 100 microns can be picked up by the respiratory tract through the nose and mouth. Particles greater than one micron can be removed effectively by commercial air filters or other conventional air cleaning techniques. The other size particle range includes those produced by evaporation/condensation and other processes that are less than one micron in size. Nuclear-grade HEPA and Ultra Low Penetration Air (ULPA) filters provide a higher cleaning efficiency to remove those submicron particles; ULPA filters can remove 99.999 percent of sub-micrometer particles. The need for ULPA filters at DOE sites is only occasionally seen and is site-specific to the DOE application. HEPA filters are less expensive than ULPA filters and are acceptable for removing submicron particles in most applications.

For reactor operations, process-generated contaminants include radioactive noble gases and halogens. Because of their chemical inertness, limited reactivity with available sorbents, and the great difficulty of separating them, the noble gases (xenon and krypton) have been treated in the past by simple holdup to allow time for radioactive decay of the shorter half-life elements, as well as dilution with clean air before discharge to the atmosphere. They can also be separated by cryogenic fractionation, charcoal adsorption, or fluorocarbon adsorption and stored until a significant degree of radioactive decay takes place. Halogen gases, essentially elemental iodine and certain volatile organic iodides are captured by adsorption either on activated carbon or certain synthetic zeolites.

3.3 Environmental Conditions

Although some air cleaning system components are prequalified to operate in a given temperature range, the air cleaning system designer should verify all components of the system will function between the maximum and minimum temperature conditions for the specified application. If the temperature range of the specific application exceeds the components' design qualification temperature, requalification is necessary to meet the operational and design life requirements of the system.

In general, continuous operation at high temperature (greater than 250 degrees Fahrenheit) is detrimental to both HEPA filters and activated carbon adsorbers. At high temperatures, the shear strength of adhesives and binders used in the manufacture of HEPA filters and filter media may diminish, thereby limiting the safe pressure drop to which they can be subjected. The limiting temperature varies with the specific adhesive and binders used. Filter manufacturers have designed HEPA filters for temperatures above 250 degrees Fahrenheit (a 500-degree Fahrenheit filter is also available). The filter manufacturer should provide objective data that the filters are qualified for the higher-temperature environments of the specific application. Alternatively, for high-temperature applications, particulate filtration can be accomplished with the use of metal filters constructed of sintered metal or metal mesh.[1] Ceramic filters are an emerging alternative (see Section 5.1.3.34).

Metal filters are manufactured for medium efficiency and HEPA efficiency ranges. Due to their relatively high cost, metal filters should be considered only for those applications where standard glass fiber filters would not meet the environmental or design conditions.

The limiting temperature of adsorbents for capturing radioactive iodine and iodine compounds is related to the desorption temperature of the adsorbed compound and the chemicals with which it has been impregnated to enhance its adsorption of organic radioiodides. For example, the limiting temperature of adsorbents impregnated with chemicals (e.g., triethylene-diamine- and potassium iodine-impregnated activated carbon) is 280 degrees Fahrenheit.

When temperatures higher than the operating limits of air cleaning system components need to be accommodated, chilled water coils, heat sinks, dilution with cooler air, or some other means of cooling should be provided to reduce temperatures to levels that the components can tolerate. Environmental qualification of an air cleaning system should address thermal expansion and the heat resistance of ducts, dampers, filter housings, component mounting frames and clamping devices, and fans. Operational consideration also should be given to the flammability of dust collected in the ducts and on the filters.

The complexity of the air cleaning system needed to provide satisfactory working conditions for personnel and to prevent the release of radioactive or toxic substances to the atmosphere depends on the following factors:

- Nature of the contaminants to be removed (e.g., radioactivity, toxicity, corrosivity, particle size and size distribution, particle shape, and viscidity);
- Temperature (e.g., process heat, fire);
- Moisture (e.g., sensible humidity process vapors, water introduced from testing);
- Radiation (e.g., personnel exposure and material suitability considerations);
- Other environmental conditions to be controlled; and
- Upset or accident hazard considerations.

In designing an air cleaning system, development of the environmental operating conditions is the first step. Before appropriate individual system components can be environmentally qualified, the designer should consider all environmental parameters on an integrated basis. This may require additional qualifications.

The facility owner normally identifies the design and environmental parameters that are compatible with the overall facility design. These parameters should be identified prior to system design because they are the basis for the equipment design. If the environmental parameters are carefully considered, a detailed analysis of cost versus long-term operation will

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[1] The construction and performance requirements for metal filters will be found in Section FI, Metal Media Filters, of ASME AG-1 (Code on Nuclear Air and Gas Treatment).

provide an environmental maintenance schedule for replacing components and parts throughout the intended operational life of the system. This will ensure that the system will perform its intended function properly, efficiently, and cost-effectively. **Table 3.2** lists some common system environmental parameters that should be considered for system design.

Table 3.2: Environmental Parameters for System Design

Parameters	Examples
Types of gases treated	Air, hydrogen, oxygen, nitrogen, and argon.
Flow rate(s)	The maximum and minimum operating flow rates for normal and accident conditions.
Pressure and pressure drop	The external pressure and/or vacuum pressure at the inlet and/or outlet of the system; the maximum system pressure, usually accident or upset mode; the maximum allowable pressure drop across the air cleaning system components.
Temperatures	The maximum and minimum operating temperatures of the airstream and equipment.
Radiation	The maximum expected alpha, beta, and gamma radiation dose rates (rads/hour) and cumulative levels (rads).
Relative humidity, condensation, and direct introduction of liquids	The maximum and minimum relative humidity of the gas entering the air cleaning system, condensation with potential for wicking.
Contaminants that may be removed (or not) from the gas stream	Removal efficiencies for particulate, gaseous, entrained water, chemical, radiological, volatile organic chemicals, and other materials, as well as considerations of other materials' capabilities for air contaminants.
Seismic requirements	Seismic response curves for the expected equipment location.
Pressure-time transients	Deflagration, detonation (internal), and tornado (external).
Design life and operating life	Projected facility and equipment operating life [e.g., filter service life].
Concentration of contaminants within the facility or area to be ventilated	Specified amounts of identified contaminants, in curies per volumetric unit, grams per volumetric unit, or particles per volumetric unit.
Allowable concentrations of contaminant in the occupied areas of the facility	Specified amounts of identified contaminants, in curies per volumetric unit, grams per volumetric unit, or particles per volumetric unit.
Regulatory limits for stack release of contaminants	Specified amounts of identified contaminants, in curies per volumetric unit, grams per volumetric unit, or particles per volumetric unit. This may also be expressed in dose units of exposure to radiation.

Many radiochemical operations generate acid or caustic fumes that can damage or destroy filters, system components, and construction materials. Some products of radiochemical operations can produce shock-sensitive salts (e.g., perchlorate acid salts and ammonium nitrate) that should be considered in the design and operation. The air cleaning system designer should select components and materials of construction suitable for the corrosive environment to ensure high levels of system performance and reliability. Acid-resistant medium efficiency filters and HEPA filters are available. These filters utilize media constructed with Nomex® or Kevlar® fibers mixed with glass fibers during manufacturing, epoxy-coated separators to extend the life of the aluminum separators, and stainless-steel frames.

Metal filters with a demonstrated suitability for a moist corrosive atmosphere, in accordance with ASME AG-1[2] code requirements, are recommended for hydrogen fluoride or other highly acidic applications. Hydrogen fluoride is a concern because it will attack the glass media. Wood-case filters are vulnerable to attack by nitric acid that will form nitrocellulose and negatively affect filter performance.

Stainless steel is recommended for ductwork and housings when corrosion can be expected. Since this material may be insufficient in some cases, coated (e.g., vinyl, epoxy) stainless steel or fiber-reinforced plastics may be necessary.[3] The system designer can either: (1) use existing databases containing information about the performance of materials (including the filter media) exposed to various concentrations of corrosive contaminants, or (2) perform actual testing to validate the air cleaning system design.

Scrubbers or air washers may be employed to pretreat the air or gas before it enters the air cleaning system or to scrub the airstream of perchlorate and ammonium nitrate salts and other corrosive materials, but consideration should also be given to moisture carryover if the scrubbers or air washers are not designed and operated properly. ASME AG-1 moisture separators are recommended ahead of the filters.

Corrosion is not always an obvious threat. In activated carbon-filled adsorbers, for example, even trace amounts of nitrous oxide or sulfur dioxide will concentrate in the adsorbent over time, and negatively affect the ability of the carbon to remove radioactive contaminants. In the presence of moisture, these compounds can form nitric or sulfuric acids that are capable of corroding the stainless-steel parts of the adsorber, i.e., the perforated metal screens. Aluminum and carbon steel are subject to corrosion when in contact with moisture-laden carbon. For this reason, stainless steel is always specified for adsorber cells and for adsorber-cell mounting frames.

Electrical and electronic components are particularly susceptible to corrosive atmospheres. Plastics become brittle over time, and contacts can corrode. For this reason, all electronic components are environmentally qualified for the intended application.

[2] ASME AG-1, Code on Nuclear Air and Gas Treatment, 2019 ed.

[3] Corrosion-resistant coatings are covered by ASTM D5144, *Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants*.

Care should be exercised in selecting and using gaskets, as some gasket material reacts with the moisture in the airstream and releases chlorides that can corrode steels (including stainless steel). Gasket material selection should also include consideration of the effects of the material's use in acidic, radioactive, or other harsh environments. Note that radiation may cause undesirable reactions such as decomposition of TeflonTM into hydrofluoric acid. The ASME AG-1 Code (Articles FC-3120 and FK-3120) contains specifications for acceptable gasket material.

3.4 Backup Power

Backup electrical power is required when specified by facility design and safety documentation. The amount of backup power needed for fans, dampers, valves, controls, and electrical heaters to control the relative humidity of the effluent airstream (as dictated by the facility design requirements) should be estimated for both off-normal and accident conditions. Close coordination between the system designers of both the air cleaning and electrical systems is needed to ensure that there is adequate backup power available.[4]

3.5 Work Area Ventilation

Work area ventilation systems should be designed to ensure that concentrations of radioactive gases and aerosols in the air of occupied and occasionally occupied areas do not exceed the derived air concentrations (DAC) established for occupationally exposed persons under normal or abnormal operating conditions.

Workroom ventilation rates are based primarily on heating and cooling requirements, the potential combustion hazard, and the potential inhalation hazard of substances that are present in or could be released to the workroom. Releases to the atmosphere should not exceed permissible limits for nonoccupationally exposed persons (see 40 Code of Federal Regulations (CFR) Part 61 Subpart H). Because radioactive gases and aerosols might be released accidentally in the event of an equipment failure, a spill, or a system upset, the ventilation and air cleaning facilities should be designed to maintain airborne radioactive material within prescribed limits during normal operations. In addition, the ventilation and air cleaning facilities should perform in accordance with expectations established during the evaluation of potential accident conditions.

The current DACs for radioactive substances in air are specified in 10 CFR Part 835, Appendix A. These DACs should be applied to the design of a ventilation system using a hazard categorization process where the level of ventilation control is commensurate with the radiological risk present in the proposed operation. (In a similar manner, the same conceptual process can also be applied to non-radiological airborne hazards.) NRC's rule 10 CFR Part 20 provides regulatory guidance on the use of DACs.

Based on the guidance cited above, one approach would be to group the material in use into the hazard classes shown in **Table 3.3**, and then to zone the facility ventilation systems based

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[4] See NFPA 110, "Standard for Emergency and Standby Power Systems" and IEEE 446-1995, "IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications."

on the criteria shown in **Table 3.4**.[5] An alternative approach would be to classify the risk based on the anticipated airborne and surface contamination levels, as shown in **Table 3.5**. The user should note that these criteria are based on the potential for the activity to generate airborne radioactive materials; they do not consider the direct radiation from the material, which would require separate shielding considerations. By introducing such indexes of potential hazards and limitations on the quantities of materials that can be handled, it is possible to establish a basis for ventilation and air cleaning requirements in various parts of a building or plant. **Figure 3.3** illustrates a typical zoning plan for a nuclear facility. Not all of the confinement zones listed in **Table 3.4** would be required in all buildings, and an entire building could possibly be designated a single zone. Confinement zones are defined with respect to function and permitted occupancy in the following paragraphs.

Confinement Zones

As shown in **Figure 3.3**, the general approach is to establish ventilation zones in a three-tiered manner. Multizone buildings are usually ventilated so that air flows from the less contaminated zone to the more contaminated zone. The interiors of exhaust and recirculating ductwork are considered to be of the same hazard classification as the zone they serve. Airflow should be sufficient to provide the necessary degree of contaminant dilution and cooling and to maintain sufficient pressure differentials between zones where there can be no backflow of air spaces of lower contamination, even under upset conditions. The pressure differentials should be determined during the facility's design and should be in accordance with the applicable standards. Substantially higher differentials are often specified between Primary and Secondary Confinement Zones (see below) than for other boundaries.

Table 3.3: Hazard Classification of Radioisotopes

Hazard Class	***Relative Hazard***	***DAC, Air (μCi/ml)***
1	Very High	$>10^{-6}$
2	High	10^{-8} to 10^{-6}
3	Moderate	10^{-10} to 10^{-8}
4	Negligible	$<10^{-10}$

Table 3.4: Zoning of Facilities Based on Radiotoxicity of Materials Handled

Quantity of Material Permitted in Zone at any One-Time [a, b]			
Radiotoxicity of Isotopes	***Primary Confinement***	***Secondary Confinement***	***Tertiary Confinement***
Very High	> 10 mCi	0.1 μCi-10mCi	0-0.1 μCi
High	> 100 mCi	1.0 μCi-100mCi	0-1.0 μCi
Moderate	>1 Ci	10 μCi-1 Ci	0-10 μCi
Negligible	>10 Ci	100 μCi-10 Ci	0-100 μCi

[5] The limits given in the tables are guides and should not be considered absolute.

[a] There are practical upper limits to the quantities of materials in any particular zone, based on the type of material and design of the confinement systems. For example, criticality safety concerns may restrict the amount of fissile material that can be handled at one time, fire protection concerns may limit the amount of pyrophoric materials, and shielding considerations may limit the amount of materials when penetrating radiation is emitted. An activity-specific hazards analysis should always be conducted to determine the actual limits to be applied in practice.

[b] These criteria are based on the potential for the activity to generate airborne radioactive materials.

Table 3.5: Zoning of Facilities Based on Contamination Levels

	Anticipated Contamination Levels		
Type of Contamination	***Primary Confinement***	***Secondary***	***Tertiary***
Airborne [a]	>100 x DAC	1 x DAC to 100 x DAC	< 1 x DAC
Removable Surface [b]	>>RSCV [c]	>RSCV [c]	<RSCV

[a] For airborne contamination, the DAC value is listed in 10 CFR Part 835, Appendix A, for the type and chemical form of the material being handled.
[b] For removable contamination, the RSCV is the removable surface contamination value listed in 10 CFR 835, Appendix D, for the type of the material being handled.
[c] Removable surface contamination levels do not always directly lead to an increasing level of airborne contamination. The level of airborne contamination strongly depends on the potential for the particular activity to resuspend the deposited particles into the atmosphere. For this reason, it is difficult to establish a generic correlation. If the RSCV is the main consideration for differentiating between a secondary and primary confinement specification, then the approach established in Tables 2.3 and 2.4 should be applied.

Areas from which air is not recirculated include areas that produce or emit dust particles, heat, odors, fumes, spray, soot, smoke, or other contaminants that cannot be sufficiently treated and could be potentially injurious to health and safety of personnel or are potentially damaging to equipment. These areas are 100 percent exhausted. Recirculation within a zone (circulating the air through a high-efficiency air cleaning system before discharge back to the zone) is permitted, but recirculation from a zone of higher contamination back to a zone of lesser contamination is typically prohibited.

The methodology used above is based on the DACs for radioactive substances in air, as specified in 10 CFR Part 835. For toxics and noxious substances, the DACs should be replaced with Permissible Exposure Limits (PEL), including irritant and nuisance substances, as specified in 29 CFR 1910. The federal PELs are obsolete in some cases. A more convenient (and generally more current) tabulation of occupational exposure limits is published by the American Council of Governmental Industrial Hygienists (ACGIH) in the annual issue of *Threshold Limit Values* (TLV). The latter reference includes a procedure for determining TLVs for mixed toxicants, as well as limit values for heat stress, nonionizing radiation, and noise. DOE Order (O) 440.1B, *Worker Protection Management for DOE Federal and Contractor Employees*, specifies how to select PELs and TLVs.[6]

Primary Confinement Zone

The primary confinement zone comprises those areas where high levels of airborne contamination are anticipated during normal operations. Facility personnel do not normally

[6] See Section 4m.(9) of the Order.

enter primary confinement zones. When entry is necessary, it is done under tightly controlled conditions. This zone includes the interior of a hot cell, glovebox, piping, vessels, tanks, exhaust ductwork, primary confinement HEPA filter plenums, hood, canyon, or other confinement for handling highly radioactive material. Confinement features should prevent the spread of radioactive material within the building under both normal operating and upset conditions up to and including the Design Basis Accident (DBA) for the facility. Complete isolation (physical separation) from neighboring facilities, laboratories, shop areas, and operating areas is necessary. Unavoidable breaches in the primary confinement barrier should be compensated for by an adequate inflow of air or safe collection of the spilled material.

The exhaust system should be sized to ensure an adequate inflow of air in the event of a confinement breach. An air exhaust system that is independent of those serving surrounding areas is desirable. HEPA filters are typically required in air inlets, and independent testable HEPA filters should be installed in the exhaust, depending on the application. The exact number of testable stages is determined by safety analysis.

Secondary Confinement Zone

The secondary confinement zone comprises those areas where airborne contamination could be generated during normal operations or as a result of a breach of a primary confinement barrier. This zone consists of the walls, floors, ceilings, and associated ventilation systems that confine any potential release of hazardous materials from primary confinement. Related areas include glovebox operating areas, hot cell service or maintenance areas, and the ventilation system servicing the operating areas. Pressure differentials should be available to produce inward airflow into the primary confinement should a breach occur. These pressure differentials should be established in conjunction with particle recommended capture velocities across boundaries between primary and secondary confinement zones. A rule of thumb for capture velocities is 100 fpm. Penetrations of the secondary confinement barrier typically require positive seals to prevent migration of contamination out of the secondary confinement zone. Air locks or a personnel clothing-change facility are installed at the entrance to the zone. Restricted access areas are generally included in the secondary confinement zone.

Tertiary Confinement Zone

The tertiary confinement zone comprises those areas where airborne contamination is not expected during normal facility operations. This zone consists of the walls, floors, ceilings, and associated exhaust system of the process facility. It is the final barrier against release of radioactive and toxic material to the environment. The secondary and tertiary boundaries may exist in common, as in a single-structure envelope.

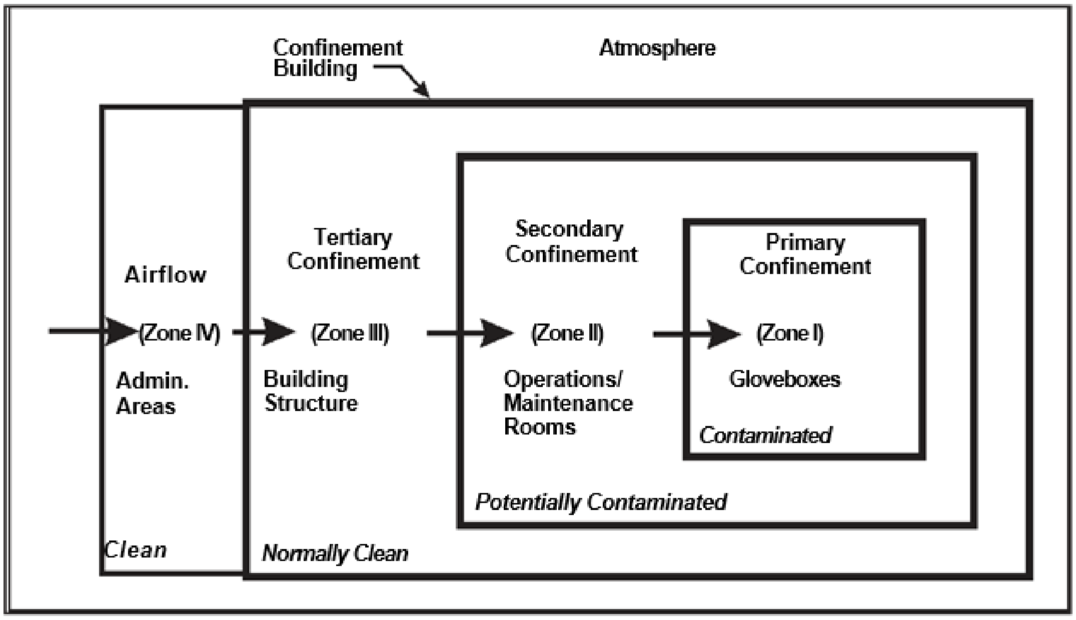

Figure 3.3: Typical Process Facility Confinement Zones

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4.0 Component Level Guidance and Best Practices

4.1 Filtration Components and Filter Testing

4.1.1 Introduction: Filtration Components

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), ceramics, metals, or a wide selection of plastic materials. For filtration purposes, although all filters do not contain fibers, fibers in filters 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. Additional information on ceramic filters is contained in Section. 5.1.3.34. The porous structure can be produced as high strength media with a fiberglass woven fabric laminated to one or both sides of the media for added strength and durability.

Other kinds of air cleaning devices (e.g., adsorbers, liquid scrubbers, electrostatic precipitators (ESP)) 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.

4.1.1.1 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. 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 medium efficiency filters 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 a rigid casing enclosing the full depth of the pleats, with a minimum efficiency of 99.97 percent when tested with an aerosol of 0.3-µm diameter test aerosol particles. (Filters of different flows and resistances are allowable by the ASME AG-1, Code on Nuclear Air and Gas Treatment.) A filter of identical construction and appearance but having a filtering medium with a retention of

99.999 percent for 0.1 µm particles, is referred to as an 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.

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.

There are also 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 should be cleaned periodically, usually by reverse compressed air jets.

4.1.1.2 Filtration

The high porosity of air filters 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 sub-micrometer openings, because each collected particle closes a sieve opening so that very soon no air can pass through.

In contrast, filters collect particles from air and gas streams in 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.

4.1.1.3 Particle Collection by Filters

Figure 4.1 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 should 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* (I in **Figure 4.1**) becomes greater as both aerodynamic equivalent diameter[7] 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 (Brownian) motion (II in

[7] The aerodynamic equivalent diameter can be defined as that of a sphere with a certain density and settles in still air at the same velocity as the particle of interest. This does not necessarily correlate to specific particle sizes listed throughout this handbook.

Figure 4.1). 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.

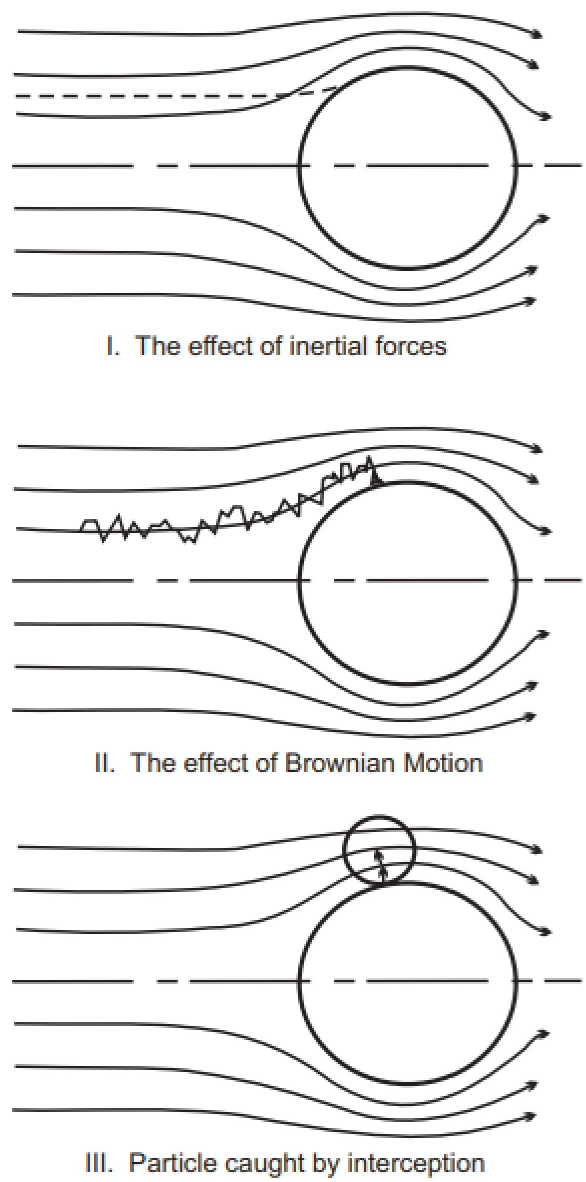

Figure 4.1: Streamlines Around a Filter Fiber

Particle collection by *interception* (III in **Figure 4.1**) occurs when a particle traveling in a streamline that approaches a fiber within one particle radius contacts 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 4.2**, 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 redlined summation curve. **Figure 4.2** 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 effect of flow velocity on particle penetration for HEPA filter medium also shows a minimum efficiency point.

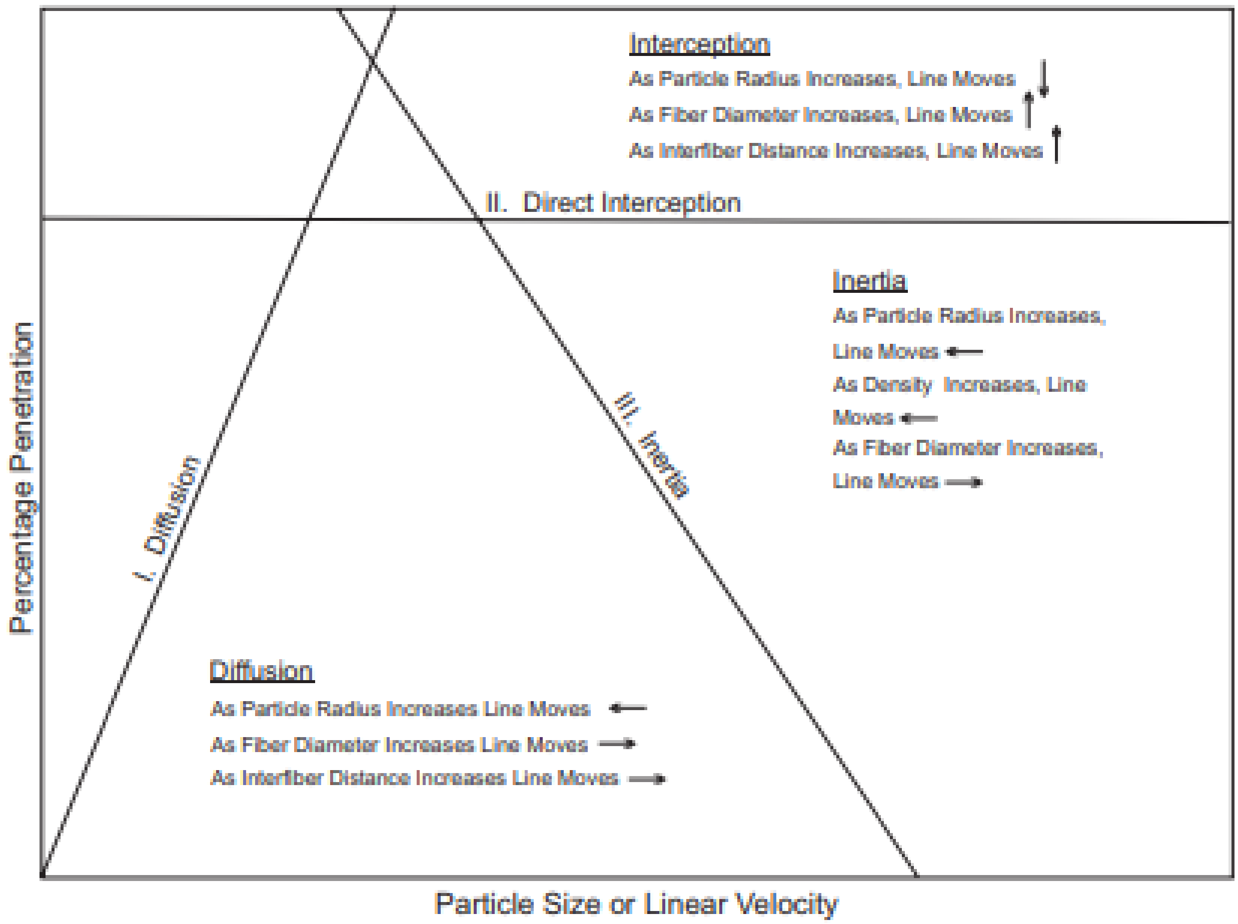

Figure 4.2: The Effects of Inertia, Diffusion, and Interception on the Penetration-Velocity Curve

4.1.1.4 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.

4.1.1.5 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.

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.

4.1.1.6 HEPA Filters: Historical Background

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. For this reason, military standards MIL-F-51068, MIL-F-51079 (filter construction and filter medium preparation), and MIL-STD-282 (filter testing) were issued in an unclassified format.

MIL-F-51068 and MIL-F-51079 were withdrawn by the U.S. Department of Defense (DoD) and replaced by ASME AG-1 and DOE-STD-3020-2015. While MIL-F-51068 and MIL-F-51079 were active, the Edgewood Chemical and Biological Center 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. Though the process remains basically the same, Edgewood now issues letters to manufacturers after qualification testing in accordance with DOE STD-3020-2015.

4.1.1.7 Filter Medium

HEPA filter media used for nuclear service consistently provide collection efficiencies greater than 99.99 percent when qualified in accordance with ASME AG-1 and DOE STD 3020-2015. 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.

4.1.1.8 HEPA Filter Construction

HEPA filter units have historically been constructed via a continuous length of filter medium 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. Additionally, separatorless designs, radial designs, metal media filters, and ceramic filters have different methods of construction. 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 medium 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, discussed in Section 4.1.1.14., **Figure 4.3** shows the assembled components of an open-face, deep-pleat HEPA filter with corrugated separators.

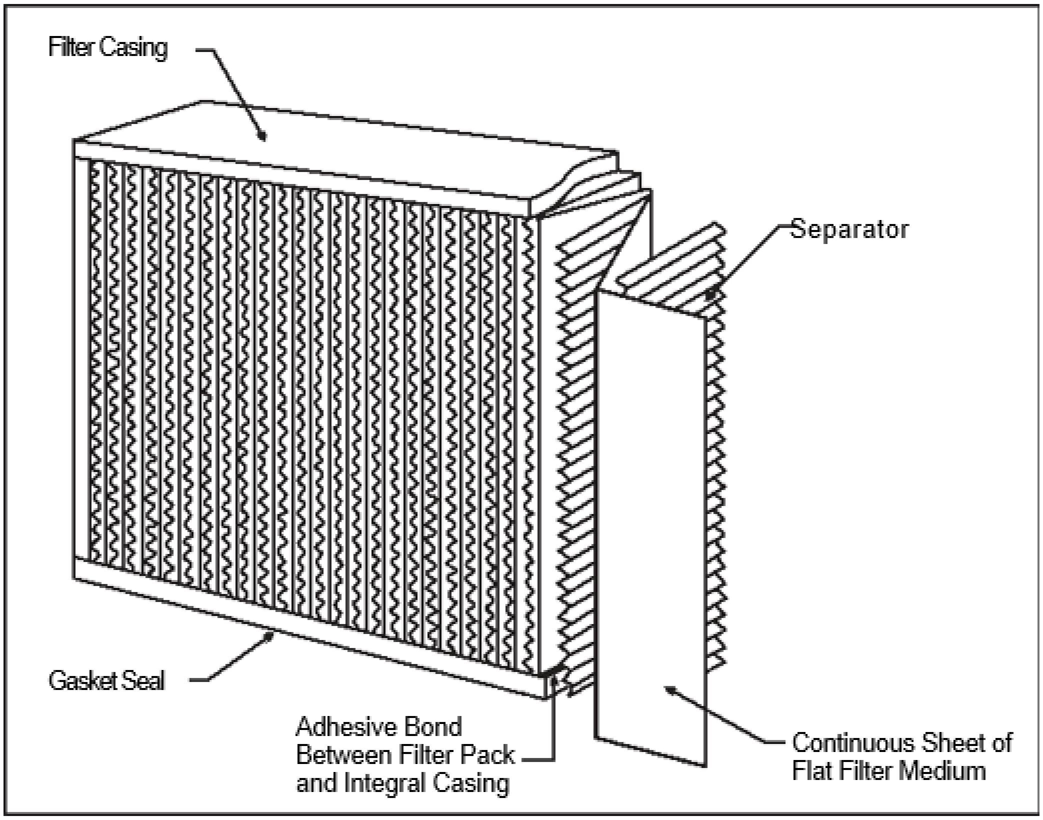

Figure 4.3: Open-Face Deep-Pleat HEPA Filter – Type A Filter Pack

4.1.1.9 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*. ASME AG-1 provides specific guidance on allowable alloys, depending on whether the separators are aluminum or acid resistant aluminum. 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. 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.[8] A dye should be added to clear coating materials so that defects in the plastic coating can be easily detected. ASME AG-1 FC-4150 should be consulted for additional information on separator coatings. According to ASME AG-1, any coatings are required (a) to meet a 3A rating of ASTM D3359, (b) not provide excessive off-gas volatiles, and (c) pass a flexibility test in accordance with FED-STD-141C.

4.1.1.10 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

[8] If significant radiation is a concern, the use of organic materials may not be appropriate.

case materials include fire-retardant plywood[9] and stainless steel in accordance with ASME AG-1 Article FC-3000. 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 14-gauge sheet metal. Grade A-C, American Plywood Association (APA) PS-1 fire-retardant-treated plywood is acceptable, but the “A” face should 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. For wooden case filters, case panels are joined with rabbeted 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. 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.

4.1.1.11 Sealants

Sealants used to provide a leak-free bond between the filter pack and case should 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. Room temperature vulcanizing silicone rubber sealants have been used successfully at operating temperatures up to 392 degrees Fahrenheit (200 degrees Celsius). Additional materials may be used as research and operations experience indicate is appropriate. The continuous updating and re-issuance of ASME AG-1 will reflect these latest advances. ASME AG-1 Sections FC and FK contain additional information on sealants.

4.1.1.12 Gaskets

Filters should be installed so that even the smallest volume of air or gas does not escape filtration; therefore, gaskets 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 yet 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.

[9] The use of plywood casing is discouraged in DOE nuclear facilities.

Gaskets should be oil- and ozone-resistant. Closed-cell sponge gaskets composed of synthetic rubber (neoprene) that conforms to grade 2C3 or 2C4 of ASTM D1056, *Sponge and Cellular Rubber Products,* are required by Article FC-3000 of ASME AG-1. Gaskets should have a minimum thickness of 1/4 inch and width of 3/4 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.

4.1.1.13 Faceguards

To guard against damage from careless handling and faulty installation, a recessed faceguard across both faces of the filter is required according to ASME AG-1 Article FC-4160 and Article FK-4160. Woven or expanded 4X4 mesh metal 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. ASME AG-1 requires faceguards conforming to either galvanized steel ASTM A740, or 304 stainless steel ASTM A580.

4.1.1.14 Separatorless HEPA Filters

A separatorless HEPA filter design, shown in **Figure 4.4,** is constructed without corrugated spacers inserted between the folds of the filter medium. Instead, a continuous sheet of filter medium 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 medium surface than the corrugated separator type, and thus provides greater airflow capacity at equal resistance. Tests of Type C filters conducted at Mississippi State University[10] have suggested that failures may occur under certain accident conditions. These filters are no longer being manufactured.

[10] 19-REP-DOE-SEP/SEPLESS-FINAL, December 17, 2019, Mississippi State University Institute for Clean Energy Technology, work performed under DOE Contract DE-EM0003163.

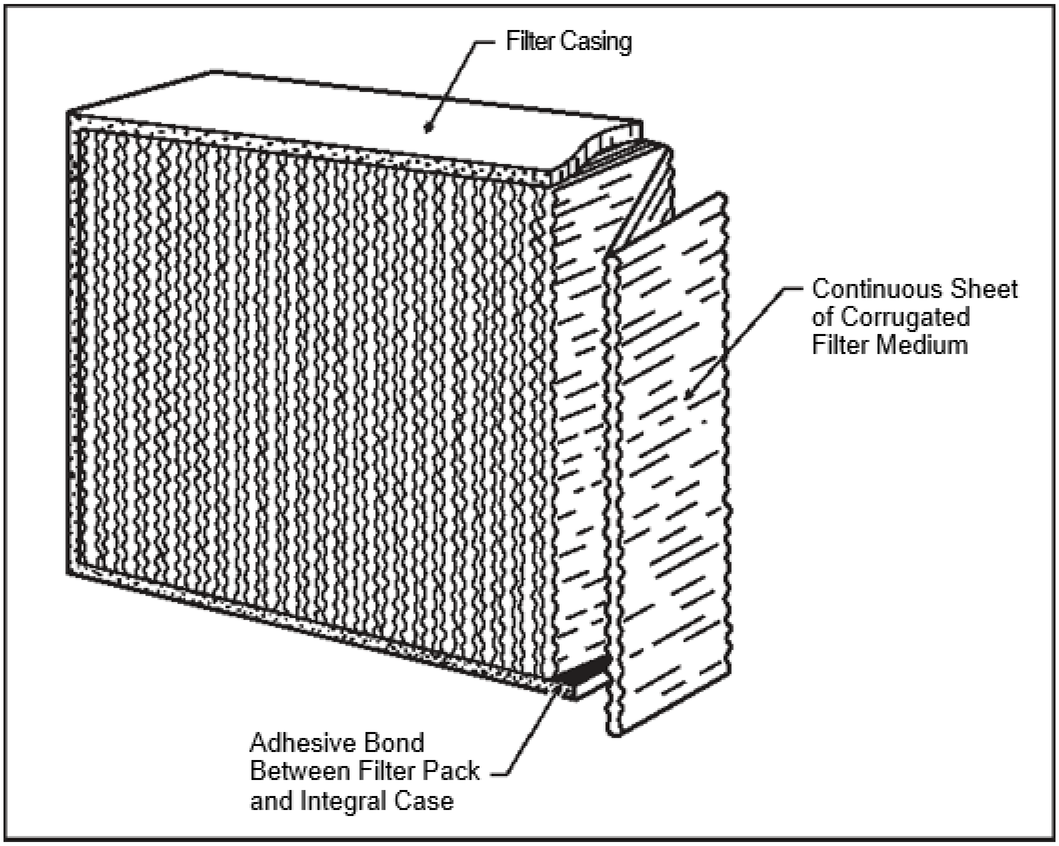

Figure 4.4: Separatorless Style Filter – Type C Filter Pack

A similar filter with more useful filter medium is the ASME Type D filter. This filter does not have a metal separator but contains glass ribbons for support. It is regularly used in nuclear installations and has shown excellent operating performance. The Type D filter is commonly referred to as a "separatorless filter" since there is no metal filter, but it does have a glass ribbon that functions as a separator. Separatorless HEPA filter designs can be more susceptible to pleat collapse than separator filters as documented in DOE Operating Experience-3: 2013-02 "Laboratory Tests Indicate Conditions that Could Potentially Impact Certain Type of HEPA Filter Performance".

4.1.1.15 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 medium 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 medium as deep-pleat, corrugated separator filters of equal frame size **(Figure 4.5)**. 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 or extending filter life by operating at lower than rated airflow capacity. This is called downrating a filter.

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 is 1.6-fold due to the higher media velocity affecting efficiency, and dust bridging across the very narrow air passages between the paper pleats to form a filter cake covering the face area. An efficient medium efficiency filter 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.

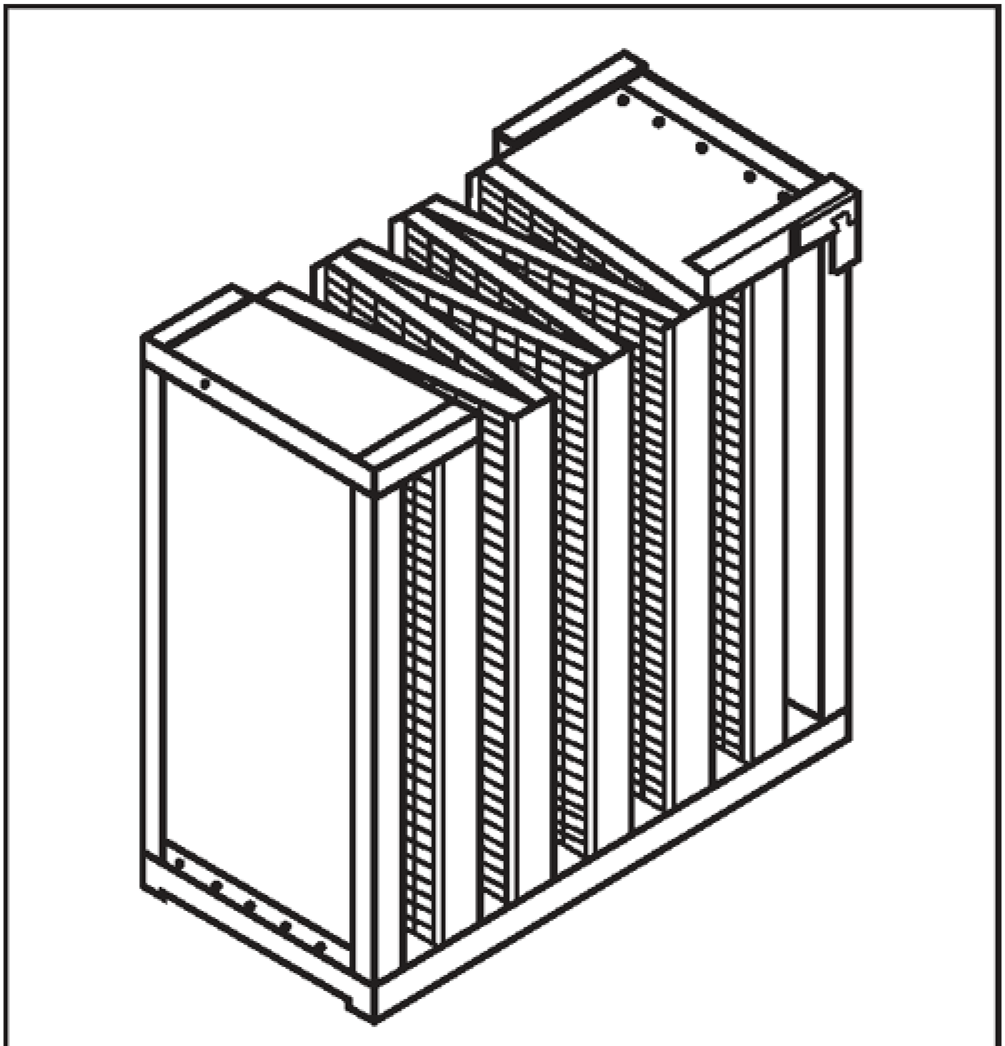

Figure 4.5: Mini-Pleat (Thread Separator) Filter – Type B Filter Pack

The subcomponents are panels that hold the pleated filter medium 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.

4.1.2 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 by the Institute of Environmental Sciences and Technology (IEST) as IEST-RP-CC001.3. This standard lists the classifications described below.

4.1.2.1 Filter Construction Grades

Grade 1 – Fire-Resistant Filters. Filters of this grade 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 should 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 or FK.

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 Underwriters Laboratories (UL) UL 586.

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. These filters comply with UL 900.

4.1.2.2 Filter Performance Levels

IEST-RP-CC001 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) should exceed 99.97 percent for 0.3-µm particles.

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 as well as at rated flow 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.

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 (>99.999 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. 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."

Type B filters are recommended for most nuclear applications, particularly in single-pass systems, and should be qualified in accordance with UL-900. These units comprise a large part of those manufactured by industry and are used extensively in nonnuclear industries as well. Type C filters are common in clean room applications where laminar flow requirements are coupled with low particle penetration and should be qualified in accordance with UL-900. Type D filters presently are used in printed-circuit or microprocessor clean rooms and should be qualified in accordance with UL-900.

4.1.2.3 Enclosed Filters

Most HEPA units are used in the open-face configuration (**Figure 4.3**). 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 4.6**). Enclosing casings may be metal or plywood, but care should be taken to ensure the casing material is compatible with UL requirements for resistance of the filter to heated air and flame. The enclosing casing forms the leak-free pressure boundary in addition to the filter case, and care should 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.

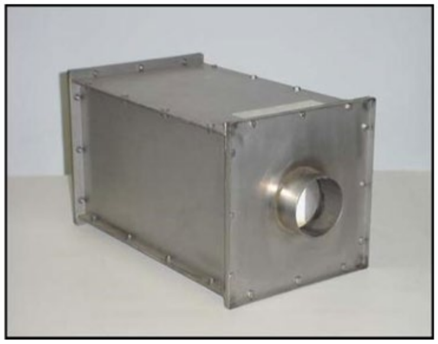

Figure 4.6: Enclosed HEPA Filter

Enclosed filters are sometimes referred to as encapsulated (nipple-connected, closed-face, or self-contained) HEPA filters. ASME AG-1, Section FK contains information on Special HEPA Filters, including radial flow filters that may be considered a subset of encapsulated HEPA filters. Specific guidance applicable to nipple-connected filters is currently not available but is under development by ASME for inclusion in ASME AG-1.

4.1.2.4 Cylindrical Filters

Cylindrical filters may be either open-faced cylindrical axial (**Figure 4.7)** or radial flow (**Figure 4.8**). Filters fabricated with cylindrical cases are easily mounted in circular ducts and offer significant advantages regarding simplified gasketing and automated filter-changing techniques. A "push-through filter system" 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.

Figure 4.7: Open-Faced, Cylindrical Axial Flow HEPA Filter

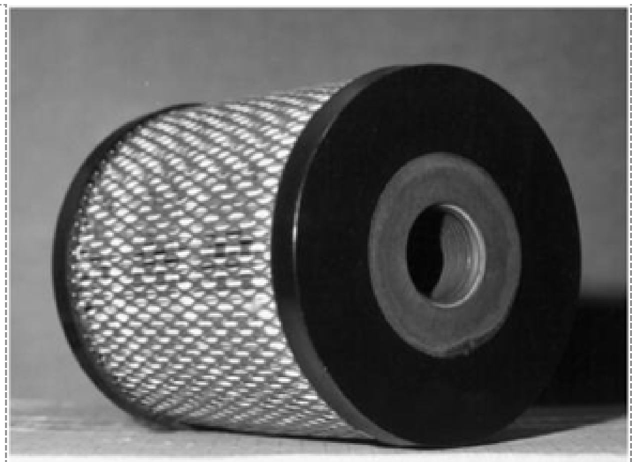

Figure 4.8: Radial Flow HEPA Filter

4.1.2.5 Filter Sizes

The physical dimensions shown in **Table 4.1** have been standardized for the HEPA filters currently used in nuclear service and by U.S. Government agencies. Other sizes can be manufactured and purchased but are considered "special orders." Special applications such as clean rooms, biological safety cabinets, and medical facilities, generally use the same filter height and depth dimensions shown in **Table 4.1** but may have lengths up to 72 inches. Filter configurations for computer applications use many different sizes and shapes depending on the volume available within the computer cabinet.

Table 4.1 (from ASME AG-1, Section FC-4100, "HEPA Filters," by permission)

Table FC-4110-1 Nominal Sizes and Ratings

	Size		Minimum Rated Airflow		Maximum Resistance	
Number Designation	in.	mm	scfm	m^3/h	in. wg	Pa
1	8 × 8 × 3¹⁄₁₆	203 × 203 × 78	25	40	1.3	320
2	8 × 8 × 5⅞	203 × 203 × 150	50	80	1.3	320
3	12 × 12 × 5⅞	305 × 305 × 150	125	210	1.3	320
4	24 × 24 × 5⅞	610 × 610 × 150	500	850	1.0	250
5	24 × 24 × 11½	610 × 610 × 292	1000	1700	1.0	250
6	24 × 24 × 11½	610 × 610 × 292	1250	2100	1.3	320
7	24 × 24 × 11½	610 × 610 × 292	1500	2500	1.3	320
8	24 × 24 × 11½	610 × 610 × 292	2000	3400	1.3	320
9	12 × 12 × 11½	305 × 305 × 292	250	420	1.3	320

4.1.2.6 Filter Weight

The weight of a filter unit is an important factor in design and maintenance. **Table 4.2** lists the weight of clean, open-faced filters and enclosed filters of rectangular design (ASME AG-1 Section FC). The weights for radial, metal, and ceramic filters differ. For design purposes, the weight of a dirty filter that is ready for change-out is approximately 4 pounds heavier per 1,000 cubic feet per minute (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. New and modified ventilation system designs should consider the recommendation in USNRC[11] Regulatory Guide 1.52 that filter housings are no more than 3 HEPA units high for ease of maintenance and changeout.

Table 4.2: Weight of Unused HEPA Filters

Filter Size (inches)	Nominal Airflow Capacity (cfm)	Approximate Weight (pounds) of Filters	
		Wood Case	Steel Case
Open-face			
8 x 8 x 5-7/8	50	3.6	5.8
12 x 12 x 5-7/8	125	4.8	7.3
24 x 24 x 5-7/8	500	17	22
24 x 24 x 11-1/2	1000, 1250, 1500	32	40
24 X 24 X 11-1/2	2000	NA	85
Enclosed			
8 x 8 cross-section	25	5	9
8 x 8 cross-section	50	7	10.5
12 x 12 cross-section	125	17	20
24 x 24 cross-section	500	64	72
24 X 24 cross-section	1000	78	95

4.1.3 HEPA Filter Performance Characteristics

4.1.3.1 Airflow Resistance

Resistance to airflow (pressure drop) of a clean nuclear-grade, 1,000 cfm capacity filter should not exceed 1 inch water gauge (in. wg) when tested at rated airflow for ASME AG-1 Section FC, HEPA Filters. See Table 4.1 for additional filter capacities and pressure drops. Pressure drop may vary for other filter types, e.g., metal, radial flow, and ceramic filters. For these filters, higher initial pressure drop may result in higher rated flow. 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 to maintain reliable operation.

4.1.3.2 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

[11] U.S. Nuclear Regulatory Commission

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 medium efficiency filter 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 for ASME AG-1 Section FC, HEPA Filters. Different dust-holding capacities should be considered when using emerging technology filters, such as metal, high-strength, or ceramic filters. An increase in dust accumulation on the filter medium 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 and concentration 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 sixfold pressure increase. The use of a medium efficiency filter (described in Section 4.1.5) increases the service life of HEPA filters and helps make the combined filtration system cost effective.

For high dust-loading applications, bag house filters are useful due to the ability to self-clean by intermittent back-pulsing of the filters.

4.1.3.3 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.

The values listed in **Table 4.3** are the maximum shocks that can be tolerated without visible damage or loss of filtration efficiency. These data show that: (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 4.3** by 0.5 to 1.0 psi, the filter medium ruptured or experienced cuts on the downstream face. At pressures 2 pounds per square inch (psi) greater than those listed in **Table 4.3**, 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.

Table 4.3: Shock Overpressure Resistance of Open-face HEPA Filters

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

a Clean filter with 4 by 4 mesh faceguards on both faces.
b These filters when tested did not have faceguards.

4.1.3.4 Heat from Fire and Explosion

Grade 1 fire-resistant filters as defined by IEST 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 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 (overpressures), 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. Filters using emerging technologies, such as ceramic pre-filters, may also be used to prevent direct flame, or burning ember, impingement on HEPA filters. See DOE STD-1066 and Section 5.1.3.34 for additional information.

The recommended limitation for filter operating temperature is 250 degrees Fahrenheit. 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 4.4 and 4.5** 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 4.4: 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] Pittsburgh Plate Glass.
[d] Minnesota Mining and Manufacturing (3M).

Table 4.5: 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 [a]
¾ inch thick plywood [a, c]	750	300	275	200	180

[a] Subject to sealant limitations given in Table 4.4
[b] Maximum temperature of 120 degrees Fahrenheit where relative humidity is 75 percent or higher.
[c] Exterior grade, fire-retardant-treated.

4.1.3.5 Moisture and Corrosion Effects

Water exposure is unquestionably an important factor leading to the deterioration of HEPA filters. Detrimental effects occur as a result of repeatedly wetting the filter and drying it. Repeat wetting and drying of a HEPA filter causes a loss of strength. There also are very strong effects of operational time on the behavior of HEPA filters under wet conditions. In such conditions, 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 and soot particulates. Moisture and corrosion effects may be minimized by the use of emerging technology filters, such as metal media and ceramic filters.

The most likely scenario for filter damage in these systems involves filter plugging by the water spray, followed by fan pressure 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 medium can be carried through it by air pressure or capillary action and become re-entrained into the downstream air.

Humidity

High relative 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. The most frequent failure mode is rupture of the downstream pleat. With particle deposits, the filter would absorb water at a lower relative humidity and would rupture even with a demister installed to protect the filter.

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.

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 relative humidity) 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.

4.1.3.6 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. Reactor accidents can result in 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. For these reasons, emerging technology filters, including metal media and ceramic filters, are better suited to high radiation environments.

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 ASME AG-1, Section FN Filter Media: High Efficiency, requires filter media to support a 6-inch column of water after exposure to an integrated gamma dose of 6.0 to 6.5 x 10^6 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 x 10^6 rads ruptured in 100 seconds) but a sample irradiated to only 1 x 10^6 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.

4.1.4 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 an additional independent inspection and penetration tests at the designated DOE Filter Test Facility (FTF) prior to installation at its destination, in accordance with DOE-STD-3025.

The manufacturer's testing regimen involves two distinct phases: (1) a quality control (QC) 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.

In addition, DOE-STD-3020 and DOE-STD-3025 provide additional information on DOE mandated independent inspection and penetration testing for specific types of filter purchases. 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. The filters are tested for compliance with the requirements for physical characteristics, efficiency, and airflow resistance. This testing is conducted at the DOE-supported independent FTF before the filters are released to the customer's facility. The purchaser/customer should request that the manufacturer's test report and a Certificate of Compliance be forwarded for documentation. 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.

In addition to the two regimens, qualification of HEPA filters is performed by the Edgewood Chemical and Biological Center at Aberdeen Proving Grounds, MD. The required qualification tests are specified in DOE-STD-3020-2015.

4.1.4.1 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. 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 medium efficiency filters. For medium efficiency filters, resistance is a power function of airflow 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 (U.S.) 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. 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.

The Q107 penetrometer is used for filters of 1,700 m^3/hr rated capacity, and the Q76 penetrometer tests smaller filters. 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.

The test aerosol particle size is determined by passing a sample through an optical particle-sizing instrument called an OWL 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 monodispersed.

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 when finely tuned and used by a skilled operator. For routine testing, a downstream concentration of 10^{-4} mg/m can be measured with reliability when the upstream concentration is 10 mg/m, 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 99.999 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. 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 $1x10^{-9}$ 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. 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.

4.1.4.2 Quality Control/Assurance Considerations

Systematic QC and quality assurance (QA) 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, 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.

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 and FK, 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 (temperature and moisture extremes).

Nebulized Sodium Chloride

The standard test method used in Great Britain for new HEPA filters 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 U.S., Germany, and a number of other countries.

Nebulized Uranine

The French standard test method, AFNOR NFX 44.011, 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. 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 media. After the sampling period has expired, the filter media 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.

4.1.5 Effects of Aging, Wetting, and Environmental Upsets on HEPA Filter Performance

Intuitively, the aging of filters in storage or in use in-place should lead to a higher probability of media or structural failure. 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.

4.1.5.1 Aging

The deterioration mechanisms involved in HEPA filter aging are:

- Aging and weakening of glass fibers.

- Deterioration of the resin binder and the organic sealant.
- Corrosion of the aluminum separators.
- Moisture damage.
- Mechanical stresses caused by handling the filter and airflow pulses.

Aging of filters leads to degradation in performance. It has generally been accepted that a conservative approach indicates that the maximum total life (storage and in-service) of HEPA filters for consistently removing greater than 99.97 percent 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. Guidance and recommendations can be found in ASME AG-1 Non-Mandatory Appendix FK-A, Determination of HEPA Service Life. Ongoing research[12] on HEPA filter shelf and service life has begun publication (Refs 20, 21, 22, 59, 60, and 61) and can be referred to as guidance in developing a HEPA filter Service Life program. See also the graded-approach PNNL document TPD-012 for HEPA filters.[13] Note that service life as used herein refers to storage and service of the HEPA filter, and thus the manufactured date of the HEPA filter is critical.

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 can 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 should be considered for replacement.

4.1.5.2 Upset Environmental Conditions

Document 12.5 of the Lawrence Livermore National Laboratory (LLNL) Environment, Safety, and Health Manual, HEPA, HEGA, and ULPA Filter System Design for LLNL Applications, states that continuous exposure to the following operational environments will permanently damage or compromise HEPA filters:

- Moisture: 95 to 100 percent relative humidity.
- Hot Air: Temperatures higher than 275 degrees Fahrenheit.
- Fire: Direct fire or high concentrations of particulate matter produced by fire.
- High Pressure: 8.0 in. wg or more, internal or differential across the filter media.
- Corrosive Mist: Dilute moist or moderately dry concentrations of acids and caustics.
- Any acid and some caustics will attack uncoated aluminum separators.
- Hydrofluoric acid will attack the media.

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[12] For further information, see "Effects of Aging on Nuclear Grade HEPA Media and Filters Summary Report, 21-REP-DOE-AGING-FINAL, July 2021 prepared by Mississippi State University Institute for Clean Energy Technology"

[13] https://www.researchgate.net/publication/326882075_PNNL_Technical_Position_Document_TPD-012_Regulated_HEPA_Filters

- Nitric acid will attack wooden boxes making highly flammable nitrocellulose.
- Shock Pressures: More than 1.7 psig.

In addition, the filter exterior should not be exposed directly to outdoor environments.

The following criteria are recommended:

- 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 relative humidity, or at 120 degrees Fahrenheit and between 75 and 95 percent relative humidity. 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 relative humidity.
- Fire: A single occurrence of direct flame impingement.[14]
- 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.

4.1.5.3 In-Place Testing of Filter Installations

An in-place leak test is done after filters are installed at a 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 should be retested until it meets the established criteria for leak-tightness.

4.1.5.4 Packaging, Storage, and Handling of HEPA Filters

The manufacturer should have a quality program such as ASME NQA-1 for the packaging, shipping, handling, and storage of HEPA filters. HEPA filters are normally packaged in

[14] Filters subjected to smoke from fires should have an in-place leak test performed on them immediately by the responsible in-place testing group (i.e., within 24 hours) and should be replaced if the filter fails the in-place leak test.

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. 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 that 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.

When a filter is inserted in the cardboard shipping container, the pleated folds should be oriented in the vertical direction, except for Type B filters as defined in ASME AG-1, Article FC-4100). For filters including Type B, both the filter frame and the enclosing carton should be labeled with a vertical arrow or the notation, "This Side Up." 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 ASME AG-1 Article FC-7000, Packaging, Shipping and Storage. For special HEPA filters, similar information can be found in ASME AG-1 Article FK-7000, *Packaging, Shipping and Storage.*

4.1.6 Medium Efficiency Filters (Prefilters) for HEPA Filters

4.1.6.1 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 medium efficiency filter 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. Selection of an appropriate medium efficiency filter 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 medium efficiency filter efficiency, and (4) the disposal costs for contaminated HEPA filters and potentially uncontaminated medium efficiency filters.

It has been estimated that, with frequent medium efficiency filter replacements, savings in filter system operation could be as much as one-third the cost of operating without medium efficiency filters. Assessment of an acceptable combination of medium efficiency filters 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 medium efficiency filters.

The types of filters used as medium efficiency filters 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 costliest 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.

ASME AG-1 provides information on emerging technology media that can be used for medium efficiency filters, such as metal media and ceramic filters. Section 5.1.3.34 of this Handbook also provides further information.

The user/owner of the facility should incorporate written specifications on the service life of the HEPA filters for change-out criteria based on the use and availability of medium efficiency filters.

4.1.6.2 Classes, Sizes, and Performance Characteristics of Medium Efficiency Filters

Table 4.6 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.

Values stated in **Table 4.6** 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 medium efficiency filter replacement. Although manufacturers recommend specific values of resistance for medium efficiency filter 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 efficiency filter by adding "cake" filtration principles to the existing physical mechanisms.

The extended-medium efficiency filter 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's Standard 52.2-2017 gives methods for testing filter efficiency by particle size using optical particle counters, including lasers, and defines MERV as the minimum efficiency reporting value corresponding to a specific intended dust spot efficiency.

Table 4.6: Dust-Holding Capacity

MERV Std 52.2	Intended Dust Spot Efficiency Std 52.1 (1)	Average Arrestance	Particle Size Ranges	Typical Applications	Typical Filter Type
1 - 4	<20%	60 to 80%	> 10.0 µm	Residential/Minimum Light Commercial/ Minimum Minimum Equipment Protection	Permanent / Self Charging (passive) Washable / Metal, Foam / Synthetics Disposable Panels Fiberglass / Synthetics
5 - 8	<20 to 60%	80 to 95%	3.0-10.0 µm	Industrial Workplaces Commercial Better / Residential Paint Booth / Finishing	Pleated Filters Extended Surface Filters Media Panel Filters
9 - 12	40 to 85%	>90 to 98%	1.0-3.0 µm	Superior/Residential Better/Industrial Workplaces Better/Commercial Buildings	Non-Supported / Pocket Filter / Rigid Box Rigid Cell / Cartridge V-Cells
13 - 16	70 - 98%	>95 to 99%	0.30-1.0 µm	Smoke Removal General Surgery Hospitals & Health Care Superior/ Commercial Buildings	Rigid Cell / Cartridge Rigid Box / Non-Supported / Pocket Filter V-Cells

Note: This table is intended to be a general guide to filter use and does not address specific applications or individual filter performance in a given application. Refer to manufacturer test results for additional information.
(1) ANSI/ASHRAE 52.1 ranges are provided for reference only. The ANSI/ASHRAE 52.1 Standard was discontinued as of January 2009.

4.1.6.3 Commercial and Industrial Grade Filters Performing as Medium Efficiency Filters

As previously discussed, medium efficiency filters (prefilters) provide protection for HEPA filters and extend their service life by removing large particles and other particulate matter in the flowing air stream. In addition to medium efficiency filters that satisfy the requirements of ASME AG-1 Section FB, ANSI/AHRI Standard 850 (I-P)-2013, provides information and classifies commercial and industrial grade filters that perform the same function. These filters are classified into groups:

Group I - Unit or panel

Group II - Extended surface

Group III - Electronic Air Cleaner

Group IV - Air Filter Media

Group V - Self-cleaning, Self-renewable Air Cleaner, or any combination thereof

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 V filters that provide better protection for the HEPA filter.

Group V (moderate-efficiency) and Group II (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 V filters is moderate to poor for sub-micrometer-sized particles, but often approaches 100 percent for particles greater than 5 µm. In most cases, the pressure drop of extended-media Group V 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. For high dust-loading applications, bag house filters are useful due to the ability to self-clean by intermittent back-pulsing of the filters.

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

Group II filters are recommended for nuclear applications, and ASME AG-1 Section FB, Medium Efficiency Filters, should be consulted for additional guidance on the design, manufacture, operation, and maintenance of medium efficiency filters.

4.1.6.4 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. Tribo-electrification 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.

Electrofibrous filters provide greater efficiency and longer service life for the medium efficiency filters used to protect HEPA filters. They have been used in gloveboxes and for other applications. Laboratory tests conducted at LLNL using test and sodium chloride aerosols have shown that an electrofibrous medium efficiency filter 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 sub-micrometer particles. When continuously charged electrofibrous filters were applied as medium efficiency filters for HEPA filters in exhaust air systems or gloveboxes used to burn uranium turnings, they significantly prolonged the life of the final filters.

4.1.6.5 Operation and Maintenance of Medium Efficiency Filters (Prefilters)

All medium efficiency filter construction materials should be compatible with those of the downstream HEPA filters they are designed to protect. Therefore, they should 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 should be addressed when medium efficiency filters 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 medium efficiency filter and result in more frequent replacement. In general, a medium efficiency filter 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).

Most types of medium efficiency filters 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 medium efficiency filters should take a conservative view of performance claims, particularly claims related to efficiency at high operating temperatures.

Because of waste disposal requirements, the preferred choice of a medium efficiency filter for nuclear applications is the single throwaway cartridge. A replaceable-medium efficiency 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 efficiency 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. For this type of application, ASME AG-1 Section FB contains guidance that should be considered for DOE facilities.

4.1.7 Deep-Bed Filters

Deep-bed filters were designed, built, and placed in service early in the development of nuclear technology for treating off-gassing 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 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.

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.

4.1.7.1 Deep-Bed Sand Filters

Initially, sand filters were installed at the Hanford Reservation and at the Savannah River Site (SRS). Following their success, more were added at Hanford and SRS and others were constructed at nuclear facilities in Morris, Illinois, and Idaho Falls, Idaho. The Argonne National Laboratory compiled a bibliography (ANL-7683, *Sand-Bed Filtration of Aerosols: A Review of Published Information on Their Use in Industrial and Atomic Energy Facilities*) of Deep-Bed Sand (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 use of an elevated steel grating platform can also be used for this purpose, as identified in ASME AG-1, Section FL. The total bed is enclosed in a concrete-lined pit. The superficial velocity is generally 5 to 7 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. More details on DBS Filters are provided in Section 5.4 of this handbook.

Detailed guidance on DBS filters is contained in ASME AG-1, Section FL, Deep Bed Sand Filters. This guidance is based on operational experience from the use of DBS filters at SRS.

4.1.7.2 Deep-Bed Glass Fiber 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 Deep-Bed Glass Fiber (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 (240 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 air flowing 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.

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.

4.1.7.3 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 off-gas 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, non-agglomerating 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 sub-micrometer 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 off-gas cleaning systems, particularly when heat recovery from the hot filtered gases is desired. However, care should 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).

Ongoing research at several laboratories worldwide is ongoing for metal media filters. A future edition of ASME AG-1 Code will contain applicable sections on this topic.

4.1.7.4 Moisture Separators (Demisters)

Liquid droplet entrainment separators, known as moisture separators or demisters, 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 should 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 sub-micrometer-sized aerosols, but the droplets may grow rapidly to multi-micrometer size by acting as condensation centers for additional cooling vapors and by coagulation when the concentration of droplets exceeds 10 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.

In USNRC Regulatory Guide 1.52, 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. As previously discussed, HEPA filter medium is treated for water repellency, however high-water loadings rapidly saturate the paper leading to degradation of filter performance and potential catastrophic failure of the filter. 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 $8x10^7$ rads integrated dose without visible deterioration or embrittlement of the materials of construction. ASME AG-1 Section FA, Moisture Separators, should be consulted for the specific design criteria for moisture separators.

An entrainment separator with these characteristics will provide long-term protection for a downstream HEPA filter. 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. Details of construction can be found in ASME AG-1, Section FA.

4.1.8 Testing

4.1.8.1 Introduction

Testing of high-efficiency nuclear air cleaning systems is required to achieve and maintain high performance and continued safe operation of nuclear facilities. In nonreactor nuclear facilities throughout the DOE complex, HEPA filters in confinement ventilation systems can be constantly challenged with radioactive aerosols. Nonreactor nuclear facilities comprise the bulk of DOE nuclear facilities, and failure of their air cleaning system components can lead to uncontrolled atmospheric release of radioactive aerosols. Thus, maintaining nuclear facility operability depends on the performance of these air cleaning components. At the same time that HEPA filters and adsorbers were being developed for nuclear applications, methodologies were being developed to assure their performance. These methodologies eventually evolved into a performance assurance program with three major components: (1) design qualification of individual components through destructive testing, (2) QA of individual components through nondestructive testing, and (3) performance assurance of nuclear confinement ventilation systems through in-place testing. This overall performance assurance program was designed to be hierarchical because components were built on a foundation laid down by preceding components. Design qualification assured that filters produced according to a manufacturer's design met specific performance criteria for normal and off-normal operation.

HEPA filters for DOE nuclear service now undergo four tests: (1) design qualification test performed by a qualified laboratory, (2) production inspection and testing at the manufacturer, (3) DOE-required QA inspection and testing at a DOE-designated FTF, and (4) receipt inspection and system leak test at the facility where the filter will be used. Manufacturers submit prototype filters for design qualification testing. This testing examines areas such as media penetration and resistance to airflow, rough handling, pressure, heated air, and spot flame. The filter medium receives the most rigorous and extensive control and evaluation. The U.S. Army's Edgewood Chemical and Biological Center performs the tests required for qualification, with the heated air and spot flame test being performed at UL in accordance with UL-586. This testing is required to be repeated every 5 years. Manufacturers receive a letter stating whether their filter designs passed the qualification tests. Further information can be found in DOE-STD-3020 and 3025.

After being installed at a DOE nuclear facility, an in-place leak test is done to ensure the performance of the confinement ventilation system. Unlike bench tests for new filters that are designed to determine filter quality via a penetration test utilizing an aerosol containing a substantial fraction of particles in the range of the minimum filterable size, in-place tests are designed to reveal the presence of defects in the filter unit that result from such things as rough handling during transportation, paper and gasket damage during installation, inadequate pressure against intact gaskets, and penetrations through the housing to which the filter units are attached. Procedures are conducted to locate and correct the defects. Such procedures include increasing gasket compression; examining gaskets for breaks and tears; replacing broken filters (repairs are not permitted for nuclear service in the U.S.); and welding closed any unauthorized penetrations, cracks, and open seams in the filter house and mounting frames (patching with caulking compounds is not permitted for nuclear service in the U.S.). Following each repair, the system should be retested until it meets the established criteria for leak tightness. ASME AG-1, Section TA, Field Testing of Air Treatment Systems, contains information on repairs and required in-place tests after repairs, and ANSI N-511 contains information on in-service testing. When repairs require re-qualification of equipment, the applicable sections of AG-1 apply.

The performance of the periodic/surveillance in-place test cannot be overemphasized. The in-place leak test described by ASME/ANSI N-510 has been used to conduct a periodic surveillance to reconfirm the performance of the filter system. This standard is no longer published through ASME and has been superseded by ASME AG-1, Section TA, Field Testing of Air Treatment Systems. This Code section should be referenced for any in-place leak testing done at any DOE facility. The in-place leaks test confirms the safety basis assumptions "system efficiency." The final result is a measure of efficiency that forms the basis for removal efficiency assumed in the safety bases. The in-place test results may also be credited by the radcon and air emission permits for removal of respirable particles. Unlike the filter penetration test which validates the filter design assumption using a mono-disperse aerosol test, the in-place leak tests use a poly-dispersed (0.7 mean diameter) and determines the system efficiency where the system components (i.e., gaskets, frame, housing) are challenged. The test is performed under actual conditions and at operational airflow. The criteria for the in-place leaks tests are typically provided by the safety basis or other operating licenses/permits. The test results may also be used as a service life indicator.

4.1.8.2 Proof of Design – HEPA Filter Design Qualification Testing for Nuclear Service

As discussed previously, the U.S. Army's Edgewood Chemical and Biological Center tests prototype HEPA filters to qualify the designs for use in DOE nuclear facilities (this testing is required to be repeated every 5 years). ASME AG-1, Section FC and Section FK, requires quality product qualification testing for efficiency, airflow resistance, rough handling, overpressure, heated air, and spot flame. The following subsections discuss each design qualification test and associated acceptance criteria.

4.1.8.2.1 Penetration (Efficiency)

The performance of a HEPA filter may be expressed either as a particulate collection efficiency (percent of particulate concentration stopped by the filter) or as a penetration. Penetration where the total aerosol penetration through the filter medium, frame, and gasket of a filter that has been encapsulated should be no greater than 0.03 percent of the upstream concentration at rated airflow and at 20 percent of rated airflow (except for filters rated at 125 cfm or less). The reason for the 20 percent flow test is to increase sensitivity for pinhole determination. Concentration may be given 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 is indeterminate), or light-scattering intensity per unit air volume (emphasizing small particle sizes).

4.1.8.2.2 Airflow Resistance

The resistance of a filter to airflow, often called "pressure drop" and "back pressure," is usually given as the height of a water column (measured in in. wg) that exerts an equal pressure. 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 even though the air approaching the filter may be turbulent. Resistance to airflow at the rated airflow of the filter should be no greater than 1.0 in. wg for filter sizes 4 and 5, and 1.3 in. wg for filter sizes 1, 2, 3, 6, 7, 8, and 9. (See ASME AG-1, Section FC for filter definitions.) ASME AG-1 also includes information on resistance to airflow for other HEPA filter configurations.

4.1.8.2.3 Aerosol Test

Equipment and procedures to aerosol test HEPA filters can be found in ASME AG-1, DOE-STD-3025, IEST-RP-CC034, and previous versions of this Handbook (with reference to Military Standard MIL-STD-286). Room air is drawn through filters and split into three streams. One stream of 85 cfm is heated to 365 degrees Fahrenheit and is passed over liquid test aerosol heated to 390 ± 20 degrees Fahrenheit. As the heated air passes over the surface of the hot test aerosol, it becomes saturated with aerosol vapor. Traditionally the test aerosol of choice was dioctyl phthalate (DOP). Other non-carcinogenic test aerosols, such as poly-alpha olefin (PAO) are allowable as indicated in ASME AG-1 and DOE-STD-3025. When the test-aerosol-saturated air contacts the second airstream (265 cfm held at approximately 71 degrees Fahrenheit), the condensation aerosol is formed. The third stream of diluent air (850 cfm) is introduced in a mixing chamber to dilute and disperse the aerosol-laden air. A forward light-scattering photometer is used to measure test aerosol penetration, and a manometer is used to measure filter resistance at rated airflow. Modern penetrometers that use jet impactors to obtain the same aerosol without heating the test aerosol liquid are commercially available.

4.1.8.2.4 Resistance to Rough Handling Qualification Test

In accordance with ASME AG-1 Section FC and FK, new, unused test filters (at least 2 of the size and design to be qualified) should undergo rough handling for 15 minutes at a total amplitude of 0.75 inches (using sharp cut-off cams that result in both a slow and an instantaneous 0.75-inch drop) and a frequency of 200 Hertz (Hz), with pleats and filter faces in vertical orientation. The filters should withstand this treatment without visible damage (cracked or warped frames, loose corners or joints, cracked adhesive, loose or deformed medium) or a decrease in filtration efficiency from 99.97 percent, as determined with nominal 0.3 rim test aerosol at full and 20 percent flows.

4.1.8.2.5 Moisture and Overpressure Resistance Qualification Test

At least four new, unused filters of the type to be qualified should be aged a minimum of 24 hours under static conditions at 95 ± 5 degrees Fahrenheit and 95 ± 5 percent relative humidity after which they should be installed in a wind tunnel that has been modified to permit the introduction of water spray. After conditioning, the filters should withstand a spray of 1.25 pounds per 1,000 cfm, adjusted to produce a 10-in.wg pressure drop across the filter, and a flow environment of 95 degrees Fahrenheit. The minimum test duration under these specified conditions is 1 hour. After the test and the filters are dried out, there should be no visible evidence of failure. Within 15 minutes after completion of the pressure test and while still wet, the 0.3-rim test aerosol efficiency at full and 20 percent rated flow should be a minimum of 99.97 percent. This is the most stringent test an assembled HEPA filter will undergo and is limited to a 10-in.wg pressure drop. Additional details can be found in ASME AG-1, Section FC and FK.

4.1.8.2.6 Fire and Hot Air Resistance Qualification Test

New, unused filters should be exposed to heated air in a wind tunnel at 700 ± 50 degrees Fahrenheit for 5 minutes. After exposure to heat, the filters should be cooled down and tested in-place, with the filter remaining in the heated air tester. An aerosol generator and photometer may be used for the aerosol test. The penetration at equal to or greater than 40 percent of rated flow should be less than 3 percent. Additional details can be found in ASME AG-1 Section FC and FK.

4.1.8.2.7 Spot Flame Resistance

In this test, the HEPA filter is inverted in a test duct and operated at its rated airflow. A gas flame from a Bunsen burner is directed against the upstream face of the HEPA filter. The Bunsen burner is adjusted to produce a flame with a blue cone 2.5 inches long with a tip temperature of 1750 ± 50 degrees Fahrenheit. The tip of this flame is applied so that it is not less than 2 inches from the filter face. The flame is applied for 5 minutes at each of 3 separate locations on the filter face. The Bunsen burner flame then is directed into the top corner of the filter unit so that the tip of the blue flame cone contacts the frame, filter pack, and pack sealant. The flame is applied for a period of 5 minutes. After the removal of the test flame at each point of application, there should be no sustained flaming (burning) on the downstream face of the unit. Additional details can be found in ASME AG-1 Section FC and FK.

4.1.8.2.8 Quality Control, Inspection and Testing of HEPA Filters

The manufacturer's qualification procedure involves two distinct phases: (1) a QA/QC routine intended to ensure careful manufacture of a quality product, and (2) a series of tests to verify filter compliance with preset standards concerning the properties of components and the physical characteristics of the assembled filter, as well as a set of performance criteria related to collection efficiency and resistance to airflow. When all of these factors are within the tolerance limits set by ASME AG-1 Section FC and Section FK (and other applicable sections), the manufacturer certifies that each delivered filter unit meets all acceptance criteria. The manufacturers required tests for HEPA filters are prescribed in ASME AG-1, Section FC, and in ASME AG-1, Section FK for special HEPA filters.

4.1.9 Filter Qualification, Quality Assurance Inspection, and Testing of HEPA Filters

4.1.9.1 Introduction

The operating policy of DOE's filter testing program, contained in DOE-STD-3025, *Quality Assurance Inspection and Testing of HEPA Filters*, calls for testing all HEPA filters intended for environmental protection at DOE contracted FTF. Specifications for HEPA filters to be used by DOE contractors are contained in DOE-STD-3020-2015, *Specifications for HEPA Filters Used by DOE Contractors.*

The QA activities and testing performed at the DOE contracted FTF are considered defense-in-depth and should not be relied upon to substitute for onsite receipt inspection, or other QA activities, that would normally be conducted for NQA-1 procured equipment or components.

4.1.9.2 Visual Inspection

Visual inspection is an integral and vital part of every acceptance or surveillance test. A careful visual examination should be made of each internal and external component prior to installation to verify that the items have been received in satisfactory and serviceable condition. After installation, the system should be checked as part of the acceptance test procedure to make sure that all required items have been properly installed. A required visual inspection checklist is contained in ASME AG-1, Mandatory Appendix TA-I. A suggested checklist is provided in Section 5 of ASME N510, which may be used to verify that system design and construction are in accordance with ASME N509. ASME AG-1 also provides guidance for visual inspection in Section 5.0 and Appendix 1 of Section AA.

4.1.9.3 In-Place Component Tests and Criteria

System tests fall in two broad categories: (1) prestart up acceptance tests to verify that components have been installed properly and without damage and that the system can operate as intended, and (2) surveillance tests made periodically after the system has been placed in operation to demonstrate its ability to continue performing its intended air cleaning function. Surveillance tests are leak tests of the HEPA filter and adsorber installations. ASME AG-1 Section TA, Field Testing of Air Treatment Systems, contains requirements for general inspection, field acceptance tests, corrective actions, and necessary instrumentation to perform acceptance tests. DOE facilities conduct surveillance tests with procedures that are adapted to their facility. For nuclear power stations, USNRC Regulatory Guides 1.52 and 1.140 provide guidance that can be used by DOE facilities to prepare their procedures.

4.1.9.4 Component Acceptance Testing

Acceptance tests also fall into two broad categories: (1) those that relate to the permanent elements of the system, ducts, housing, mounting frames, and location of test ports, and (2) those that verify the installation and condition of the primary air cleaning components (HEPA filters and adsorbers). Tests in the first category include leak tests of ducts, housings, and primary-component mounting frames; airflow capacity and distribution tests; gas residence time tests for systems containing adsorbers; duct-heater tests for systems containing heaters; and air-test aerosol mixing-uniformity tests. The acceptance test program for a particular system may contain any or all of these tests, depending on the nature of the system and its importance (i.e., the potential consequence of a failure.

The basic precepts of acceptance testing as specified ASME AG-1, Section TA are:

- All components such as medium efficiency filters, mist eliminators, HEPA filters, and adsorbers are qualified and tested as individual components. Their original efficiency is established, and “as-installed” tests do not require further “efficiency testing.” The in-place test is conducted to ensure the integrity of components is maintained and that no bypass exists.
- The housing is of the desired strength and integrity, which can be measured by isolating the unit envelope housing and leak testing under the specified pressure differential conditions.
- The framework integrity (framework holding critical components such as HEPA filters and adsorbers) can be measured by using blank off plates and pressure differential leak tests.

For clarity, it should be reiterated that the definition of the “Air Cleaning Unit” is an assembly of components that together comprise a single subdivision of a complete air cleaning system, including all the components necessary to achieve the air cleaning function of that subdivision. A unit includes a single housing, with the internal components (e.g., filters, adsorbers, heaters, instruments) installed in or on that housing.

Acceptance tests are outlined in ASME AG-1, Section TA. Before assembly, personnel should assure that all components meet the specified criteria. Typical QA acceptance only assures that paperwork is available. This paperwork should be checked both for original supply and for replacement parts. Before installing components, personnel should perform the following tests:

- Visual Inspection,
- Duct Leak Test,
- Housing Leak Test,
- Mounting Frame Leak Test.

During and immediately after installation of components, personnel should perform the following tests:

- Visual Inspection,
- Airflow Capacity and Distribution Test,
- Air/Aerosol Mixing Uniformity Test,
- In-Place Leak Test HEPA Stage,
- Remove Adsorbent and Perform Laboratory Testing (to establish baseline carbon efficiency),
- In-Place Leak Test Adsorber Stage, and
- Duct Damper Bypass Leak Test (if required).

4.1.9.5 Duct and Housing Leak Test

The level of duct and housing leak tightness (and therefore the acceptance criterion for the test) is based on the type of construction and the potential hazard (consequence) of a leak. Recommended maximum permissible leak rates for various duct and housing constructions are given in AG-1, Mandatory Appendix TA-III, Duct and Housing Leak Test Procedures. The designer may specify tighter requirements based on the confinement requirements of the system.

Duct leak tests may be conducted by testing the entire ductwork system at one time or by testing one section at a time and blanking off the ends of the section under test. The second method is more practical for larger systems. When segmented, the permissible leak rate for the individual sections is based on the proportionate volume of that section. The apparatus and procedure for leak testing levels 1 and 2 ducts are described in the Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) HVAC – Duct Design. ASME AG-1 offers two test methods for housing leak test: (1) the Pressure Decay Method (the most convenient for larger duct and housing systems) and (2) the Constant Pressure Method (the most effective for smaller volumes).

Test methods for level 3, 4, and 5 ducts and for housings are described in ASME AG-1. If the specified leak tightness cannot be met, leaks are located, repaired, and retested by one of the methods described in ASME AG-1. When performing the unit housing leak test, it is important to follow the normal procedures (e.g., closing doors) and thereby avoid creating a once-in-a-lifetime condition that does not resemble normal operating procedures and conditions. The test is supposed to demonstrate that the unit housing will maintain the specified leak-tightness during its operating life. To ensure the leak integrity of the housing is maintained due to deterioration of door gaskets, or occurrence of sprung doors, damaged threads on closures, and leaks due to maintenance work on the unit, personnel should perform periodic retesting (every 10 years). Other methods such as acoustical monitoring or tracer gas monitoring may be appropriate when entry into the housing is precluded.

4.1.9.6 Mounting Frame Pressure Leak Test

This test is performed to ensure the installed HEPA filter/adsorber mounting frame is installed with no leak paths through the structure. This is considered an optional test because the same evaluation is done after the filters are installed, and an in-place leak test is performed on the bank. However, this test may be useful for determining gross leakage prior to filter installation, and thus maximize the ease of any needed repairs prior to filter component installation. Any repairs required should be done before installation of any HEPA filter/adsorber. This test is also the first check for any other leak paths through conduits, drains, etc., which communicate between the upstream and downstream side of a single bank of HEPA filters or adsorber banks. Realistic test performance requires the unit housing leak test to be performed and the specified leak criterion to be met. The acceptance value set in the specifications should always be realistic.

These tests are conducted to verify there are no leaks through the HEPA filter and adsorber mounting frames or through the seal between the mounting frames and the housing. The tests also verify there is no bypassing of the mounting frames through electrical conduits, drains, compressed air connections, and common anterooms of the housing, or other inadvertent leak paths. Familiar sources of leaks are weld cracks and incomplete welds. A properly designed mounting frame should have no penetrations (via conduits, piping, or ducts), and lighting, drain, and other ancillary systems should be designed so that no bypassing of the HEPA filters and adsorbers can occur. Nevertheless, unauthorized modifications are often made in the field. The purpose of this test is to disclose such occurrences, as well as any leaks caused by poor workmanship or shipping damage. The test is recommended for any installation, whether duct and housing leak tests are performed or not, but it is particularly necessary when subsequent in-place tests of the HEPA filter and adsorber stages will be performed using a shrouded method.

This test is conducted by first blanking off all openings for filters and adsorbers and closing or blanking off all openings in the housing, then conducting a soap-bubble or spray test aerosol leak test around all welds and other potential leak paths (as described in ASME AG-1). After all leaks have been repaired, individual chambers of the housing should be checked by a pressure leak rate test to verify there are no bypasses that were not disclosed by the leak detection check. It is unnecessary to perform these tests from the upstream side of the mounting frame, and it is quite acceptable to test two mounting frames simultaneously by blanking off the openings of both and pressurizing the space between. Because the mounting frame pressure leak test is a chamber-by-chamber test of the housing, it can replace the need for a housing leak test.

4.1.9.7 Airflow Capacity and Distribution Test

This test is used: (1) to verify that the specified volumetric flow rate of the air can be achieved with the installed fan under actual field conditions at maximum and minimum filter pressure drop, and (2) to verify that the airflow distribution across each HEPA filter or adsorber stage is within the specified uniformity at the designed volumetric flow rates. ASME AG-1, Section TA contains additional information on these tests.

The air distribution test is an acceptance test (presuming the airflow capacity is both an acceptance and a surveillance test, as it should be). The unit should be operated for 15 minutes prior to the test to achieve steady-state conditions. In many existing units, there is inadequate space to perform the test downstream of the banks. Any test performed on the entry side of these banks should be more conservative for the HEPA filter banks because of the flow-straightening characteristics of HEPA filters. Therefore, if such a test meets the criteria, it should be acceptable.

4.1.9.8 Air-Aerosol Mixing Uniformity Test

The purpose of this test is to verify that the aerosol or challenge gas is introduced in order to provide uniform mixing in the airstream approaching the HEPA filter bank or adsorber stage to be tested. The test method described here includes tests to establish the adequacy of the test aerosol injection and upstream sampling port locations but does not generate data reflecting the adequacy of the downstream sampling port location. Undoubtedly, the test should be a prerequisite for performance of any in-place test of a HEPA filter bank and adsorber bank stage.

The verified locations of injection and upstream sample ports should be documented, and the locations should be tagged to indicate the date, method used, as well as the tests to be conducted. All other ports found to be unsatisfactory should be tagged to prevent later accidental use of incorrect injection or sampling ports.

The aerosol/vapor injection point for the first HEPA bank and the adsorber stage should always be ahead of any unit or system bypass line, and the downstream sampling point for the second stage HEPA filter bank and for challenge aerosol/vapor should always be downstream of the return of the bypass line into the main duct.

Good testability requires provision of permanent test aerosol injection and sample ports or other planned and pre-established means for injecting the test aerosol and for taking reliable, well-mixed samples. Details of the air-aerosol mixing test are described in ASME AG-1. It is essential that the air and test agent's mixture challenge to the filters (adsorber) is thoroughly mixed so that the concentrations entering all points of the filters, including the upstream and downstream sample points, are essentially uniform. Adequate mixing upstream usually can be obtained by introducing the test aerosol at least ten duct diameters upstream of the filters or adsorbers, or by introducing it upstream of the baffles or turning vanes in the duct.

When neither of these methods is practical, a Stairmand disk located four to six duct diameters upstream will provide satisfactory mixing. A Stairmand disk is a plate with the same geometric shape as the duct section that blocks the central half of the duct area. Air flowing past the disk creates vortices on the leeward side that compel turbulent and thorough mixing. The disk is placed into the duct for testing. At other times it is either removed, swung out of the way, or turned on a pivot so the long axis is parallel to the direction of flow. When duct arrangement makes it necessary to introduce the test aerosol directly into the filter housing, extraction of the downstream sample at a point several duct diameters downstream of the fan will usually provide a well-mixed sample.

Fan-shaft leakage should be considered in sampling downstream of the fan. Since leakage at the shaft will be in-leakage, sufficient air to dilute the downstream sample can be drawn in if the shaft annulus is large (yielding a low downstream concentration reading), or dust may be drawn into the fan to provide a high downstream reading (which may be particularly prevalent during construction). Application of a shaft seal, or at least a temporary seal, is recommended during testing. If this is not practical, a photometer leak reading should be taken with and without the aerosol generator "on" to establish shaft seal leakage. ASME AG-1 Section TA contains additional information on this test.

4.1.9.9 Duct Damper Bypass Test

The duct damper bypass test evaluates the potential of bypass leakage paths, through closed dampers or valves, to ensure that radioactive gases or particulates do not escape treatment through the HEPA and/or adsorber banks. This test allows testing of the potential leak path during the test aerosol or Halide test on the HEPA/adsorber banks, assuming the injection sample ports are located such that the potential bypass is included in the test envelope. Otherwise, the bypass (damper) may be tested using conventional pressure-testing techniques. ASME AG-1 Section TA contains additional information on this test.

4.1.9.10 System Bypass Test

A system bypass test challenges all potential bypass leakage paths and all portions of the nuclear air treatment system (including the housing stages) during the test sequence, which could potentially defeat the purpose of high efficiency nuclear air treatment components. All potential bypass leakage paths around the HEPA/adsorber banks should be included as a single overall leak test of the sum of the individual tests on the separate banks. In dealing with a series of HEPA or adsorber banks, each bank should be tested individually to ensure that contaminated air does not bypass the filter banks or escape treatment. ASME AG-1 Section TA contains additional information on this test.

4.1.9.11 Duct Heater Performance Test

The duct heater performance test evaluates the humidity control system for the carbon adsorber bank (which prevents water buildup on the carbon) to be tested to ensure satisfactory performance. For example, the voltage always has to be checked to make ammeter readings meaningful. The temperature should be checked sufficiently upstream and downstream of the heater to ensure an adequate rise in air temperature. The readings obtained also should be evaluated by a cognizant individual to ensure the desired relative humidity can be achieved with the potential minimum and maximum environmental temperatures in the inlet stream. ASME AG-1 Section TA contains additional information on this test.

4.1.10 Surveillance Testing

4.1.10.1 Introduction

There are three types of surveillance tests: (1) in-place leak tests of HEPA filter banks using an accepted test aerosol, (2) in-place leak tests of adsorber stages using a slightly adsorbable gas such as the fluorocarbon Refrigerant-11, and (3) laboratory tests of samples of adsorbent withdrawn from the system to establish its remaining adsorption capacity. These tests are also employed as part of the acceptance procedure for new installations, with the exception that laboratory tests are made on samples of adsorbent taken from batch material as furnished.

Surveillance tests of HEPA filter and adsorber systems should be made at regular intervals after installation to detect deterioration and leaks that may develop under service conditions. Regular in-place testing of standby systems is necessary because deterioration can take place even when the systems are not being operated. Aside from component damage, frequently discovered causes of failure to meet in-place test requirements include loose clamping bolts; inadequate clamping devices such as C-clamps; foreign material trapped between gaskets and mounting frames, rough or warped mounting frame surfaces; cracked welds; unwelded joints in mounting frames; incorrectly installed components (e.g., HEPA filters installed with horizontal pleats); inadequate seals between mounting frames and housings; poorly designed mounting frames; and bypasses through or around conduits, ducts, or pipes that penetrate or bypass the mounting frames.

In-place tests should be made by introducing a test aerosol upstream of the bank to be tested. The concentrations of test aerosol upstream and downstream (upstream concentration is considered 100 percent) should then be determined, and penetration should be calculated from the ratio of concentrations. The reliability of this test is determined by: (1) the ability to properly introduce the test aerosol and obtain representative samples, and (2) the availability of physical access to the banks being tested. The first can be verified by an air-aerosol mixing test.

Additional information on all of the surveillance tests described here can be found in ASME AG-1, Section TA.

4.1.10.2 In-Place System Leak Test, HEPA Filter Banks

There are three major types of in-place system testing methods. The first test method uses a light-scattering photometer with a polydispersed aerosol. The second method uses a shroud and/or scanning test technique, and the third uses a laser spectrometer in lieu of the forward light-scattering photometer. Measurements can be obtained manually or by automatic scans of the downstream side of the filters. The in-place system test is made by challenging the upstream side of the filter or filter bank with test aerosol smoke, then measuring and comparing (using a light-scattering photometer) the test aerosol concentration in samples of downstream (filtered) and upstream (unfiltered) air. If the system exceeds the specified maximum permissible penetration value, the downstream faces of the filters and mounting frame can be scanned with the photometer probe to locate localized high concentrations of test aerosol, indicating leaks.

Polydispersed aerosol may be generated thermally or by compressed air. Compressed-air generators are widely used for testing small systems. A rule of thumb for determining generator capacity is not to exceed one Laskin nozzle per 500 cfm of installed filter capacity. Compressed-air generators are suitable for systems up to about 3,000 cfm; above this size they become cumbersome. Gas thermal generators are generally used for testing systems of 6,500 cfm installed capacity and larger.

A manifold is installed in the upstream and downstream shroud. The upstream shroud should be placed over a filter, and the generator turned on. It is important to verify that the aerosol mist is filling the shroud using an upstream sample/challenge manifold located in the shroud. When the 100 percent upstream concentration is obtained, the meter is set to 0 and the downstream reading is taken. If the downstream shroud method is used, the sample tube should be connected to the downstream shroud manifold, and the downstream shroud should be placed against the frame of the filter to be tested for a minimum of 15 ± 5 seconds as determined by the photometer operator. If the downstream scan method of testing is used, each filter and gasket should be probed. The photometer is then read, and the highest leak rate reading is recorded "as found." The final leak rate readings are recorded.

A detailed description of the procedure for conducting an in-place test of HEPA filters is given in ASME AG-1, Appendix TA. An acceptance criterion of 0.05 percent maximum leakage for the in-place system test is recommended for systems that are designed in accordance with this handbook.

4.1.10.3 In-Place Testing for Adsorbers

The in-place leak test of the adsorber bank (stage) measures bypass (mechanical) leakage around or through the installed adsorber bank. This test may be performed: (1) as an acceptance test to verify system design function following initial field installation; (2) after an abnormal incident, replacement, repair, or modification that may affect design function; or (3) as a periodical in-service (surveillance) test to monitor system condition and operational readiness.

Bypass leakage around the adsorber bank (stage) may result from mounting frame weld degradation, damaged or poorly compressed gaskets, common drains between housing compartments, common electrical conduits between housing compartments, and inadequately dampered bypass ducts. Bypass leakage through the adsorbent media may be due to poor adsorbent filling technique and subsequent settling from system vibration and air or gas pulsation.

Since the in-place leak test only provides a measure of bypass leakage, this test should be performed in conjunction with the laboratory test of the adsorbent media. Assuring that the adsorber bank meets bypass leakage acceptance criteria and the adsorbent media itself performs adequately provides the necessary information required to determine whether the adsorber bank is performing as designed.

There are two methods commonly used for in-place leak testing of the adsorber bank stage. One uses a fluorocarbon refrigerant gas or an alternative tracer gas. The other uses a radioactive tracer gas (iodine or methyl iodide). The first method, developed by Savannah River Laboratory, is the most frequently used, particularly in commercial applications. The second method involves the use of radioactive isotopes and personnel licensed to handle these isotopes.

For commercial nuclear power plants, typical bypass leakage acceptance criteria for the adsorber bank (stage) range from 1.0 percent to 0.05 percent, depending on specific plant license bases and the plant technical specifications. NRC Regulatory Guide 1.52 specifies that in-place leak testing for adsorbers be performed: (1) initially; (2) at least once each 18 months; (3) following the removal of an adsorber sample for laboratory testing if the integrity of the adsorber section is affected; (4) after each partial or complete replacement of a carbon adsorber in an adsorber section; (5) following detection or evidence of penetration or intrusion of water or other material into any portion of an ESF atmosphere cleanup system that may have an adverse effect on the functional capability of the adsorber; and (6) following painting, fire, or chemical release in any ventilation zone communicating with the system that may have an adverse effect on the functional capability of the system. The Regulatory Guide further specifies that the in-place leak test should be performed in accordance with ASME AG-1 Section TA and the in-place leak test should confirm a combined penetration and bypass leakage quantity around or through the adsorber of 0.05 percent or less of the test gas at system rated flow of ± 10 percent.

4.1.10.4 Nonradioactive Tracer Gas Test

The non-radioactive tracer gas test is made by challenging the upstream side of the adsorber with a slightly adsorbable and readily desorbed fluorocarbon gas [usually Refrigerant-11, trichloro mono fluoromethane], then determining the concentrations immediately upstream of the adsorber bank and at a point downstream of the adsorber bank where satisfactory mixing with air occurs. Bypass leakage is calculated from the ratio of downstream-to-upstream reading. Since it is the ratio of concentrations that matter, the units may be expressed in terms of peak height or some other measure directly related to tracer concentration, although the measure may not necessarily reflect the actual volumetric or mass tracer concentration.

Refrigerant-112 was originally used but is no longer produced. Refrigerant-112 was more strongly adsorbed by the adsorbent bed than Refrigerant-11 and allowed testing of banks under conditions of high relative humidity or elevated adsorbent moisture content. With the introduction of ASME AG-1, alternative, substitute tracer gases are allowed (permitting tracer gases with stronger adsorption potentials than Refrigerant-11), providing the selection is made in accordance with the AG-1, Nonmandatory Appendix TA-C, Challenge Gas and Aerosol Substitute Selection Criteria, and ASME N511, Appendix B, Challenge Gas Substitute Selection Criteria.

4.1.10.5 Radioactive Iodine Tests

Two tests are used, one with radioactively traced elemental iodine, and the second with radioactively traced methyl iodide. Equipment requirements for controlling the injection and sampling flows during elemental iodine testing include an iodine injection tube, two sampling units, a sample extraction pump, and two calibrated flowmeters. The sampling units are filled with charcoal of known efficiency for elemental iodine. The test gas is Iodine-127 containing the iodide-131 tracer.

A combination of injected radioactivity (in microcuries), sampling rate, and counting technique (usually dictated by the kind of counting equipment available) should be developed to give the required test precision. Sampling rates as low as 0.03 percent of the system flow rate have been used, but sampling rates of about 1.0 cfm per 1,000 cfm (0.1 percent) of rated adsorber capacity are recommended.

The amount of iodine required, and the size of the injector tube are not critical. The radioactive iodine source is prepared by mixing the required quantities of Iodine-127 and Iodine-131 as sodium iodine, precipitating the iodine fraction of palladium iodide by treatment with acidified palladium chloride, then decomposing the palladium-iodide under vacuum. The liberated iodide-127 and iodide-131 is collected in a liquid-nitrogen-cooled U-tube and transferred to a glass ampule that is installed in the injector. Preparation of the iodine and loading of the injector should be carried out in a laboratory equipped for handling radioactive materials. To inject iodine during the test, the injector tube is crushed, breaking the ampule, and releasing the iodine vapor. Heat may be applied to the injector tube prior to its being crushed and during the test to assist in vaporizing the iodine source. Compressed air is passed through the tube at a carefully controlled rate for 2 hours.

After system flow and background radioactivity levels are established, iodine is injected far enough upstream to ensure adequate mixing with the main airstream, and samples are withdrawn simultaneously through the upstream and downstream sampling units. Injection of iodine is continued for approximately 2 hours, but system airflow and downstream sampling are continued for another 2 hours to catch any iodine that may desorb from the beds, in addition to that which penetrates immediately. Exhaust air from the sampling units is usually dumped back into the upstream side of the main system. The iodine content of the carbon in the samplers is determined by direct gamma spectroscopy, and the bypass leakage is determined from the following equation.

The methyl iodide test for determining the efficiency of adsorbers for organic radioiodine compounds is similar to the test for elemental iodine and uses the same equipment, except for the injector. The injector used for the methyl iodide test is a U-tube and a vapor expansion chamber. Sampling and analytical procedures are the same as those for the elemental iodine test. The test vapor is methyl iodine-127 containing methyl iodine-131 tracer. Because the methyl iodine test determines a different property of the adsorbent and depends on a different sorption mechanism, it cannot be used in place of the elemental iodine test. Therefore, both tests may be needed for a complete evaluation of impregnated charcoal adsorbers. Both of these tests suffer from the limitations of using radioactive tracers in the field and from the number of variables that should be controlled to achieve reliable results.

4.1.10.6 Test Sequence and Frequency

ASME AG-1, Section TA, and ASME N511 for Periodic In-Service Programs, provide guidance on testing sequence and frequency. Section TA is used for equipment qualification and acceptance testing after field installation, while ASME N511, is used for in-service testing to verify equipment availability and to obtain data for operational considerations. ASME N511 also provides procedures for surveillance (interval) testing to satisfy technical specifications or specific site surveillance requirements.

Due to the potential for unauthorized flow adjustment and duct damage, all air cleaning system airflows should be rebalanced at least every 5 years. Regularly scheduled testing and air balancing properly verifies the safe, effective operation of air cleaning systems and ensures that design parameters are being met and systems are operating within specified acceptance criteria. ASHRAE STD 111, *Practices for Measurement, Testing, Adjusting and Balancing of Building Heating, Ventilating, Air Conditioning and Refrigeration Systems*, should be followed.

4.1.10.7 In-Place Testing for Multistage Systems

HEPA filters are sometimes used in series to increase system reliability or to reduce the effluent air concentrations released from transuranic materials-handling operations. Two questions of importance arise when HEPA filters are employed in series: (1) how can they be tested in place, and (2) what will be the ultimate DF?

With a lower size detection limit at 0.1 µm and excellent analytical characteristics, laser spectrometer counting, and sizing instruments have been proposed as a feasible and satisfactory method for testing two or more HEPA filters in series when it is not possible to test each individually. Some uncertainties, however, remain. To have an adequate number of particles downstream for a statistically reliable penetration measurement, high upstream particle concentrations are required; this, in turn, calls for an accurate aerosol dilution device to reduce the particle concentration entering the laser spectrometer to a point where coincidence counting becomes insignificant. This often calls for a reducing concentration by 2 to 4 orders of magnitude, a difficult procedure. In addition, overall tests fail to indicate the status of individual filters in the series. This is important because there are no agreed-upon criteria for permissible penetration through two or more filters in series.

Systems that contain two or more HEPA filter stages and/or two or more adsorber stages in series in the same housing give special problems because of the difficulty of obtaining a representative single-point sample downstream of the first bank and the difficulty of introducing the second-stage test aerosol at a point where good mixing can be achieved. Some series banks are too close, so neither of these objectives can be achieved in the normal manner. Because of the high collection efficiency of the first-stage elements, sufficient test aerosol cannot be introduced upstream of the first stage to permit effective testing of the second stage. It has been shown that accepted test aerosols have no adverse effect on activated carbon or other adsorbents when used for testing nuclear air cleaning systems, and the refrigerant gases used to date have no adverse effect on HEPA filters.

4.1.10.8 First-stage Downstream Sample

The first-stage downstream sample can be obtained by using a multiple sampling technique. For testing multistage HEPA filter banks, scanning the downstream face of the stage to be tested is an approved technique, in accordance with the procedure outlined in Section 4 of IEST-RP-CC-034 (2016). The recommended scanning pattern for each filter in the bank is shown in **Figure 4.9**. Prior to starting scanning, the upstream side of the stage is challenged with test aerosol and the photometer is adjusted to read 100 percent. A high concentration will always exist directly downstream of a leak. During the downstream scan, the relative magnitude of each leak is determined by turning the scale shift knob of the instrument until a reading about halfway between half and full scale is obtained. The reading is recorded, and the leak flow for that point is calculated from the following equation.

Defective filters should be replaced, and installation deficiencies should be corrected before the final test is conducted. This method is considered more sensitive than the usual method of HEPA filter testing and is recommended for multistage systems with plutonium or transuranic element source terms.

Figure 4.9: Recommended Scanning Pattern

4.1.10.9 In-Place Testing for Multistage Adsorber Systems

Systems containing two or more adsorber stages in series in the same housing pose the same problems as multistage HEPA filters. The same techniques can be used for gas injection and testing as used in the aerosol HEPA filter systems described above. Additionally, since any tracer gas injected upstream of the adsorber bank is only temporarily adsorbed, additional difficulty with desorption interference may be encountered when attempting to test subsequent adsorber stages. Normally, it is advantageous to start with the downstream bank when testing series adsorber banks to minimize desorption interferences. It may be possible to perform individual bank leak testing of series adsorber banks by using temporary or permanently installed sampling manifolds or by providing a temporary jumper duct to bypass airflow around the second stage to either the system fan or to a temporary auxiliary fan.

4.1.10.10 Test Aerosol/Gas Injection, throughout Second-Stage Upstream Sample

When the test aerosol/gas is introduced through an auxiliary duct, the upstream sample can be taken any place in the auxiliary duct (upstream of the bank to be tested), assuming the auxiliary duct is long enough to ensure good mixing and medium efficiency filters are not installed. When using an auxiliary blower, a downstream sample can be taken downstream of the blower. Another method of ensuring proper mixing of the test aerosol/gas with air is to shroud adjacent filters (adsorbers) and introduce the agent to each filter element (adsorber cell) individually by using a multiple discharge distributor, as shown in **Figure 4.10**. The X cross sections are used as the injection ports. The upstream sample is taken downstream of the perforated distribution plate. The downstream sample is taken with a multipoint sampling probe (**Figure 4.11**). The penetrations of the individual filters (adsorbers) are averaged to find the gross bank penetration.

This method requires that a mounting frame pressure leak test be made, usually at the time of acceptance testing, and that the air-containing test gas be passed through a unit (filter or adsorber cell) or group of units one at a time. This method has the advantage of substantially reducing the total quantity of test aerosol/gas introduced to the system if scanning is required to locate leaks; however, it requires more time than the usual method of taking single-point upstream and downstream samples. The vapor test gases have no adverse effect on HEPA filters, and it is possible to inject the gas upstream of the HEPA filters when testing adsorbers.

Modern air cleaning systems should be designed to eliminate back-to-back series adsorber elements within a single housing. Gasketless deep-bed adsorbers or series adsorbers contained in separate, testable housings may be used when the design requires bed depths in excess of the standard two inches. ASME AG-1 Section FE contains additional information on deep bed activated carbon adsorbers.

Figure 4.10: Adsorber Tray Mounting Frame

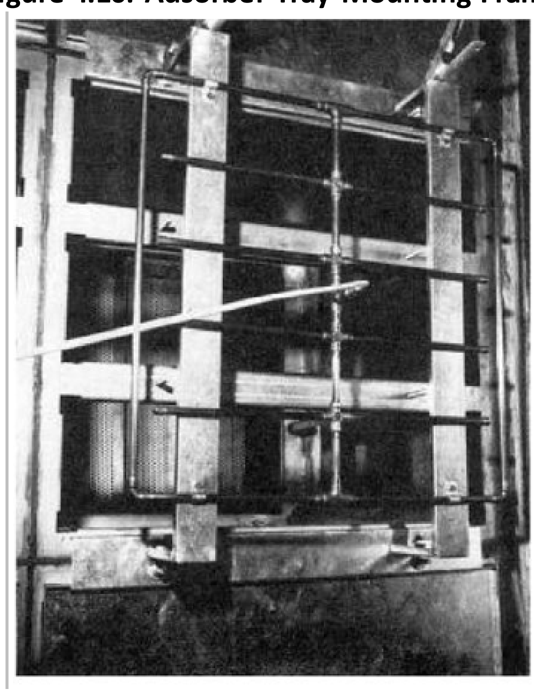

Figure 4.11: Multiple Point Sample Probe

4.1.11 Adsorbent Sampling and Laboratory Testing

4.1.11.1 Sampling

The effectiveness of the adsorbent may be impaired due to aging, weathering, and/or poisoning by chemical contaminants. The charcoal ages as a result of oxidation of the adsorptive sites at the adsorbent surface. Aging may occur in the drum (static) or in the operating air cleaning system (dynamic). Weathering typically occurs during system operation when the adsorbent is exposed to normal atmospheric, low-level contaminants in the airstream, e.g., oxides of nitrogen and sulfur and outgases from plant materials and equipment. Moisture adsorbs on the activated carbon plays a significant role in degrading carbon performance. Poisoning generally refers to an acute exposure of the adsorbent to chemical compounds that temporarily or permanently impair its ability to remove radioiodine and radioiodides. Periodic sampling of the adsorbent provides a means of providing a representative sample of adsorbent for radioiodine testing. The radioiodine laboratory test, together with the in-place adsorber leak test, provides a means of assessing overall adsorber system health.

Flow-through cartridges should be provided and installed in an area of the bank where air will flow through them, and not in obvious low-flow areas such as the outside edge of the mounting frame. If sample cartridges are not provided, other means of sampling are necessary. ASME AG-1 contains additional information on obtaining representative samples of carbon from a carbon bed. In a multicell system, samples can be obtained by removing and emptying a cell, taking a sample of the loose adsorbent, refilling the cell (using a qualified filling procedure), and reinstalling it in the bank. For some adsorber systems, it may be possible to take a “grain thief” sample. In small adsorber installations, when considering the cost of the tests and labor involved in obtaining the sample, it may be beneficial to simply replace the adsorbers or adsorbent. Some users have found it more economical to replace the adsorbent at the stipulated sampling frequency rather than making surveillance sample tests.

When using a “grain thief” as described in ASME AG-1, multiple samples should be taken from all sections of the adsorber bank. For deep bed adsorbers, it is important to sample from below the tops of screens so that carbon from the overfill is not commingled with the service carbon. In filters with a bed thickness greater than two inches (50.8 mm), samples should be taken from the center of the bed. Samples taken from the inlet side of a carbon bank will show more radioiodine penetration than samples taken from the exit side. Therefore, samples should be taken symmetrically from the exit screen side, the entrance screen side, and the middle of the bed. When sampling Type II adsorber trays, the entire tray should be emptied, and the contents mixed to yield a homogeneous composite sample. A smaller, grab sample may be taken from the tray contents for laboratory testing. If the bank is not being replaced, a new tray should be installed in the bank and marked as “Not Representative for Future Sampling.”

Sample canisters may be used to take a representative carbon sample from the adsorber bank. Sample cartridges should be provided in sufficient numbers to permit taking samples at specified intervals for the life of the adsorbent. Sample cartridges should be designed so that bed depth, airflow, and pressure drop across the cartridges are the same as for the adsorber stage. Properly designed sampling canisters should have the same bed depth as the main bank and be filled with adsorbent identical to that installed in the main adsorbent bed. Sampling canisters should be mounted vertically so that any bed settling within the canisters will not create a mechanical bypass of the carbon media.

Carbon samples taken from the adsorber bank should be thoroughly mixed and packed into vapor-tight containers such as a plastic bottle. At least 125 ml of carbon for each two inches of bed thickness are required for the laboratory test. All samples that are to be sent to a testing laboratory should be marked with the following minimum information:

- Utility/Company.
- System Identity.
- Sample Date.
- Purchase Order Number.
- Test Standard.
- Test Temperature.
- Test Humidity.
- Face Velocity.
- Adsorbate (methyl iodide).
- Pressure.
- Bed Thickness.
- Contact Person/Telephone Number.

Test results for samples sent to a laboratory for radioiodine penetration analyses should be available within 30 days of their sampling date.

4.1.11.2 Laboratory Testing

Radioiodine penetration analysis is conducted in the laboratory using the ASTM D3803-2019 standard test method (or later versions of ASTM 3803 as discussed in ASME AG-1). Testing is conducted in sophisticated environmental chambers that are capable of precisely controlling the temperature and humidity. The activated carbon sample is loaded into stainless steel testing canisters, one canister for each two inches of adsorber bank bed depth. Along with two more canisters containing new carbon, the canisters with the activated carbon sample are assembled into a canister stack for testing. The canister stack is placed into the environmental chamber and plumbed into the testing system. The system environment is adjusted to the required temperature and humidity, normally 90 degrees Fahrenheit and 95 percent relative humidity. All test parameters are monitored by a computer monitoring system for the duration of the test.

After an initial thermal equilibration period, humid airflow is started through the carbon beds for the duration of the pre-equilibration and equilibration periods. The loading period begins with the introduction of methyl iodide into the airstream. The methyl iodide is fed into the system for a period of 60 minutes, called the loading period. After completion of the loading period, the injection of methyl iodide is stopped, and the humid air continues for an additional 60 minutes. This is called the “post sweep.” The carbon canisters are then disassembled and carbon from them is loaded into plastic counting canisters for analysis. Each carbon sample is counted in a gamma spectrometer to determine the amount of radioactivity contained in each carbon canister. Knowing the amount of radioiodine present in each carbon canister allows calculation of the radioiodine penetration in percent penetration.

Detailed descriptions of the penetration measurement may be found in ASTM D3803-2019 and referenced in ASME AG-1. The actual test method and parameters, as well as the acceptance criteria, will be found in plant specific documents such as technical specifications or site-specific operating procedures.

4.1.11.3 Frequency of Testing

The following test schedule (**Table 4.7**) is suggested for both continuous and intermittent online adsorber systems designed in accordance with this Handbook.

Table 4.7: Test Schedule for Adsorbers

Application	Frequency
All systems.	Before system startup, following any major system repair or modification, and following each filter (adsorber) replacement.
Radiochemical plants, fuel reprocessing plants, and laboratory fume hoods.	Semiannually or quarterly where high moisture loadings or high temperatures are involved. In some systems, frequent (even monthly) testing is often specified where the environment is particularly severe. The frequency may be reduced if experience indicates a lesser frequency is satisfactory.
Reactor post-accident cleanup systems and post-accident cleanup systems of fuel reprocessing plants.	Annually or 720 hrs of system operation, whichever comes first (as specified in NRC Regulatory Guide 1.52).
Zone III or tertiary confinement areas of facilities that handle radioactive materials.	Annually.
Zone II or secondary confinement areas of plants and laboratories that handle radioactive materials.	Annually.
Zone I or primary confinement areas (glovebox lines, hot cell exhaust, etc.) of laboratories and plants that directly handle moderate to large quantities of radioactive materials.	Semiannually unless experience indicates that annual testing is sufficient. If filters (adsorbers) are replaced at short (less than 6-month) intervals to limit exposure of personnel to radiation during a filter (adsorber) change, or to permit contact maintenance of the system by limiting the amount of radiation that can be collected in the filters (adsorbers), systems should be in-place [i.e., leak-tested following each filter (adsorber) change]. Laboratory testing of adsorbents may not be necessary if the adsorbent is replaced frequently.

Application	Frequency
All systems.	Before system startup, following any major system repair or modification, and following each filter (adsorber) replacement.
Systems that are continually on standby but are operated occasionally during plant maintenance to ventilate the system.	At least semiannually.

4.1.12 Testing of Deep Bed Sand Filters

Deep bed sand filters are not true HEPA filters, although their efficiency approaches that of a true HEPA filter when tested for aerosol penetration. The test method used, which is the same method used to leak test HEPA filter systems, uses a poly-dispersed aerosol with a light scattering mean diameter of 0.7 micron. Aerosol should be injected into the system as far upstream of the sand filter as possible for good mixing. An Air-Aerosol Mixing Uniformity Test, as described in ASME N510, should be performed to determine the best injection point and sample points. Although ASME N510 may be used as guidance, supply and return tunnels for deep bed sand filters are generally underground. It is not practical to add injection or sampling points after operation begins, so these injection and sampling points need to be included in the original design of the system to ensure adequate mixing. A perforated dip tube designed and installed per ANSI/HPS N13.1 should be used upstream and downstream of the sand filter to further ensure a representative sample of the aerosol concentration is used. Due to the large volumetric flow rates of deep bed sand filters, multiple generators working in parallel are needed to obtain the necessary concentrations to perform adequate testing.

The upstream and downstream concentration of background aerosols (dust test) that may interfere with the test results should be performed prior to the introduction of aerosol into the system. The background test is performed by setting the aerosol photometer's internal calibration feature to reference the instrument to a concentration equivalent of 100 micrograms of aerosol per liter of air. The background concentration is then measured upstream and downstream (upstream first) and recorded. The background levels should be stable and allow for detection of aerosol penetration smaller than the maximum allowable penetration. The aerosol should be injected into the sand filter for a period of 15 to 30 minutes, depending on the size and cfm of the sand filter, prior to the test sampling to allow time for distribution of the challenge aerosol throughout the sand filter.

4.1.13 Testing Portable HEPA Filtration Systems

4.1.13.1 General Testing and Periodic Maintenance Considerations

Problems with operating portable HEPA filtration systems (PHFS), are often not visually observable or detectable by onboard instrumentation. Therefore, filter replacement and testing are important to the continued safe operation of the unit. In-place testing is designed not only to validate the HEPA filter, but also to verify the integrity of associated seals, gasketing, ducting, and housings regarding leakage.

HEPA filters used in the system should be tested by the DOE FTF before initial use. In addition, the device should be leak-tested after installation at the site and prior to operation. Most importantly, a thorough leak test should be conducted every 6 months or any time the unit is jarred or bumped. Leak tests are conducted by first injecting an aerosol challenge into the inlet of the PHFS and measuring the aerosol challenge concentration at the inlet to establish a 100 percent baseline. Then the detector samples particle free air to establish a 0.000 percent baseline. With these two baselines, created samples of the PHFS outlet can be sampled to measure any aerosol leakage.

PHFS tend to be overlooked when it comes to maintenance and testing. Many standards and procedures address maintenance and testing of permanent HVAC HEPA filtration systems. However, no national standards and procedures are available for PHFS. Worse, because of their size and portability, personnel assume they are functioning correctly. Ironically, these units are capable of discharging contamination over the specific areas of the work site they are supposed to be protecting if filter bypass leakage is occurring.

These units by their very nature are prone to leakage. This is mainly because they are small and portable, and thus are transported from workplace to workplace in the back of trucks and are subjected to substantial rough handling by workers. This action creates leaks in units that were previously tested, giving personnel a false sense of security. For this reason, these units should be tested anytime they are transported to another workplace. When testing PHFS, test personnel should apply the same rigorous procedures outlined in ASME AG-1 for the permanent HVAC HEPA filtration systems.

4.1.13.2 Portable Filtration Systems Testing Applications

There are two basic designs for these systems: those that “pull” air through the HEPA filter and those that “push” air through it. Therefore, some units locate the HEPA filter upstream of the motor/blower assembly, and others place the HEPA filter downstream of the motor/blower. The advantages and disadvantages of each design concept are summarized in **Table 4.8**.

Table 4.8: Downstream/Upstream HEPA Filter Locations in PHFS

(+) Advantages, (-) Disadvantages	***(+) Advantages, (-) Disadvantages***
Type A DOWNSTREAM HEPA	Type B UPSTREAM HEPA
(+) Easier access to HEPA filter for scanning or leak testing	(-) Difficult access to HEPA filter for scanning or leak testing
(+) May not require mixing chamber to assure uniform mixing of test aerosol	(-) Requires mixing chamber to assure uniform mixing of test
(-) Motor/blower may become contaminated	(+) Motor/blower should stay uncontaminated unless filter leaks
(-) Cabinet interior may become contaminated	(+) Cabinet should stay uncontaminated unless filter leaks

Design, materials, specifications, and quality of construction vary widely among PHFS. These variables have a tremendous impact on overall performance and effectiveness. In particular, the cabinet material should remain rigid and undistorted during shipping, handling, and the rigors of daily operation to prevent the contaminated air from bypassing the HEPA filter. The type and gauge of metal fabrication methods, braces, holes, cracks, fasteners, welds, gaskets, and seals should be designed, specified, and assembled with potential leakage, durability in service, and maintenance in mind. Many of the above items may not be applicable to units constructed and certified to ASME AG-1 criteria.

4.1.13.3 Testing Problems and Special Considerations

Some of the designers and manufacturers of PHFS have not put much thought or effort into creating units with integrity leak tests in mind. Not only do they unintentionally "design in" leaks, but they also often overlook the inclusion of features that allow access to areas that are critical for leakage testing. Access to the downstream face of the HEPA filter for the purpose of scanning is virtually impossible in most units where the blower is downstream of the HEPA filter. A mixing chamber with baffles is necessary at the inlet of this type of unit to provide adequate challenge aerosol mixing. Downstream measurements of the exhaust airstream can be subject to error due to channeling—the opposite of mixing. The aerosol from a specific leak may simply remain concentrated in a segment of the exhaust airstream. Therefore, sampling should be done at various points across the face of the exhaust air outlet, in effect a "scanning" of the opening. A single-point sample is usually not representative of what is in the exhaust airstream because the leak becomes diluted with the particle free air. The same considerations are included in making air velocity measurements across the exhaust opening or duct in accordance with ANSI/ASTM 41-2 (1987). A single-point reading is not representative, as discussed in ACGIH's *Industrial Ventilation – A Manual of Recommended Practice*.

The following potential problems may be detected by testing PHFS:[15]

- Poor design.
- Poor workmanship and inadequate QC by the manufacturer.
- Leaks in the filter media itself.
- Leaks due to failure of the adhesive bond between the filter media and its frame.
- Leaks between the filter frame and cabinet sealing frame seals.
- Leaks between the cabinet main frame and the cabinet housing.
- Leaks in the cabinet or housing due to damage in transit or handling.
- Leaks from misalignment or misassembled components.
- Leaks resulting from incorrect or inadequate maintenance.
- Leaks resulting from improper installation and operation of the PHFS at the work site.

4.1.14 Testing HEPA Filter Vacuum Cleaners

HEPA filtered vacuum cleaners (HEPA-Vacs) are most commonly used to control particulate before it becomes airborne. They are also used to control airborne particles and liquids in and

[15] Units constructed and certified to ASME AG-1 criteria are less likely to have these problems.

around work areas and to provide localized control of loose debris when work operations could potentially spread contamination. When used in the nuclear industry, HEPA-Vacs are commonly referred to as nuclear or radiological vacuum cleaners.

4.1.14.1 Description of Radiological Vacuum Cleaners

Radiological vacuum cleaners are generally well-constructed, well-sealed devices with a HEPA filter on the exhaust. They are normally mounted on a cart with a comfortable handle and lockable, steerable wheels for portability and control during use. The power module consists of a blower powered by an electric motor and controlled by an onboard switch. The filter module consists of a positively mounted and sealed HEPA filter protected by a medium efficiency filter. All units should have a positive plenum (tank)-to-vacuum head seal. Vacuums that have latches but provide a loose tank-to-head seal that depends on the vacuum force to provide a positive seal (as in many commercially available shop vacuums) should not be used.

Some vacuum cleaners are equipped with controllers that allow the worker to regulate the flow. This works well in providing negative ventilation in small glove bags. Using HEPA filtered vacuum cleaners can significantly improve how contamination is controlled.

An inline HEPA filter can be installed in the suction hose to collect radioactive material before it reaches the vacuum cleaner. Fittings can be made to connect the vacuum cleaner hose to the HEPA filter. As debris is sucked into the hose, it is deposited on the inline HEPA filter instead of the HEPA filter inside the vacuum cleaner. Temporary shielding should be installed around the inline filter before operation, as the filter becomes highly radioactive.

If a large amount of debris will be collected, installation of a waste drum in the suction hose should be considered to ensure the debris collects in a waste drum and not the vacuum cleaner. Commercial systems are available, or one can be made by welding two pipes into a spare drum lid. As each drum is filled, the lid can be installed on a new drum and a regular lid can be installed on the full drum. Personnel doses are reduced because the debris is collected directly into the waste drum instead of the vacuum cleaner.

Vacuum cleaners should be constructed of a material that is easily decontaminated without damage to components. Units that use silicone-based material to prevent leakage should not be used. All hose connections should provide positive seals and should be constructed of a material that will not be damaged by repeated use or rough handling.

HEPA filters should have a positive seal and pass in-place leak testing. The filter hold-down clamps should provide the required force (20 psi) to seal the filter and prevent dislodging during rough handling and repeated use. They should be constructed of a material that will not warp or bend with repeated use.

The HEPA filter replacement method should be both simple and achievable in minimum time to reduce exposure and the chance of radioactive contamination. The vacuum cleaners should be designed to ensure HEPA filter integrity under all conditions of use and to prevent unauthorized or accidental access to the inner surfaces of the vacuum. Units should be constructed with no sharp edges or burrs that could injure personnel or damage protective clothing.

HEPA filters used in HEPA-Vacs should meet the efficiency and construction requirements for HEPA filters listed in ASME AG-1 or IEST-RP-CC001, 021, and 034. The maximum flow rate of the device should not exceed the flow rate at which the HEPA filter was efficiency-tested.

4.1.14.2 Operation

HEPA-Vacs are used to cleanup radioactive debris. Improper use of HEPA-Vacs may result in generation of airborne radioactivity, loose surface contamination, or high dose rates. HEPA-Vacs used for radioactive material should be marked, "For Radioactive Service Only." A nuclear safety review should be performed and documented prior to use of a HEPA-Vac for fissile material.

HEPA-Vacs should be appropriate for the type and amount of radioactive material involved. The health physicist is responsible for determining the levels of filtration required on the exhaust.

Programmatic organizations are responsible for the following items:

- Maintaining control of HEPA-Vacs.
- Ensuring that HEPA-Vacs are properly labeled, controlled to avoid improper use, and serviced or emptied only by individuals trained to do so, and that the health physicist is contacted before they are opened.
- Ensuring that HEPA-Vacs (a) undergo visual inspection by the operator prior to each use, and (b) are leak-tested every six months, after HEPA filter replacement, and after being subjected to mechanical trauma (e.g., dropped, tipped over, struck by hard object). (See Section 4.1 of DOE-STD-1269-2022.).

HEPA-Vacs used in contaminated areas should be equipped with HEPA-filtered exhausts or with exhausts that are directed to installed systems that are equipped with HEPA filters. Such provisions may not be necessary when these systems are used in areas where only tritium or radioactive noble gases are present or when the material to be vacuumed is wet enough to prevent the generation of airborne radioactive material or removable surface contamination. Extended use of air handling equipment may cause a significant buildup of radioactive material in the ductwork and filters. Periodic sampling of the exhausted air and surveys of the accessible surfaces of the equipment should be performed to assess the radiological impact of equipment operation. While use of the devices discussed above has been proven effective in reducing contamination spread and associated decontamination costs, these benefits should be weighed against the potential costs. Use of engineering controls may require expenditure of worker doses to set up, work in, maintain, and remove the device. There may be financial costs associated with device purchase or manufacture, worker training, possible reduced productivity, and device or component maintenance and disposal.

4.1.14.3 HEPA Filter Vacuum Cleaner Tests

Numerous suppliers manufacture HEPA-Vacs, and each supplier has several models available. This leads to unique characteristics that should be considered when performing in-place testing. As in the permanent HVAC systems, a thorough visual inspection by trained personnel of the unit to be tested should be performed before conducting the test. This inspection should be done using a checklist tailored to the specific make and model to be tested. These units should also be tested for proper flow and suction capabilities. Generally, a 4-to-6-inch diameter duct or flex hose 8 to 10 feet long is used to introduce the challenge aerosol to the input of the HEPA-Vacs under test. An upstream probe can be fitted close to the end of the hose for transition to the inlet connector on the unit under test. The output of the aerosol generator should be directed to the other end of this hose. This configuration usually allows adequate aerosol-air mixing of the aerosol challenge.

The greatest challenge to testing HEPA-Vacs is obtaining a representative downstream reading. For most HEPA-Vacs, downstream air is discharged radially in all directions rather than through a duct (as in permanent HVAC systems). To accomplish this, test personnel usually fabricate a collection hood to collect all of the downstream air discharged from the unit under test and connect a duct or hose to the hood. The hose or duct can be fitted with a downstream probe located at least 10 diameters downstream of the hood. After the upstream/one hundred percent baseline and the 0 percent baselines have been established, a downstream reading should be taken both with and without the aerosol generator operating. This is done to verify whether there is a background leakage reading. Some HEPA-Vacs generate significant amounts of particles due to their design configuration. If a background reading is detected, it should be recorded and deducted from the downstream reading obtained with the aerosol generator operating.

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4.2 Glovebox Filtration

4.2.1 Introduction: Filtration Components

Gloveboxes are enclosures that enable operators in various industries to use their hands to manipulate hazardous materials through gloves without exposure to themselves or subsequent unfiltered release of the material to the environment. In the nuclear industry, gloveboxes provide primary confinement for radioactive material handling and process protection and are used to handle a diverse range of chemical, oxygen-sensitive, pyrophoric, hazardous, and nuclear materials. There are many other factors, such as seismic hazards, that could affect glovebox filtration design and operation. Secondary confinement may be provided by the room or building where the gloveboxes are located.

Ventilation is the heart of the glovebox system. Nuclear materials requiring handling inside a glovebox usually present little or no penetrating radiation hazard but emit radioactive particles that could be dangerous if inhaled. Gloveboxes prevent operators from inhaling radioactive particles as they work with various nuclear materials and help provide a clean, controlled, safe working environment. For glovebox ventilation to be effective, however, proper design pressures and flow criteria need to be maintained. Glovebox pressures range from mostly negative (for confinement) to positive pressure environments (for process protection). Failure to maintain correct operational pressures or to follow established operational procedures could render a glovebox both ineffective and unsafe.

4.2.2 Glovebox Types and Characteristics

To understand the importance of glovebox filtration, a clear understanding of glovebox characteristics and functions is necessary. A glovebox is a windowed, airtight (sometimes gas-tight) enclosure that may be capable of both positive or negative internal pressure. It is equipped with one or more flexible gloves for manipulation of materials and performance of operations inside the enclosure from the outside, uncontaminated environment. **Figure 4.12** defines and lists characteristics of gloveboxes, with a focus on their use in the nuclear industry.

Originally, many gloveboxes were vendor-designed, so the designs were proprietary. As a result, many older boxes have unique ventilation designs. Later on, professional societies such as the American Glovebox Society (AGS) issued documents such as AGS-G001, *Guidelines for Gloveboxes*, and AGS-G006, *Standard of Practice for the Design and Fabrication of Nuclear Application Gloveboxes*, written by experts who design, manufacture, and operate gloveboxes. This document contains useful information on subjects ranging from the need for a glovebox to QA acceptance programs.

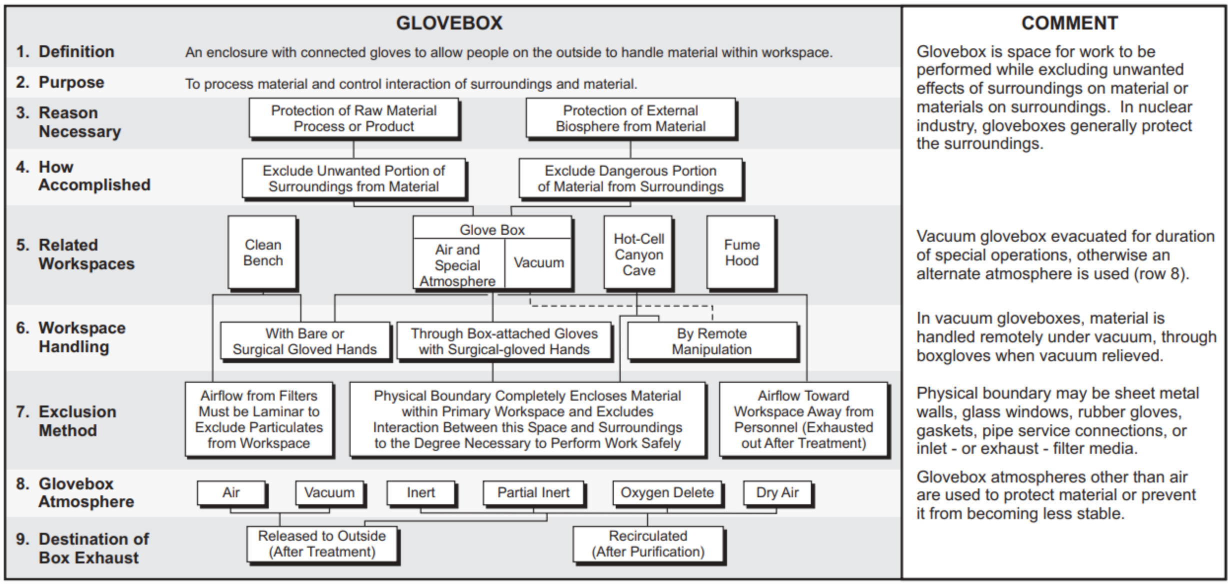

Figure 4.12: Characteristics of Gloveboxes

Gloveboxes generally have several common characteristics. Gloveports (window-mounted or in the stainless-steel shell) are usually available in multiples of two at various locations in the glovebox walls. Interior workspace is reserved for primary operating purposes on the box floor between the gloveports and within reach of a gloved hand.

Gloveboxes are normally kept at a negative pressure of 0.3-to-0.5 in. wg relative to their surroundings. The maximum safe operating differential pressure between the interior and exterior of the box is usually less than 4 in. wg; greater differential pressure may damage or rupture a glove or window, causing subsequent loss of confinement. Operators experience fatigue when pressures inside a glovebox are greater than 0.5 in. wg, and performance of intricate tasks becomes tedious. However, alternate[16] operating pressures may be used if evaluated and based on system effects, operating conditions, hazard mitigation, and protection of worker. Material and HEPA filter transfers between glovebox interiors and exteriors are commonly made through a bagging port which, although time-consuming and user-dependent, is still the safest practical way of maintaining confinement. New versions of this technology use a banding system. Other material transfers use rapid transfer ports (RTPs), which allow simple docking from glovebox to glovebox. This is a reliable method of maintaining confinement, as long as the seals are maintained and undamaged.[17] Gloveboxes with RTPs are still equipped with bagging ports for filter changes and waste disposal.

[16] Reference AGS-G001-207, Sections 5.6.1 and 9.4.2 on normal operating differential pressures range from -0.5 to -1.5 in w.g.

[17] Transfers of powders can egress past the seals if exposed. Such powders should be contained in a secondary container and the seals protected during operations.

Special atmospheres such as inert gas and dry air are often used in gloveboxes for fire suppression and for oxygen-sensitive and/or moisture-sensitive materials and processes. Gas purification systems are commonly used in conjunction with inert environments to maintain environmental control. These units purify and dry the environment to prevent consumption of large volumes of inert gas and desiccant. These devices should be protected from contamination because they constantly recirculate the volumes of the gloveboxes they serve.

4.2.3 Importance of Glovebox Ventilation and Filtration

Operations conducted in gloveboxes often provide the elements for unstable conditions (e.g., fire and pressurization). A properly designed and operated glovebox ventilation system minimizes these instabilities as well as the possibility of an accidental release of airborne radioactive material. Room air is a safe glovebox environment for many applications. On the other hand, operations with pyrophoric materials such as plutonium or the presence of reactive gases such as hydrogen may require a special environment (e.g., nitrogen, low oxygen, inert gas, and moisture control).

For air-atmosphere boxes, ventilation at relatively low flow rates provides sufficient dilution of the limited combustible volatiles found in well-operated gloveboxes. The correct airflow volume, along with the proper location of supply and exhaust filters, minimizes the likelihood of fire while providing sufficient dilution to prevent the buildup of explosive gases. Good glovebox ventilation dictates that HEPA filters are operated at their designed airflow. HEPA filters should be tested and certified at the manufacturers' rated airflow.

Normal air changes through a glovebox remove some of the heat generated by equipment inside the box and help maintain reasonable working temperatures for the operator. However, this convective cooling may be insufficient to remove all of the process heat generated in the box, and auxiliary cooling or higher airflow volume may be required.

Most glovebox ventilation systems include some form of pressure relief and adequate pressure control to maintain proper pressure differentials between the glovebox and its surroundings. If a glove should tear or accidentally come off, there should be an assured, sufficient ingress of air through the gloveport to prevent egress of contamination until the port is closed. This safety feature is inherent if the glovebox ventilation is designed and operated properly. Pyrophoric operations, however, should have appropriate safeguards to prevent air intake from starting a severe reaction.

Proper instrumentation should be provided to warn of inlet/exhaust filter blockage and loss of pressure/confinement. Pressure gauge/transducer line filters should be used to protect this instrumentation.

4.2.4 Design of Glovebox Ventilation Systems

4.2.4.1 Introduction

The principals of glovebox confinement are basic. Airflow of 125 ± 25 feet per minute (fpm) through a breached (8-inch diameter) gloveport will maintain confinement. This is an inherent (defined as "real time, at the moment of failure") safety feature that should be incorporated into the glovebox system. Most nuclear, biological, and pharmaceutical facilities in the U.S. are designed to provide this capability (within a range of 10 percent).

The air change rate is an important consideration for all gloveboxes. As glovebox volume increases, airflow should increase. Nonetheless, the inherent safety feature of 125 ± 25 fpm through a gloveport should be maintained. For normal operations, flow rate is based on the dilution of evolved combustible or corrosive gases and heat dissipation, as well as prior experience. The exhaust capability should be sufficient to provide safety under postulated abnormal conditions, including the gloveport breach. In certain other applications, the exhaust capability should be sufficient to provide safe access for planned activities.

Operating personnel, industrial hygienists, and radiation specialists can assist the designer in establishing realistic requirements, particularly when an existing system is being replaced or revised. The types and quantities of materials to be used inside the box and their toxicity and state (e.g., wet slurry, dry powder) should be considered when establishing the air exchange rate and velocity. When exposed radioactive material is handled inside a glovebox, the box becomes the primary confinement. When handling nuclear and pyrophoric materials, consideration should be given to whether pressure inside the glovebox should be positive or negative.

A positive-pressured glovebox provides a motive force for airborne contamination to leak from the box into the secondary confinement (the room or facility). Negative pressure inside the box is essential to maintain glovebox confinement when working with radioactive material. It is not usually acceptable to design a normal operating condition that allows a primary confinement area to be positive to the secondary confinement area. However, in a unique or unusual application where an inert environment is used to control fire and explosion, the box may be slightly positive or even neutral, and the facility becomes the primary confinement. This suggests the need for a secondary confinement and also flags the need for personal protective equipment and appropriate procedures to protect the worker. The designer should design for failure (i.e., using the worst-case scenario) to predict the consequences of a glovebox failure. The designer also should consider test and acceptance criteria.

4.2.4.2 Blowers

Regardless of the type of blower or manufacturer, the required airflow and pressure requirement needs to be attained for safe operation of a glovebox. Another criterion for blower selection and design is selection of a blower that does not exceed the pressure limits of the glovebox. Depending on their size, most stainless-steel gloveboxes with 7-gauge walls are designed and tested at -4 in. wg. Exceeding this pressure may cause damage to the glovebox windows, seals, and shell. If the blower exceeds this limit, the glovebox should be equipped with a pressure relief device. loading the exhaust filter will prevent the blower from quick recovery. Exhaust filter and gloveport sizes also influence recovery. This is the reason for maintaining the inherent safety feature at the design phase of a glovebox project. If larger gloveports (greater than 8-inch-diameter) are selected, the need for additional airflow should be engineered. Site-specific filter housings and filters may not address the need for increased airflow.

Blower location depends on several variables in glovebox applications. If a scale or other vibration-sensitive device is used in the glovebox, the blower should be isolated from the glovebox shell with vibration isolators and a flexible inlet/exhaust connection. Although this works in most applications, some may require remote location of the blower away from the glovebox. Blower noise should be considered to prevent annoying the workers. Noise levels should be kept to less than 80 decibels A-weighted.

4.2.4.3 Filter Housings

A filter housing design should consider safety, ergonomics, and reliable operation. Filter change-out should be simple and should maintain a safe level of confinement. The design should prevent any form of contamination from reaching the downstream ductwork or secondary confinement (the facility). The design should satisfy the ergonomic requirements of filter changes and allow the operator to perform the operation safely (without exposure or injury). A top-mounted filter housing should be located as close to the front of the glovebox as possible and should be aligned with a gloveport. Process activities and materials could block the exhaust filter. Without the exhaust filter airflow, it would be difficult to maintain confinement. The filter housings on gloveboxes differ from most filter housings in that they are very small due to ergonomic limitations and low airflow requirements. Changing a glovebox filter is difficult because it has to be performed through a gloveport with limited operator movement. Use of larger filters should be avoided because they are difficult to handle safely inside a glovebox without special tooling.

Types of Housings

The types of filter housings selected for use on gloveboxes have always been application-specific.

“Pressure recovery” is a term that evolved from quick insertion and removal of operators’ arms into and out of the gloves, although the blower will deal with most of the volumetric changes caused by glove movement. As many nuclear facilities functions under different directives, filter housings have evolved to suit their respective applications. Early gloveboxes often had externally mounted HEPA filters. Because of the potential for spreading contamination during filter changes, this practice should be avoided.

Internal filter installations range in design, however, and all have a mechanism to restrain the filter (a HEPA filter) and a sealing mechanism. These mechanisms also vary; however, it is critical that the mechanism be free of sharp edges that can easily cut gloves. Cracks and crevices should be kept to a minimum since the location makes cleaning difficult. Filter housing construction typically requires clean, smooth finishes to allow cleanup of contaminated or potentially contaminated areas. Experience has shown that areas exposed to contamination can be difficult to clean. The rougher the surface of the housing, the more difficult it is to clean. Valves, located to the outside, are used to isolate the spent filters during filter changes. Most applications use a medium efficiency filter to protect the HEPA filter, as well as a fire screen when there is a potential for fire.

The last basic requirement is a means and method to remove the contaminated filter from the glovebox. The most common method is the bag-in/bag-out method. Push-through filter housings differ in that they hold the standby filter in the filter housing. (See **Figure 4.13** for push-through filter housing). The filter is a cartridge type with chevron seals located at the inlet and the exhaust of the round cartridge filter. One of its advantages is that it is designed to maintain confinement during a filter change. A new filter displaces the spent filter as it is pushed through. The old filter and spacer are displaced to the inside of the glovebox. The inner pipe "tube" of the housing is honed to obtain a smooth, round surface. The chevron seal, which is larger than the internal diameter of the tube, creates the seal.

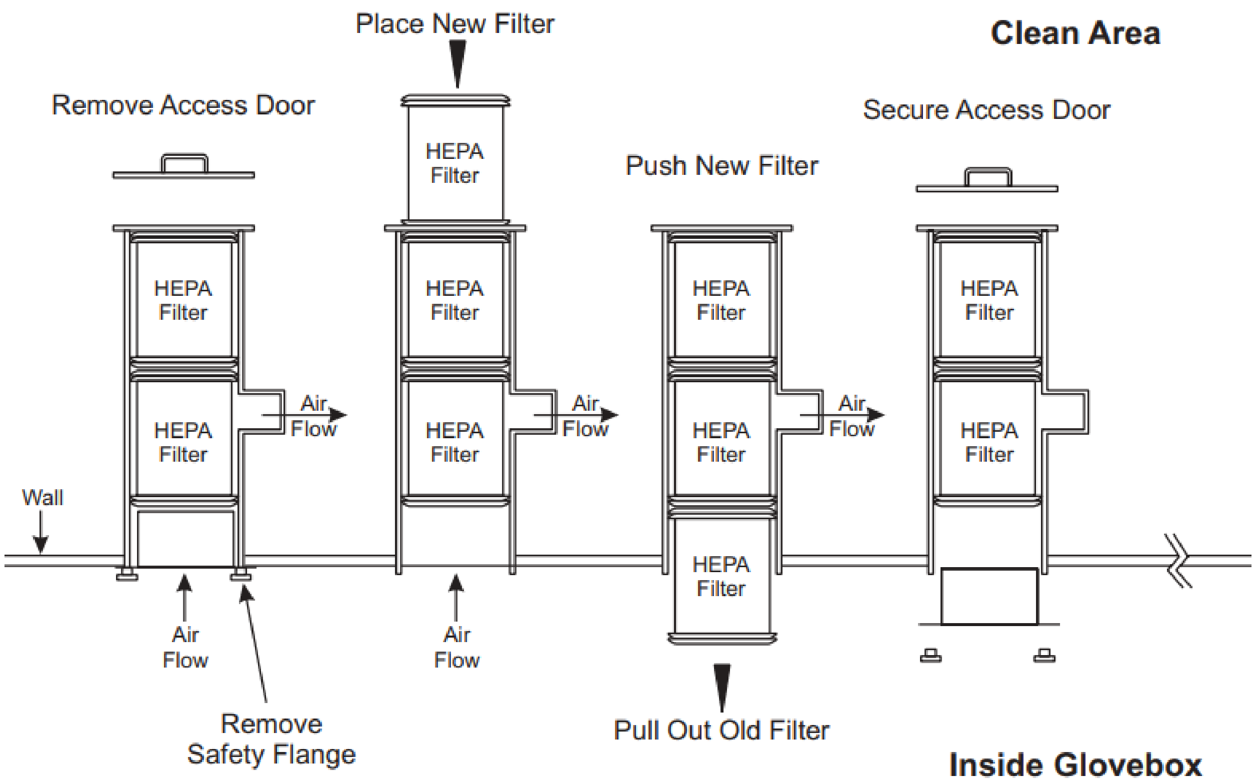

Figure 4.13: Push-through Filter Housing

Although this system has been used with great success, seal quality and tube finish are critical to its proper operation. This filter housing design is vulnerable, however, when it is used for applications involving light, easily airborne materials. Such materials, if surface-deposited on the inside tube, can bypass the seals during a filter change because the seal can "roll over" the material. Another potential drawback of this design is its orientation. It should be installed in a vertical position for proper sealing. A horizontal installation will enable the seals to "take a set" and eventually bypass the filter. This filter housing has been used at nuclear facilities in the U.S. for many years with good reliability; however, its limitations should be noted.

Cartridge filters can be used for glovebox operations for both radioactive and nonradioactive applications. These filters incorporate the filter housing and filter as a single unit and are supplied from the manufacturer with options for pipe nipple connections on both the inlet and exhaust or on one end only. Test ports should be specified when ordering, as these filters range in size and airflows. A valve should be located on the outside of the glovebox filter housing.

Radioactive Applications

In some radioactive applications, the cartridge filter should be located on the inside of the glovebox for safe filter changing. The isolation valve is located on the outside of the glovebox filter housing.

Bag-in/bag-out side-access filter housings are used in some glovebox applications. They are available in sizes from 35 cfm on up and in rectangular or round configurations, as discussed in Chapter 4. For radioactive applications, it is desirable to mount the housing as close to the glovebox as practical. Long ducting or plenum runs are not desirable due to their lack of access for cleaning. Mounting the filter housing directly to the glovebox reduces the potentially contaminated surface area.

Redundant filter housings (**Figure 4.14**) are used when working with materials that, if released through the exhaust system, would be detrimental with respect to both safety and associated cleanup costs. All nuclear facilities use a secondary exhaust before discharging to the outside air. In some older facilities, manifold systems were not designed for safe, clean decontamination. If contamination migrates into these systems' ducting, cleanup is both costly and time-consuming. As a result, use of a redundant filter should be considered. The design of a redundant system requires the use of an in-place-tested primary and secondary HEPA exhaust filter installation. **Figure 4.14** shows two redundant filter housings—one filter changed from inside the glovebox (primary); the other (secondary) is shown as a bag-in/bag-out type changed from the outside.

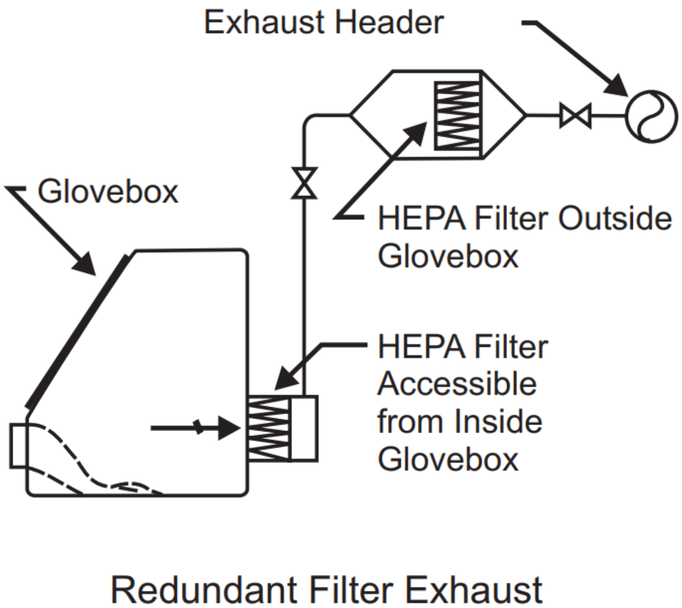

Figure 4.14: Redundant Filter Housings

Materials

It is important to understand (a) the construction materials used on the filters and filter housings for gloveboxes, particularly chemical processing gloveboxes, and (b) which chemicals and gases will be introduced into the airstream of the glovebox and where they will be processed if processing is required. If a bag-in/bag-out port is used, the bag material is subject to the same exposure to chemicals and gases as the rest of the ventilation. If the process performed in the glovebox changes or other materials are introduced into the glovebox system, the compatibility of the materials should be re-evaluated. Simply put, the materials, ducting, and blower unit need to be compatible with the chemicals and gases exposed to the exhaust airstream.

In-Place Test Ports

A glovebox filter housing is relatively small compared to most filter housing installations. As with any HEPA filter installation, test ports should be placed on the filter housing to validate the installation. The criteria for testing gloveboxes focus on the proper location to inject the challenge aerosol, upstream, and downstream samples. The test ports should be designed to be sealed after each use and to be as cleanable as possible. This is usually a 3/8- to 1/2-inch half-coupling/nipple with the appropriate plug/cap. The weld and finish of a test port should emphasize clean smooth surfaces, especially from the inner diameter of the port to the filter housing. Cracks and crevices in this area are next to impossible to clean via access through gloveports.

Bag-in/Bag-out Ports

Bagging ports are used on gloveboxes for multiple purposes such as transferring materials and equipment and removing the waste generated during operations. Significantly, they are also used to transfer new or spent filters while maintaining confinement. The bagging port should be sized to accomplish this purpose. Use of a cylindrical bagging port is preferred because this design is “operator friendly.” A typical bagging port should have two outer-raised ribs around the outer circumference to prevent the bag from being easily pulled off during operations. The ribs are normally raised approximately 1/4- to 3/8-inch above the outer circumference and 1 to 1.5 inches apart.

A safety-restraining strap should be used to prevent the bag from being easily pulled off. It should be installed whenever the bagging port is being used and should be removed only when performing the bag-in/bag-out (new bag installation) procedure. The strap is secured between the two ribs. A cinching strap may be used to prevent the bag from being sucked into the glovebox due to negative pressure. It is installed when the bagging port is not being used. An internal access door may be used to isolate pressure surges and to act as a secondary confinement for the bag. The door should have a seal to prevent egress of contamination from the glovebox. An external cover may also be used to protect the bag and keep it out of the way of other operations. A “bagging kit” should be supplied with a bagging port. It should contain the components, tools, and procedures to perform the operation.

Sealing Mechanisms

There are multiple sealing methods for filter housings and filters used on gloveboxes. These can be application-specific or site-specific and either gasket- or fluid-sealed. The designer should consider chemical, gas, radioactivity, and heat as deciding factors in determining which sealing mechanism to employ. In some applications, the filter housing is welded and incorporated into the glovebox. In others, the filter housing is a bolted, gasketed installation. The bolted design is more versatile by design; however, a potential crack at the gasket interface may make decontamination difficult. It should be noted that a push-through filter housing should be bolted due to the housing manufacturing process. Filter seals vary by application. HEPA filters can be supplied with many different gaskets and fluid sealing systems.

Blower Connections

If a dedicated blower is to be installed on a glovebox, several installation considerations should be addressed, including vibration, exhaust connection configuration, and blower discharge configuration. It is generally accepted practice to use a flexible connection in most ventilation applications. Vibration from the blower will transmit to the filter housing and subsequently to the glovebox. If a flexible connection is used to isolate vibration from the blower, there is a potential for heat damage to the connector. Noncombustible materials should be selected for this application. Blower designs vary. Selection of the exhaust and inlet connection should prevent severe effects on blower capacity. Obstructions at the immediate inlet and outlet will grossly affect blower capacity. Elbows and tees at the inlet will also affect capacity and should be avoided.

4.2.5 Dilution of Evolved Gases

A high air exchange rate is often required to dilute fumes generated in an air-ventilated glovebox. When evolved gases, vapors, and particles are not flammable, toxic, or corrosive, flow rates sufficient to maintain a negative pressure (with differentials from 0.3 to 0.5 in. wg in the box) may be employed. However, when fumes or vapors are hazardous, a higher ventilation rate is necessary. The maximum generation rate of hazardous substances is determined to establish the minimum airflow needed for dilution.

4.2.6 Heat Dissipation

Heat removal affects glovebox ergonomics. Operators access the inside of the glovebox using gloves that are often awkward to use and gloveports that limit their operations. When higher than normal heat conditions exist in a glovebox, it leads to higher fatigue levels. This limits the operations that can be performed in the glovebox environment. For worker comfort, sufficient air should be exchanged through the box to limit the inside temperature to no more than 15 degrees Fahrenheit above room temperature. When the calculated airflow for cooling exceeds the exhaust cfm, consideration should be given to higher airflow (larger filters or more filters), supplementary cooling, better insulation of heat sources, cooling coils, or chill blocks for hot materials. In the design phase of a glovebox project, the designer should be aware of the heat load presented by the equipment located in the glovebox. It is desirable, when practical, to determine whether items like electric motors can be placed to the outside of the glovebox. This can reduce the heat load inside the glovebox significantly, as well as simplify maintenance and serviceability and reduce disposal costs.

Operations to be performed in a glovebox should be determined ahead of time. Airflow velocities can affect the operation of sensitive equipment and cause materials like powders to become airborne.[18] There are practical limits to the amount of cooling that can be accomplished by airflow, since high airflow can create strong air currents if not properly diffused. Where possible, operators should be protected from objectionable sources of radiant heat by surrounding the heat source with reflective shields or conductive jackets. Exhaust airstreams may be routed through such shields to permit the maximum pickup of convection heat before leaving the box.

Long-term operation of high-heat-producing equipment can damage filters when exhaust air temperatures approach the temperature limit of the filters for continuous exposure to heat.

4.2.7 Empirical Flow Rates

The ventilation system should be designed to provide a safe, ergonomically practical, and reliable unit. Experience has shown that filter pressure drops will vary, ductwork loss will be greater, and blower performance may be slightly different in actual working conditions (other variables also are discussed in this chapter). If the glovebox ventilation system does not

[18] Negative pressure also can cause equipment problems.

perform as designed, it should not be used or commissioned until it meets the minimum safety requirements of this document and other referenced documents.

Troubleshooting an installation should include the inspection of the ductwork and installation of the blower (including wiring); the medium efficiency filter, inlet, exhaust HEPA filters; and the manifold (if equipped). Common problems with new installations include debris lodging in the ducting, blower housing, and filter housing and finding the blower motor wiring reversed. Long flexible connections will also affect performance since a bend can dramatically choke off airflow.

4.2.8 Exhaust Requirements

The maximum airflow from the glovebox determines the required capacity of the filters and the size of the equipment for the entire downstream portion of the ventilation system. The airflow resistance of the exhaust-air path needs to be sufficiently low so that pumping of gloves (pressure recovery) by operators in the box will not result in positive pressurization. In small low-flow boxes such as those with an inert atmosphere, pressure surges due to glove pumping may be a serious problem. Fast insertion of the gloves can cause the glovebox to reach a zero or positive pressure. Typically, the glovebox is fitted with an inlet and exhaust filter in a room air application. Another filter “emergency discharge” is added and fitted between the blower discharge and the inlet air filter. The blower installation connects the exhaust filter housing to the negative side of the blower, and the inlet filter installation connects to the positive side.

When the installation is complete, the emergency discharge filter is in a standby condition. The ventilation unit basically recirculates the inert gas. If a breach or leak occurs, the emergency discharge filter becomes naturally activated. The path of least resistance during a breach discharges exhaust air through the emergency standby filter since the inlet is now the gloveport. This filter should also be sized for the gloveport “inherent safety feature.” The filter should be rated for twice the cfm or half the pressure drop of the inlet filter. If the two filters, inlet, and emergency standby, have the same airflow and pressure drop, the airflow will be directed to both instead of the emergency standby filter. If air is to be exhausted from the emergency standby filter, a bleed vent is necessary to prevent removing the inert gas and imposing additional negative pressure.

When the glovebox ventilation unit is activated, there should be no flow through the emergency standby filter. If the secondary exhaust system is directly connected without a bleed vent, the glovebox pressure will become extremely negative. The vent allows room air to be removed until the emergency standby filter requires exhaust.

The maximum rate of exhaust flow from a room-air-ventilated glovebox is usually based on the required inlet flow when a glove is ruptured or inadvertently removed. The air velocity into the open gloveport should be at least 125 linear fpm. Good contamination control is more easily achieved in a glovebox with low air leakage. Gloveboxes should have a leakage of less than 0.02 to 0.5 percent box volume per hour, depending on the application requirements. In some applications, such as inert environments, a helium leak test is performed to ensure the integrity of the glovebox. The method, technique, and criteria for testing are given in AGS-G004-2014. Section 5.3 (Helium Mass Spectrometer Leak Detection) and Section 6.2 (Pressure Decay Test).

4.2.9 Vacuum-and Pressure-Surge Relief

In some applications, gloveboxes need to be protected against physical damage resulting from excessive pressure or vacuum. The exhaust and inlet supply system should be able to handle slowly manifested pressure or vacuum disturbances. Each glovebox containing service connections or internal equipment whose malfunction might cause a pressure surge should be equipped for prompt surge relief. This also applies to fire suppression systems, as outlined in DOE-STD-1066-2016. The response time and pressure-flow characteristics of the surge-relief device will depend on the flow and pressure characteristics of the pressure source, the free volume, and the relative strength of the gloves and glovebox. The relative strength is defined as the lowest pressure differential that will cause rupture of the glovebox pressure boundary at its weakest point. Depending on the design of the box, the weakest point will usually be a window or a glove. The surge-relief device can be a liquid-filled U-tube, as shown in **Figure 4.15**. The surge-relief flow capability should exceed the flow from the largest possible source of pressurization at the design relief pressure. The HEPA-filtered surge-relief line should not be connected to a glovebox exhaust manifold because this line will be subjected to the same pressure as the normal glovebox exhaust connection. A liquid storage reservoir is provided to handle the blown seal fluid.

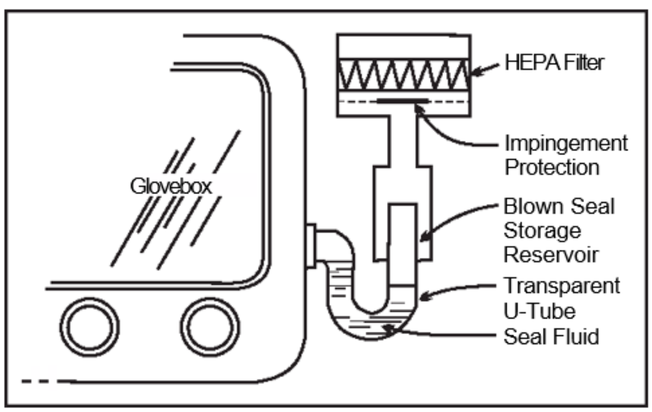

Figure 4.15: Glovebox Vacuum-Pressure Surge Relief Device

The filter and ductwork should be sized in accordance with the required cfm and pressure drop based on the pressure surge. The filter should be protected from impingement of the seal fluid. If room air cannot be tolerated in the glovebox, as is the case in some inert-atmosphere applications, a different vacuum surge-relief system is used. A U-tube can be devised to restore its seal after relieving the surge, but such a system includes a feature to alert the operator that a pressure surge has occurred so that he can make the necessary safety checks. An inlet filter may provide surge relief if no backflow device or other restriction is provided. The filter face area would have to be about four times the area of an unfiltered port to achieve an equal venting effect.

4.2.10 Glovebox Exhaust Manifold

A glovebox exhaust manifold is used when multiple gloveboxes will share a common ventilation system. This method reduces the amount of exhaust ventilation components for dedicated exhaust systems. The glovebox exhaust manifold includes all of the glovebox exhaust system downstream from the point where the exhaust from two or more gloveboxes joins and the airflow is combined.

The glovebox exhaust manifold draws air or exhaust gas from each connected glovebox at a controlled pressure and airflow (interdependently), houses secondary treatment facilities, and transmits the air for further treatment or exhausts it to the outside atmosphere. Primary exhaust treatment should be applied inside or as close to the glovebox as possible and, in all cases, before connection of the exhaust line to the exhaust manifold. It is critical to protect the manifold from contamination due to the difficulty of cleaning and decontamination. In some systems, a portion or most of the cleaned or treated exhaust gas may be recirculated back to the gloveboxes.

The manifold system should be sized and controlled for the maximum flow, based on (1) the maximum normal flow from each box, (2) the largest maximum flow under removed glove conditions from one of each of five connected boxes, and (3) an allowance for system growth. The low extreme is the sum of the minimum flows from each box. An allowance for system growth should be provided at not less than 20 percent of (1) plus (2) above for a new system. If this allowance exceeds 50 percent of (1) plus (2), other provisions such as installing an equivalent dummy flow should be considered.

4.2.11 Exhaust Cleanup Criteria

Providing as Low as Reasonably Achievable (ALARA) exposure to radioactive material is the guiding principle for determining the design of a glovebox ventilation unit. Protecting the exhaust downstream of the primary HEPA filter is paramount for nuclear installations. Experience has shown that exhaust systems are not only difficult to decontaminate but have led to unnecessary operator exposures. It is also true that, after filter breakthrough, nuclear particles can migrate to all the gloveboxes in the chain.

Installations employing redundant HEPA filters need to have features allowing in-place testing. The requirements are provided in ASME AG-1, Section TA.

4.2.12 HEPA Filters

A single-HEPA-filtered exhaust path is defined as a glovebox that does not involve highly toxic aerosols or potent, toxic, or radioactive materials, i.e., materials that do not pose a hazard to the operator during a filter change-out. A multiple-filtered exhaust path is defined as a glovebox requiring more than one line of defense from particle penetration. This occurs when the exhaust ductwork or manifold needs to be protected or the Most Penetrating Particle Size is well below the efficiency particle mean of the filters.

When continuous airflow is essential, two exhaust connections should be provided to avoid interruption of exhaust flow during a filter change and to provide standby protection in the event of system upset. The purpose of multiple exhaust connections is to allow an emergency connection to be made. **Figure 4.16** illustrates single- and multiple-filtered exhaust connections for a glovebox.

Multiple-filtered exhaust connections should be used when interconnected gloveboxes or a large enclosure with several compartmented work areas are needed. Compartmenting doors between work areas or between single boxes in an interconnected line should not isolate a work area with only one filtered exhaust connection. The multiple exhaust points required to handle total airflow in a line of interconnected boxes should be sized for maximum flow and valved individually for flow control.

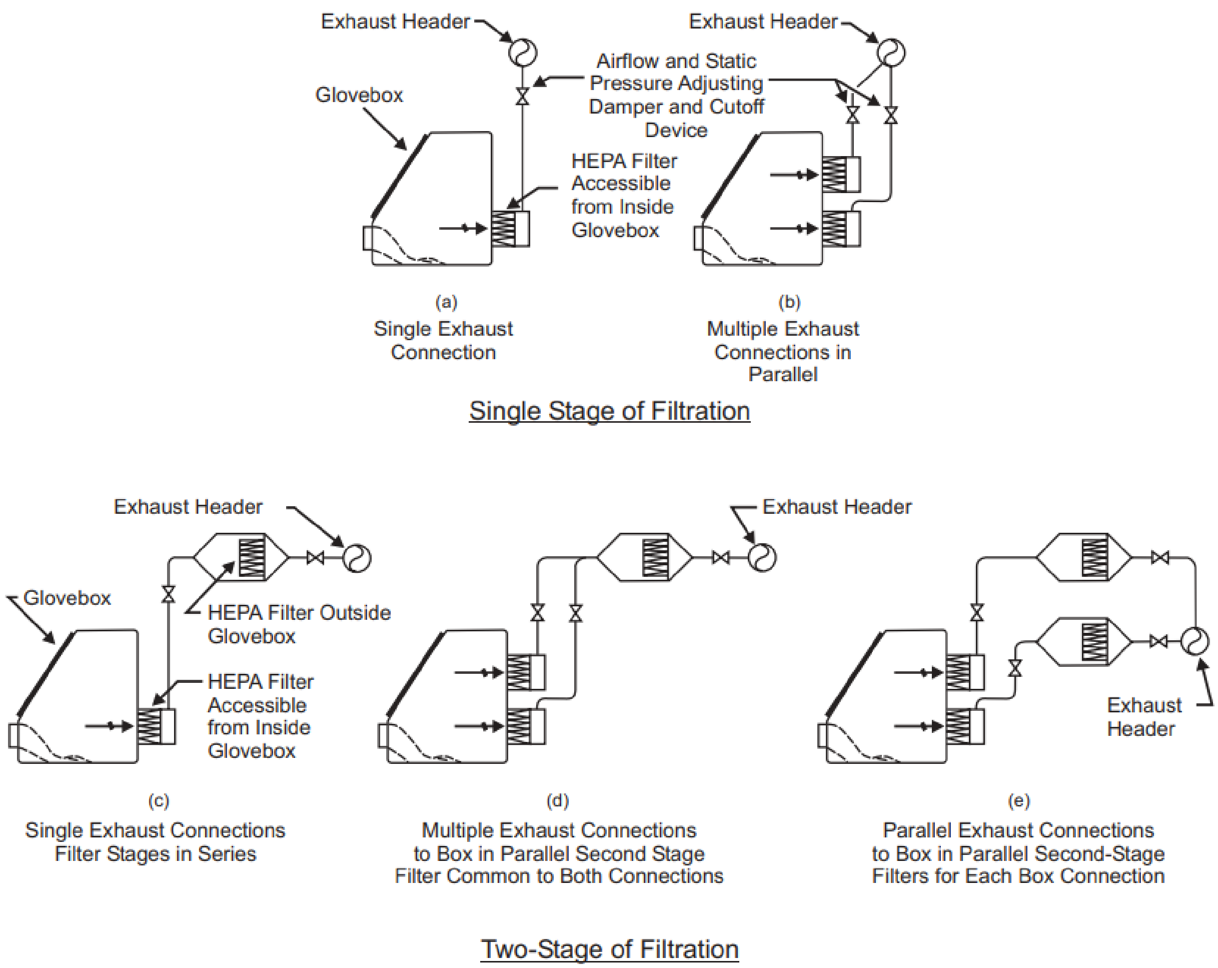

Figure 4.16: Single-Stage and Two-Stage Filtration

The glovebox designer should understand the limitations imposed by ergonomics. There is an art to designing the glovebox, ventilation service, and internal equipment operation and service. Some facilities build mockups of the glovebox concept to determine whether the operations can be done in a practical manner. It is critical to prove the practicality in some operator-intensive, hands-on operations and long-term production activities. Tasks performed within the confines of a glovebox should factor in the weight of the objects handled and the location of the operation(s) to be performed within. It is better to demonstrate the activities at the design phase than to wait for the glovebox to be built. Failure to do this can be very costly to repair and can seriously compromise operator safety.

The fatigue factor is high when working in a glovebox. The working pressure, heat, glove sleeves, gloveport location, and operations where the arms are outstretched all add to fatigue. Intricate or sensitive work significantly adds to fatigue because the operator cannot feel through the gloves. If visibility is poor or nonexistent, operations will be very difficult, if not impossible, to perform. Some operations with older gloveboxes used mirrors to perform some operations. In glovebox terms, “extended reach” is used to describe an occasional operation where something is pulled forward to a working position or a simple operation such as turning a switch off or on (e.g., lowering or pulling out a spent filter for disposal). Extended reach should be avoided in repetitive or routine operations.

4.2.12.1 HEPA Filter Selection Criteria

The characteristics listed below should be considered when selecting filters.

- A standard-size HEPA filter is located in the back- or end-wall of the glovebox.
- Inside box space is maximized by partially recessing the filter in the wall.
- Provides adequate space to transfer the HEPA filter out of the glovebox (see Table 4.9 below).
- A simple clamping method is used that has no removable pieces and is operable with a gloved hand by a simple, clean clamping mechanism.
- A retainer is used that serves as a face shield for the filter and permits attachment of a steel-cased medium efficiency filter by a flexible magnetic strip, accessible from the front, hence the filter remains in position after being unclamped because of the folded lip at the top.

Table 4.9 – Glovebox Bag-Out Port Sizes for Transfer of Standard Open-faced HEPA Filters

Filter Size	Required Port Size (inches)	
	Round (diameter)	Rectangular
8 x 8 x 2 1/16	9 3/4	8 1/2 x 4 1/2
8 x 8 x 5 7/8	10 3/4	8 1/2 x 6 1/2
12 x 12 x 5 7/8	14	12 1/2 x 6 1/2
24 x 24 x 5 7/8	26	25 x 6 1/2
24 x 24 x 11 1/12	27 3/4	25 x 12

4.2.13 Medium Efficiency Filter (Prefilter) Selection

Medium efficiency filters are used to extend the life of the HEPA filters located at the inlet and exhaust filter housings. This can be determined by noting the sensitivity of glove movement and pressure recovery. In easily airborne powder applications where a significant amount of dust is airborne in a glovebox, removing the medium efficiency filter may be the only means to restore safety (negative pressure) to the glovebox during a powder mishap.

Medium efficiency filters for gloveboxes come in a range of sizes and configurations. Some facilities use simple cut, in-place pads, and some use HEPA filters (not tested) to perform the medium efficiency filter function. For some applications where air entering the glovebox is HEPA-filtered and there is little or no dust loading in the glovebox, an exhaust medium efficiency filter may not be needed. A medium efficiency filter should be considered on the inlet HEPA filter on the glovebox unless the glovebox resides in a cleanroom. Medium efficiency filters are manufactured from a fiberglass media similar to the HEPA filters. As a result, they are susceptible to the same chemicals, fumes, and heat damage. Some medium efficiency filters are manufactured with a beverage board (coated cardboard) frame, which should be avoided if fire is a concern.

Holding devices for medium efficiency filters should be manufactured from the same material as the glovebox or a material that is resistant to the chemicals and fumes that will be present in the airstream. Retaining fasteners, when used, should be made of dissimilar materials that do not gall. It is better to dispose of a 302 stainless steel wing nut than to replace a 304-L stainless steel stud welded on a glovebox. The frame should be designed to minimize air bypass around the medium efficiency filter yet allow enough clearance between the HEPA filter and medium efficiency filter to prevent media contact. An independent holding frame should be incorporated in the design to prevent disturbing another filter installation.

4.2.14 Inlet HEPA Filters

Work performed in gloveboxes frequently requires supply air that is free of airborne contaminants. Inlet HEPA filters help maintain clean conditions inside and, when chosen properly, also serve three other useful functions: (1) extending the service life of the exhaust filter by protecting them from atmospheric dirt loading, (2) preventing the spread of contamination from the glovebox to the room in the event of a glovebox pressure reversal, and (3) providing overpressure relief.

The design of the inlet filter installation is relatively simple for air-ventilated nonrecirculating gloveboxes. Since no duct connections are required, open-faced filters may be used with an installation and clamping method that leaves one face completely exposed. Typical methods of installation are shown in **Figure 4.16(a, b)**. Because they are less likely to be contaminated, inlet air filters are easier to replace than exhaust filters; therefore, they provide fewer problems and less risk during changes. Whether mounted to the glovebox internally or externally (external mounting is preferred), the same high-quality mounting, clamping, and sealing are required.

The open face of the filter needs to be protected from physical damage and fire. Plugging of the inlet filter by smoke is a secondary concern, however, since one recommendation for glovebox fire suppression is to reduce normal airflow. Locating the inlet connection (or an attached inlet duct) high in the box tends to reduce the amount of air drawn into the box during a fire because of the chimney effect. This ventilation flow pattern of top to bottom keeps contamination away from any breathing zone and closer to the floor. The result is protection of the workers, use of engineered controls instead of personal protective equipment, and support for implementation of good ALARA principles.

4.2.15 Roughing Filters

In some installations, it is desirable to recover material from the filters for either reprocessing or waste minimization. Roughing filters may be used for this purpose. The filter medium is typically less efficient than that of the HEPA filter or the medium efficiency filter. Construction materials may be suitable for the recovery process (Category 3 - combustion, acid dissolution), but cannot present a hazard to the downstream medium efficiency filter and HEPA filters. Fire screens and other measures may be used to prevent roughing filters from affecting downstream medium efficiency filters or HEPA filters.

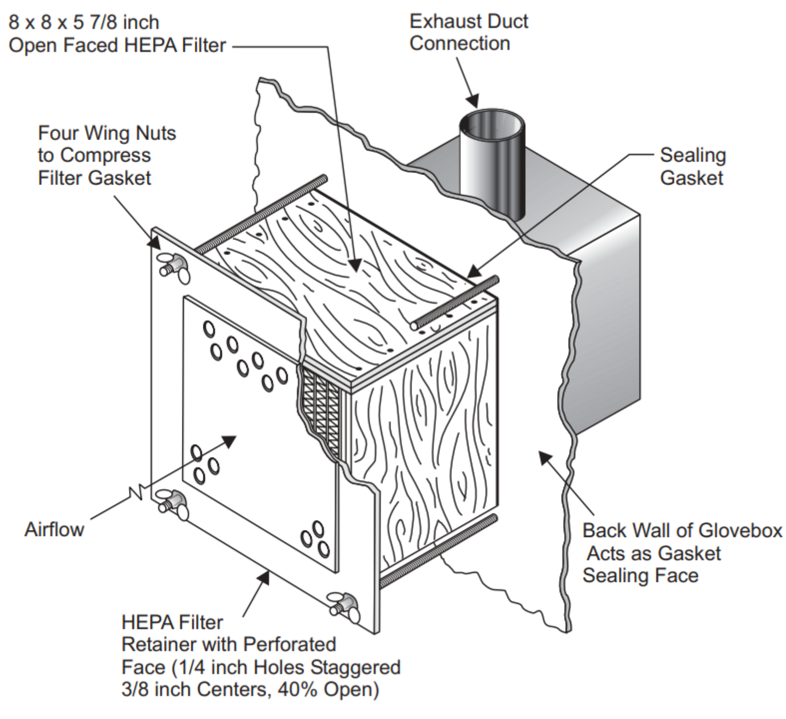

Figure 4.16a: Open-Face Filter Installation, Method (a)

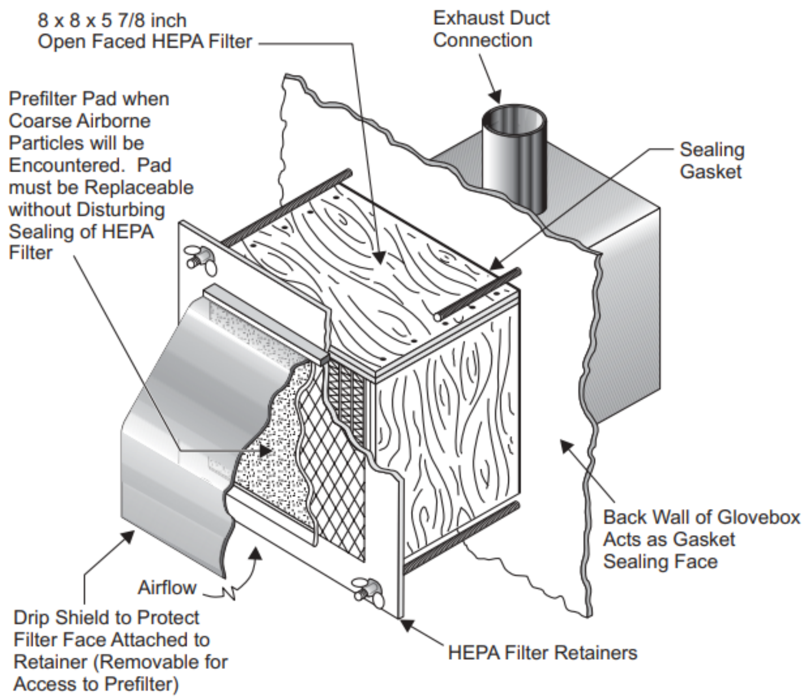

Figure 4.16b: Open-Face Filter Installation, Method (b)

4.2.16 Filter Replacement

Safe replacement of a contaminated glovebox filter should be planned in the design phase to facilitate proper execution. The filter change method and other maintenance functions, if not site-specific, should be determined and planned. The designer should prepare a written preliminary filter change procedure along with the design documents. If the design is questionable due to an extreme custom nature, the glovebox should be mocked up so that an operational demonstration can be performed. In applications where controlled inert atmospheres are present, filter changes should be planned for times when other routine or special maintenance operations are taking place inside the box to reduce interruptions to operations and loss of inert gas, and to minimize the time required to reintroduce the inert gas into the box spaces.

Replacement of a HEPA filter inside an air-ventilated box involves many steps that should be performed sequentially. Site-specific Standard Operating Procedures should be written, and the filter change team should be trained to perform the operations in a safe, controlled manner. Close coordination between maintenance and operating personnel is necessary to establish a mutually satisfactory date and time for the filter change, to identify the boxes and systems involved, to procure the necessary materials, and to schedule personnel. The health and safety requirements of the industrial hygienist, health physicist, and safety engineer should be established. One of these specialists should be designated the health and safety supervisor and should be available to monitor the operation and assist as necessary.

When the necessary materials and tools are ready, and all personnel have been instructed in their specific duties, final permission should be secured from the responsible operator to alter the airflow and replace the filters. The flow path of the exhaust system should be thoroughly understood, and persons responsible for related exhaust systems that will be affected should be forewarned. For instance, if two glovebox exhaust systems manifold to the same blower, final filters, and stack, the removal of one system from service for a filter change will affect the system flow and pressure characteristics of the other system. Safety clothing and respiratory protection should be worn as directed by the health and safety supervisor. The following steps are suggested for changing a filter and placing a box back in service:

1. Cease all glovebox operations and contain unsafe materials in suitable containers.
2. Cut off gas flow to the glovebox affected and adjust flow through the remaining branches to restore a safe negative pressure and flow rate in each.
3. Bag a clean replacement filter (and medium efficiency filter if used) in a small, clear plastic bag with sufficient tape to hold the spent filter and medium efficiency filter with all of the hand tools required, as shown in steps A, B, and C of **Figure 4.17**. It is recommended that the hand tools needed for filter changing be introduced the first time the filters are changed, and then left in the glovebox for subsequent use if space and environment permit. Decontamination is often more costly than tool replacement.
4. Using the glovebox gloves, remove the dirty filter and medium efficiency filter from their mounting frame.
5. Insert the dirty filter and medium efficiency filter into an empty plastic bag along with any residual materials, slowly expel excess air, and seal with tape or use heat sealing as shown in steps W, X, Y, Z, of **Figure 4.17**.
6. Inspect the gasket sealing face or fluid seal knife-edge of the mounting frame and clean if necessary. Place the replacement filter in position and secure the clamping devices. Place the new medium efficiency filter in position and secure.
7. Remove the dirty filters and all debris from the glovebox and place the removed items in a container for contaminated waste disposal.
8. Restore airflow through the glovebox and adjust the flow and negative pressure throughout the system.
9. Before glovebox operations are resumed, test the newly installed HEPA filter with challenge agent, using the permanent test connections on the housing. If the test result is not satisfactory, stop the flow and inspect the filter for damage. If no damage is apparent, reposition the filter, restore the flow, and retest the filter. If the second filter challenge is unsatisfactory, the filter should be replaced and steps 3 through 9 should be repeated. Continued leakage suggests a mounting frame failure, filter damage, or a faulty test, and each possibility should be examined in detail until the fault is discovered and corrected.
10. Decontaminate the area.
11. After successful filter replacement, notify the responsible operator.

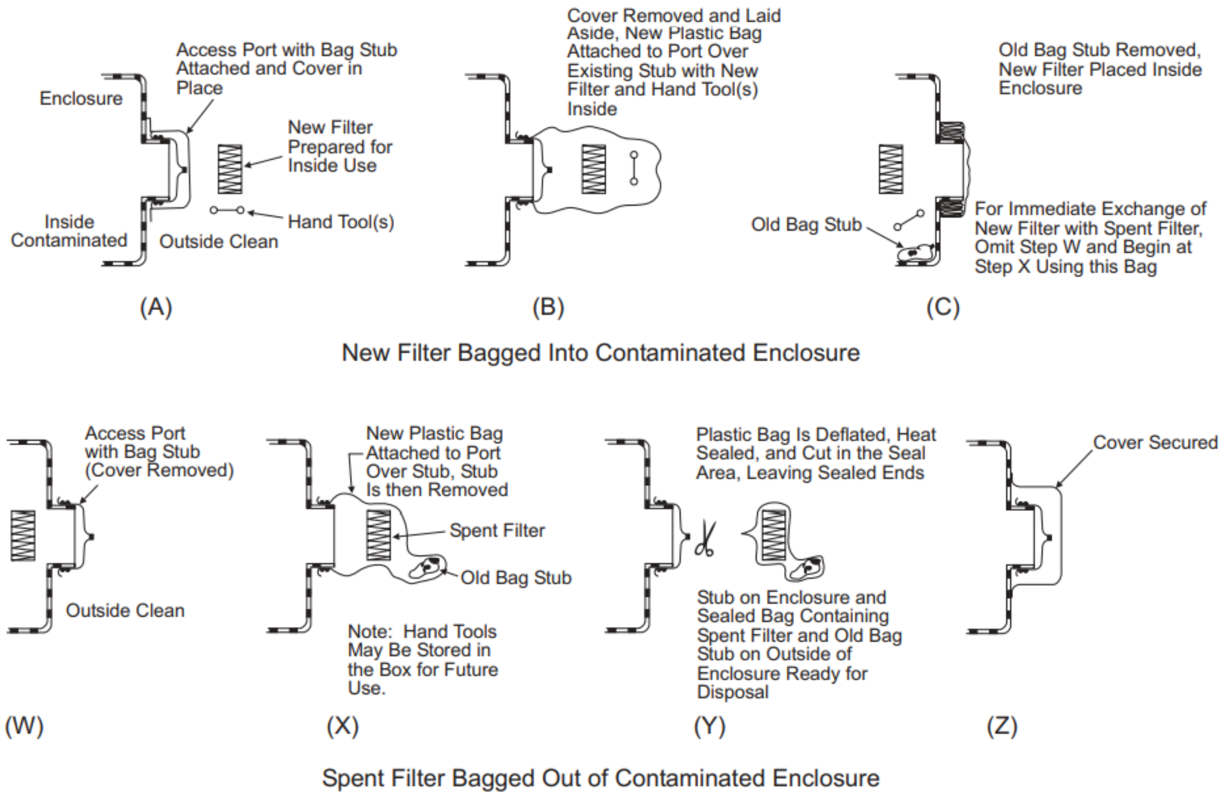

Figure 4.17: Filter Changing Process

4.2.17 Protection Against Fire and Explosion

The guidance in this subsection is offered to assist users in meeting the fire protection requirements of DOE-STD-1066-2016 and DOE O 420.1C.

4.2.17.1 General Guidance

- Use nonflammable materials as much as possible in construction. Gloves and windows are the most susceptible to fire due to their construction materials. Laminated or tempered safety glass is the material of choice regarding fire.
- For applications where explosion, overpressure, or moving or rotating machinery are a concern, impact-resistant, fire-retardant polycarbonate should be used to protect the worker.
- Some material hazards may also dictate the use of high-impact material due to the hazards to operating and maintenance personnel from a cracked or broken window. Some applications resolve this problem by placing a layer of glass inside the glovebox.
- Strictly adhere to acceptable housekeeping practices. Spontaneous combustion of certain materials can occur in a glovebox as well as in the secondary work area.

- Avoid the use of flammable materials within the box wherever possible and limit the amount of flammable material to the calculated air change when no suitable nonhazardous substance can be substituted. Use containers for flammable substances that are approved for the planned operation.
- Maintain a current in-box material inventory. Gloveboxes should be used as designed. They are inappropriate for long-term storage, especially for chemicals.
- For inoperative gloveboxes, establish a safer, glovebox configuration and periodically check to ensure the gloveboxes are in a safe condition. Precautions include isolating boxes by closing fire stops, checking through-flow, checking port covers, disconnecting electrical equipment, and removing corrosives.
- Design the box with downdraft ventilation (high air inlet, low outlet) if possible, to inhibit combustion while still purging the box. Generation of light flammable gases by the process may dictate exhausting from the top.
- Provide a protective atmosphere. This measure is listed last because those preceding it are applicable to all gloveboxes, whereas inerting is used only when there is too much risk involved in operating without a protective atmosphere. Assessing the degree of risk involved in an operation is often a subjective evaluation.

4.2.17.2 Detection

A glovebox fire detection system is recommended when there is a high risk of fire determined by a Fire Hazard Analysis (FHA). If flammable solvents, coolants, and packaging materials need to be present during operation, especially in unattended boxes, a heat detector should be installed on the glovebox. Whenever a pyrophoric material (such as plutonium) is used in gloveboxes, fire detectors are required.

4.2.17.3 Suppression

Since a fire within a glovebox may be of paper, chemical, electrical, or pyrophoric metal origin, there is no single suppression method that is best for all gloveboxes. However, when designing a glovebox, the designer should be aware of the materials, material quantities, process, and interfacing equipment that will be involved in the installation. At this point, the FHA should determine the proper suppression system for the installation. For further details, see Section 5.1 of this handbook, Section 4.4.2.3 of DOE-STD-1066-2016, and the American Glovebox Society's *Standard of Practice for Glovebox Fire Protection* (AGS-G010-2011).

There is no assurance that filters will remain functional during and following exposure to fire, smoke, or burning debris. Variable destructive effects on medium efficiency filters and HEPA filters include the temperature reached during a fire, the quantity and density of the smoke released, the heat release rate, and the duration of the fire. After exposure to fire, smoke, or burning debris, all components of the glovebox should be evaluated and tested prior to return to service.

4.2.17.4 Inert Environments

Inerting a glovebox environment is done when working with materials that are pyrophoric, oxygen-sensitive, or moisture-sensitive, or when a process needs to be protected. Inert gases such as helium, argon, and nitrogen are metered into a gas-tight glovebox to displace the “air” volume. The characteristics of the gas (lighter than air, heavier than air) are applied using proper sampling sensors to obtain a true inerted glovebox. In pyrophoric and high-fire-potential applications, oxygen sensors are used to verify real-time concentrations. Inline filters should be installed to protect the oxygen monitor, or any monitor, from contamination. Monitors and sensors are available for many different types of gases and fumes. These should be selected when fire, explosion, and any associated risk to the process would result in danger to personnel and/or the facility. This should be determined by the facility risk and fire assessment groups. In most of these instances, the facility fire department should be directly connected to any alarms related to the event.

Gas-tight systems require quality construction of all components including gloveboxes, filters, and associated ducts. Any air ingress associated with the filter mounting or connecting duct will adversely affect the quality of the inert atmosphere that can be maintained in the glovebox and thus the cost of inert gas purification. Penetrations used to pass electrical input/output signals and power into the glovebox should be hermetically sealed for this purpose.

In fire protection applications, the preventive step of inerting is safer, though more expensive, than extinguishing a fire if it does occur. National Fire Protection Association (NFPA) 801 (Section 7.1.4.5.7) states that fixed inerting systems are not substitutes for fire suppression. However, the oxygen level has to fall below 1 percent before it fails to support the burning of some pyrophoric metal. The use of dry air (relative humidity less than 20 percent) reduces the hazard of pyrophoric metal fires but does not eliminate it. Moisture in the presence of heated pyrophoric or reactive metals (e.g., finely divided plutonium) increases the possibility of explosion by generating hydrogen. The suitability and cost of an inert gas for the process are significant factors when selecting this type of fire control. The gas flow rate in most inert gas boxes is generally low. The flow should be consistent with required box-atmosphere purity levels, the scrubber, or the inert gas purification system that supports it. The inert gas may be purged on a once-through basis or recirculated through a purification unit protected with HEPA filters. While gloveboxes usually have filters installed for this purpose, the designer should assess the potential for equipment contamination and cleanup.

4.2.18 Control and Instrumentation

Glovebox instrumentation may range from simple indicators and alarms to sophisticated control systems. The type of control or instrument used will depend on the characteristics to be monitored, the relative hazards, and the method and time available to correct an upset condition. Operational characteristics to be measured and alarmed should include the differential pressure between box and surroundings, the filter resistance, the gas flow rate through the box, and the box atmospheric temperature. An alarm should be available for any activity that could lead to degradation of or loss of confinement; fire; or any other safety concerns. In addition to instruments and sensors on the box, it may be necessary to indicate and provide for readouts and/or alarms at a central panel for oxygen content, liquid level, neutron flux, gamma flux, fire, and explosive gas mixture inside the box.

When a monitored characteristic requires annunciation for safety when the level of a monitored parameter passes some predetermined point, the alarm may be local. For example, an alarm may alert the operator to an upset condition (e.g., when the glovebox pressure differential becomes less negative than its design relative to the surroundings) or it may signal an annunciator panel in an adjoining “cold” area (e.g., by the entry door to the glovebox room, in a control room, or both). Standard operating procedures and sufficient information on the current contents of each box should be available to assist evaluation of the hazard area when an alarm sounds and to aid in planning corrective action.

Minimum instrumentation for a glovebox ventilation system should include devices to indicate the differential pressure between the box and its surroundings, exhaust filter resistance, total exhaust flow rate, and exhaust air temperature. **Figure 4.18** shows the arrangement of indicating devices in a glovebox ventilation system. The items shown above the double-dashed line indicate the types of instruments commonly used to supplement the minimum instrumentation necessary to improve safety for a particular operation or circumstance.

For example, when box operators are not in full-time attendance for a continuous process, a sensor can be provided to monitor abnormal pressure, temperature, or almost any other critical process parameter and to actuate a remote alarm where an attendant is stationed. **Figure 4.19** shows an example of a local mounting for a differential pressure gauge (commonly referred to as a differential pressure gauge) on top of a glovebox. The instrument should be mounted near eye level, and the indicating face should be located so that the operator has a clear view while manipulating the gloves.

The gauge display should make operating conditions easily discernible to the operator (e.g., a differential pressure gauge with a range of 1 in. wg with “0” at the top). Sensing lines should be short and should be sloped directly back to the glovebox so that moisture will not pocket in the tube. Tubing should be at least 3/16 inch-diameter to allow the instrument to respond quickly

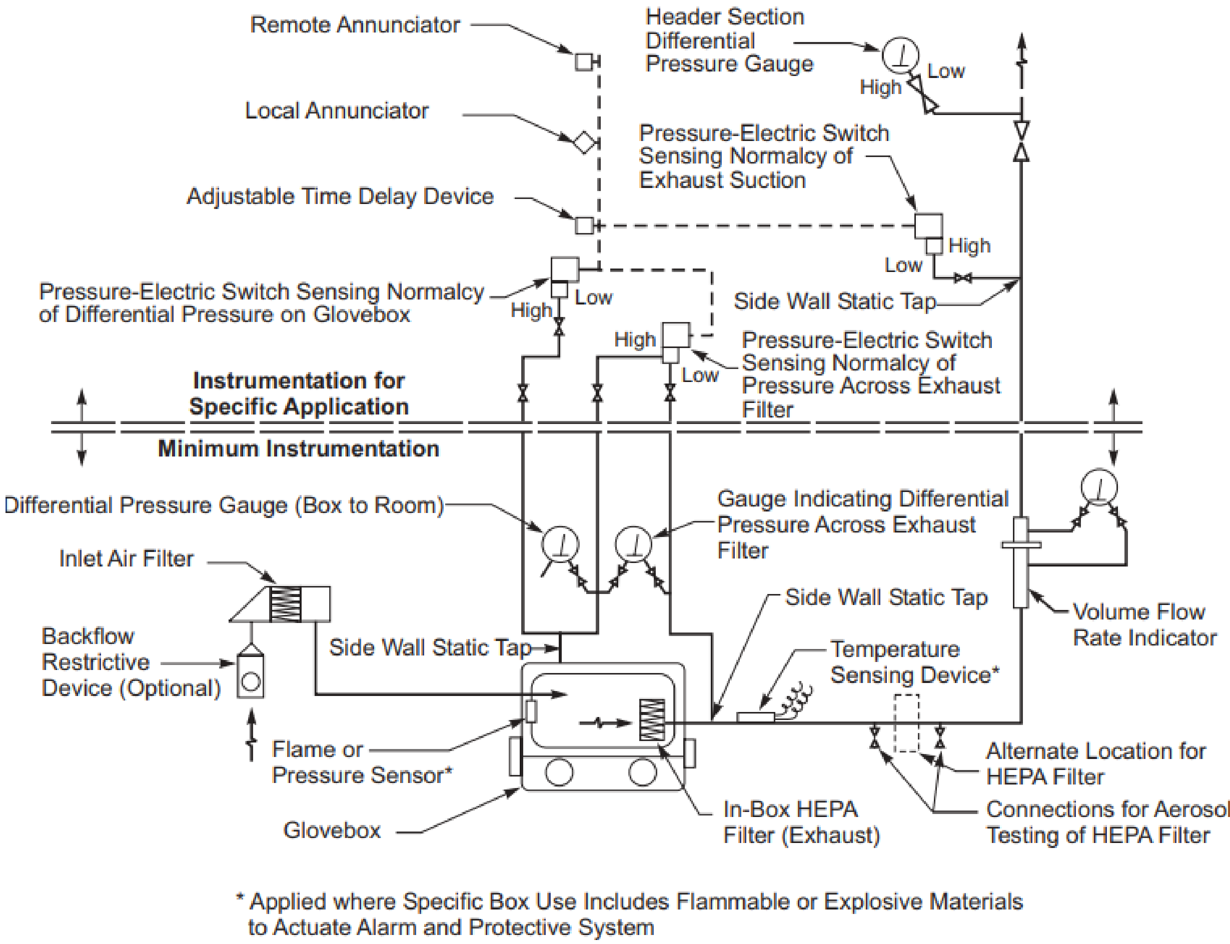

Figure 4.18: Arrangement of Indicating Devices in Glovebox Ventilation System

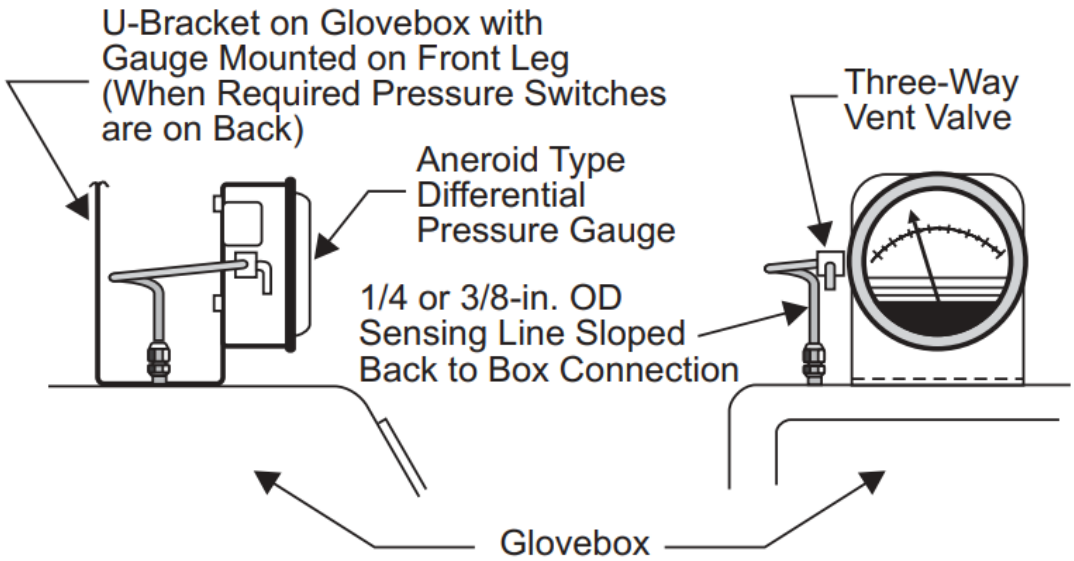

Figure 4.19: Typical Local Mounting for Differential Pressure Gauge

to rapid changes in pressure. Use of a three-way vent valve at the gauge permits easy calibration (zeroing) without disconnecting the sensing tube. Calibration of glovebox differential pressure gauges should be done routinely.

Selection of a differential pressure gauge, differential pressure gauge with switch, or transducer should be determined by the application. One advantage of using a gauge is simplicity. A line is connected across the upstream and downstream plenums of a filter where the pressure drop can be measured. Most gauges and transducers install in this manner. A differential pressure gauge with switch has the addition of an alarm function. A transducer allows multiple readouts and greater accuracy and can be used to automate the exhaust system. It is costlier, however, because it needs a power supply, readout, and transducer. The requirement for a gauge should be based on the actual system pressure. Exhaust filter pressure drops, for example, can vary up to 3 in. wg. If the inlet filter housing valve is closed, the device will see the full negative capacity of the blower. The gauge or transducer needs to have a proof pressure greater than the maximum system pressure (negative or positive) so that it will not be damaged by excessive pressure.

Devices that measure pressure have a problem with "drift." This occurs on most devices because of continual pressure on the device. As a result, they need to be recalibrated on a routine schedule. Liquid-filled devices (manometers) are not recommended for glovebox pressure indicators; however, they have been used to check the calibration of an existing device. Inlet filters on air-ventilated gloveboxes generally do not require differential pressure gauges. The pressure drop across the inlet filter is approximately the same as the box pressure.

A differential pressure gauge should be provided for each exhaust HEPA filter stage to indicate filter resistance. Pressure-sensing connections can be provided to permit the use of portable instruments. Suitable alarms or controls that can function on small pressure differentials (equal to 0.25 in. wg) are difficult to keep calibrated and are often expensive. **Figure 4.19** shows a method for indicating pressure drop through a filter.

Instruments used to measure airflow from gloveboxes include an orifice plate, venturi meter, flow nozzle, and calibrated Pitot tube. The important point is to use a simple, trouble-free device that gives reliable readings within an accuracy of ±15 percent. When free moisture is absent, a Pitot tube is the least expensive and most adaptable device for the small volume flow rates associated with glovebox ventilation. Immediately after installation and while filters are still clean, the measured pressure drop across the HEPA filter can be used to check airflow to a high degree of accuracy by proportioning the measured pressure drop to that stamped on the filter case at the time of predelivery testing. The pressure drop across the filter is no longer a dependable indication of gas flow rate after the filter has accumulated dust. After a filter has been in service for a period of time, it is necessary to measure both the pressure drop across the filter and the airflow through it to evaluate the filter's status and relationship to the whole ventilation system.

Written procedures for periodically testing each alarm, control, and emergency system serving the glovebox and its ventilation system are essential.

4.2.19 Challenge Aerosol Testing of Glovebox Filters

The HEPA filters used in glovebox systems are often inconvenient to test because the challenge aerosol has to be injected into the inlet duct or glovebox. The challenge aerosol cannot be fed into the inlet of the box to test the exhaust-side filters if high-efficiency filters are used in the inlet. Consideration is needed for safety, including contamination control and incompatible materials. Testing of non-safety filters, such as medium efficiency filters, is not necessary in contaminated gloveboxes. Methods A and B (**Figure 4.20**) require the challenge aerosol to be drawn into the glovebox by the suction of the exhaust system. However, the challenge aerosol should not be injected into gloveboxes housing apparatus with open or exposed optical lenses or with highly polished surfaces, delicate balances, crystalline structures, sensitive conductors, or similar equipment or products. In such cases, the filter should be installed in the duct downstream of the glovebox so that the injected challenge aerosol will not back up into the glovebox proper. Method C (**Figure 4.21**) may then be used for challenge aerosol testing of the exhaust HEPA filter.

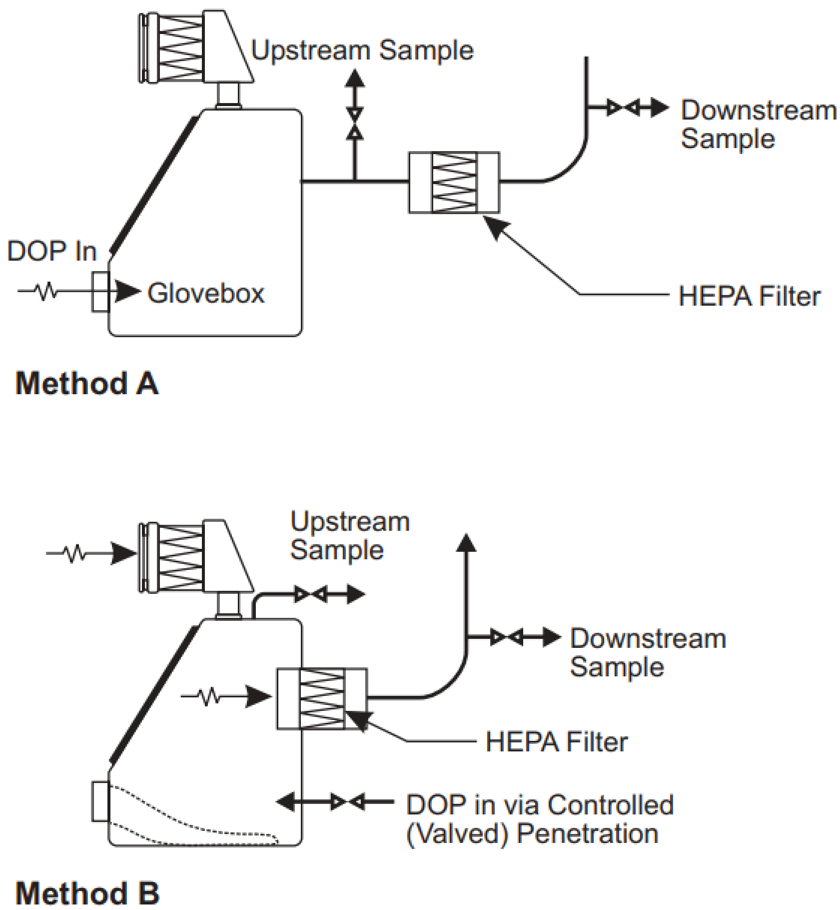

Figure 4.20: Methods of Injecting Test Aerosol and Extracting Samples

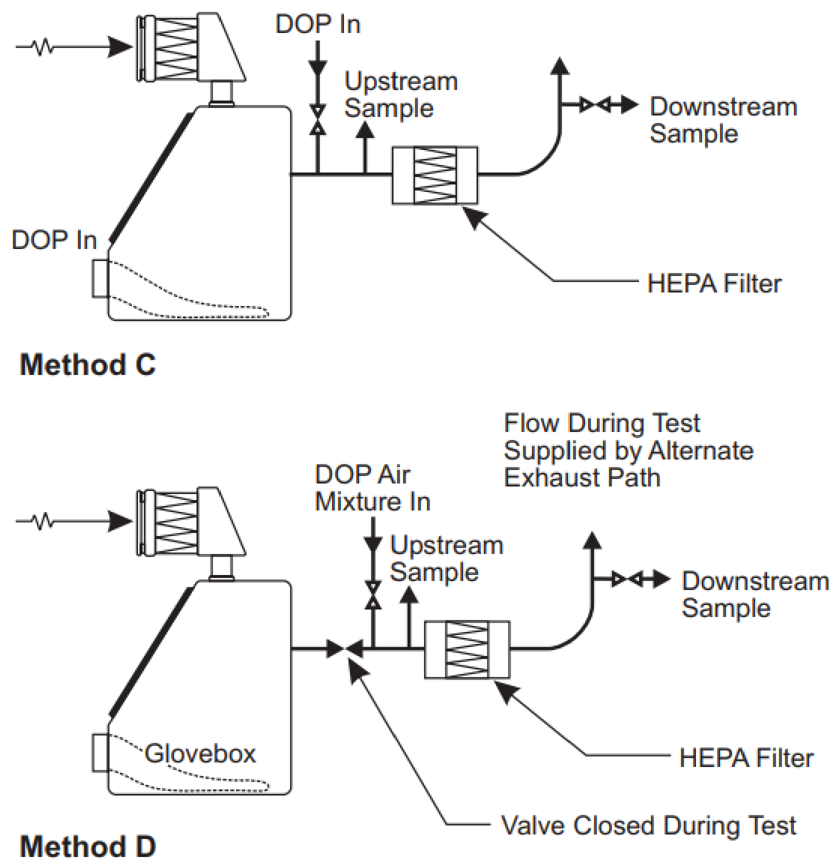

Figure 4.21: Methods of Injecting Test Aerosol and Extracting Samples

New or replacement exhaust filters are tested before restarting the ventilation system, and Method D (**Figure 4.21** above) may be used. Note that in this method the exhaust path from the glovebox is closed and the challenge aerosol-air mixture for filter testing is drawn from a separate valved path. The side path is closed and sealed after testing is completed.

Methods A and B (**Figure 4.20 above**) require injection of the challenge aerosol-air mixtures into the glovebox via some convenient opening. A gloveport can be used if confinement is not critical during testing. Otherwise, a connection can be prepared (**Figure 4.22**), or an alternate method can be devised. Methods C and D (**Figure 4.21 above**) do not require the introduction of a challenge aerosol into the glovebox. The challenge aerosol inlet connection should be sized to pass the challenge aerosol or challenge aerosol-air mixture. The connection for concentrated challenge aerosol in Method C should admit 2 to 5 cfm, while the connection in Method D should accommodate the total challenge aerosol-air mixture used for the test.

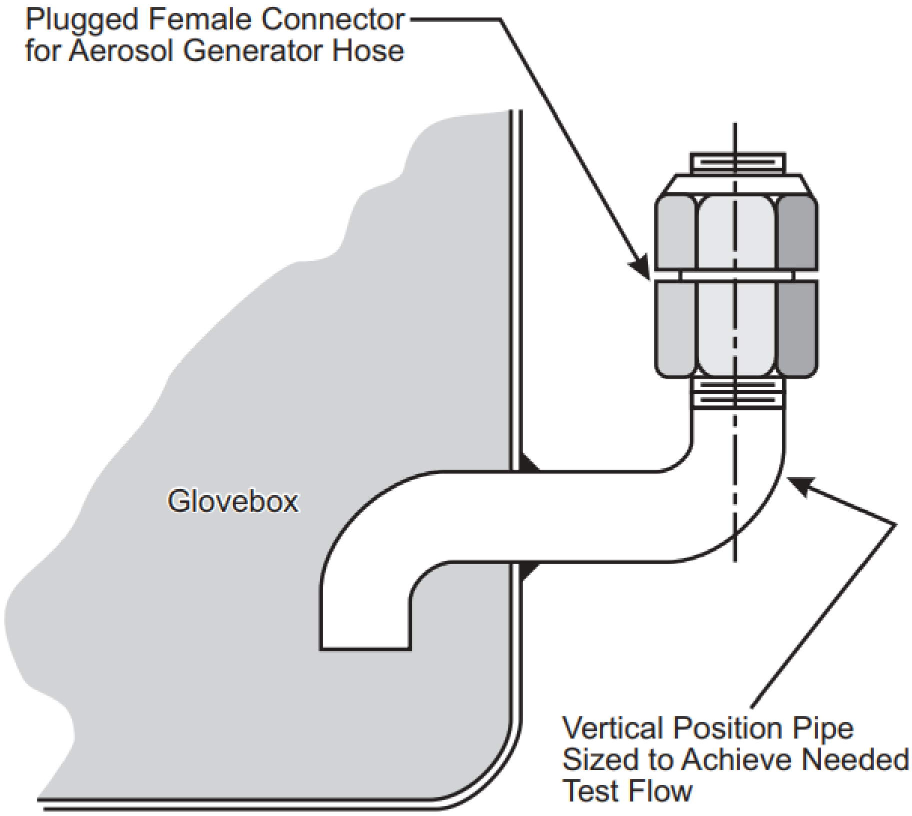

Figure 4.22: Connection for Introducing Test Aerosol into Glovebox

4.2.20 Glovebox Shielding

Some gloveboxes may require gamma, beta, and neutron shielding because of the nuclides used and the amounts of material involved. Boxes handling kilogram quantities of plutonium can be shielded by providing lead-impregnated gloves, glovebox shielding (water or any other similar mass), lead glass over the windows, and lead-hinged plugs or covers over the ports. The operating, shielding, removal, and replacement requirements of the glovebox HEPA filter should also be considered when glovebox shielding is required. The thickness of the shielding affects the design of the filter housing used on this type of glovebox. The designer should account for this by extending the service fittings (pressure measurement) and any other glovebox pass-through used in the design. This practice is also mandated for bagging ports used to remove the primary HEPA filters and the cover doors. Ergonomic operations inside shielded gloveboxes should be given careful consideration because lead-lined gloves and dimensional differences make manipulations very difficult.

4.2.21 Criticality Considerations

When criticality is a potential concern for glovebox design, geometry control and water use restrictions become essential factors. Drains, in particular, need to be designed with great care.

The buildup of fissile material on the HEPA filters should also be considered. Metal media and ceramic filters should be considered by providing more rigid geometries to reduce criticality concerns. Equipment wells or thermal wells in the floor of a glovebox should have a ridge or raised boundary to prevent liquid or debris from accumulating in the wells. The size, shape, and visibility of the interior of the wells should also be evaluated for material accumulation concerns.

4.2.22 References

1. AGS (American Glovebox Society), 2007, *Guidelines for Gloveboxes*, AGS-G001 (Third Edition), Santa Rosa, CA.
2. ASHRAE, 2016, *HVAC Systems and Equipment*, New York, NY.
3. ASME (American Society of Mechanical Engineers), 2019, Code on Nuclear Air and Gas Treatment, ASME AG-1, New York, NY.
4. ASME, 2007, Testing of Nuclear Air Cleaning Systems, ASME N510, New York, NY.
5. DOE, 2018, *Facility Safety*, DOE O 420.1C.
6. DOE, *Fire Protection*, DOE-STD-1066-2016.

4.3 Small Air Cleaning Units

4.3.1 Introduction

This section discusses the installation of internal components, primarily HEPA filters, in systems that require only a single filter per stage of each air cleaning unit. HEPA-Vac systems are not considered small air cleaning units and should not be utilized as such. Single-filter (nonparallel) installations are employed in the supply, exhaust, and recirculating air cleanup systems of rooms, gloveboxes, hot cells, chemical fume hoods, and other contained spaces; in the off-gas lines of process vessels and radiochemical operations; and in other applications in which the airflow is 1,500 cfm or less. Although much of the discussion in this section focuses on installation of HEPA filters, it also applies to adsorber cells and other components.

Single-filter installations can be grouped into three broad categories: (1) in-wall (filter mounted in or to a wall penetration of a room, glovebox, hot cell, or other contained space); (2) in duct (filter installed “in line” between two sections of duct, with or without transitions); and (3) duct-entrance (filter installed at the opening of the duct leading from a room, glovebox, hot cell, or other contained space). In-wall installations are generally employed to clean the air entering a contained space, to prevent backflow of contamination in the event the contained space becomes pressurized, or both. The filter may be installed bare (sides of case exposed) or in a partial enclosure. As in other installations, a medium efficiency filter is recommended upstream of the HEPA filter. Duct-entrance filters are strongly recommended to maintain the cleanliness of contaminated exhaust and air cleanup ducts. These filters should be mounted in or close to the entrance of the duct and, like the in-wall type installation, may be installed either bare, as shown in **Figure 4.23**, or in a partial enclosure.

In-duct open-faced filters should be installed in totally enclosed housings or side-access housings, as shown in **Figure 4.24**. Taping or clamping the filter between two sections of duct or a pair of transitions with the case exposed is not recommended. Such installations provide no secondary confinement in the event of a breach of the filter case, gaskets, or tape seals, and (particularly for wood-cased filters) fail to meet the requirements of Underwriters Laboratory (UL)-181A, *Closure Systems for Use with Rigid Air Ducts and Air Connectors* and NFPA 90A, *Standard for the Installation of Air Conditioning and Ventilating Systems*.

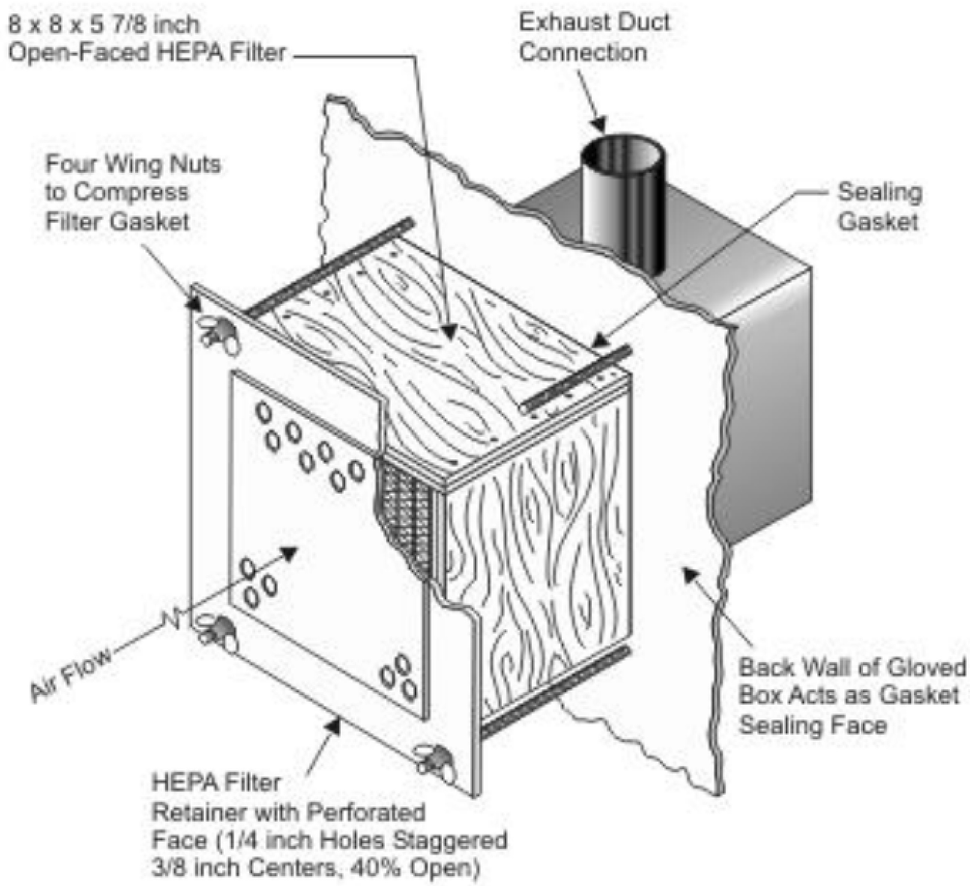

Figure 4.23: Mounting of Duct-Entrance Filters

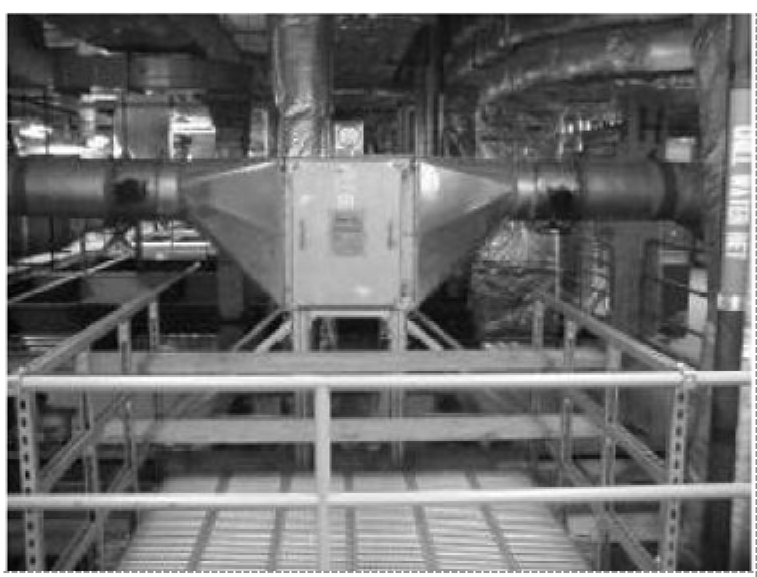

Figure 4.24: Correct Mounting of In-Duct-HEPA Filter Housing

4.3.2 Housings

Housings for in-duct installations may be as small as the side-access housing for a 25-cfm HEPA filter or as large as the complete multistage air cleaning unit containing demister, medium efficiency filter, two stages of HEPA filters, and adsorber. Probably the most common single-component housing today is the bag-in/bag outside access type. Features that should be checked carefully when purchasing standard commercial housings include the filter (component) mounting frame and clamping device, the rigidity of the box and its cover, the method of cover sealing and clamping, access to the installed component, the rigidity and construction of duct connections, and the materials of construction of all parts, including the component clamping mechanism. These same features are important in the design of one-of-a-kind shop-built housings. Provisions for in place testing should be provided on all filter housings.

4.3.3 Component Installation

Requirements for installing components are basically the same as those for bank installations. These include structural rigidity, flatness, and accuracy of the sealing surface construction; positive, reliable sealing of the component to the frame; specification of and strict adherence to close tolerances in fabrication; and leak tight welded construction. A minimum sheet-metal thickness of 0.078 inch (No. 14 U.S. gauge) is recommended for the sealing surface of commercially made and shop-fabricated housings. For gasket-sealed housings, the sealing surface should be seal-welded into the housing such that no warping of the filter (component) sealing surface will result. There should be a right-angle bend all around the seating surface to provide reinforcement and to ensure flatness. **Figure 4.25** shows a portion of the turned-angle filter sealing surface of a commercial housing, and **Figure 4.26** shows a schematic of the four-bar-linkage gasket seal clamping mechanism that is operated by means of a wrench (shown in **Figure 4.27** from outside the housing. Other clamping systems are acceptable, so long as they provide the required amount of clamping force on the gaskets.

The housing should be constructed to prevent leakage where the clamping mechanism penetrates to the outside. The structural requirements of the mounting frame will be met if 14-gauge steel is used, particularly if combined with the stiffening flange (right-angle bend).

Flat gasket-to-knife-edge seals are not recommended because they tend to leak excessively if the knife-edge is nicked or if the knife-edge and the filter face are not parallel. The compression set produced by a knife-edge in only a portion of the gasket also results in leakage if there is any degree of relaxation of the clamping device. The gel seal design does not require special tolerances and has been proven to create a very effective filter-to-sealing surface method.

A nonwelded mounting frame consists of a single 0.25-inch plate sealed by gaskets between the flanges of the body and the transition of a field-assembled housing. The filter is clamped by bolts and installed through a hatch in the side of the housing. A gasket compression of at least 80 percent is needed to create a reliable seal between high-efficiency devices such as a HEPA filter or radioiodine adsorption cell and the housing. This requires a gasket loading of something over 20 psi of gasket area for a total loading of over 1,400 pounds for a 24- × 24-inch filter; 1,050 pounds for a 12- × 24-inch filter; or 700 pounds for a 12- × 12-inch filter. Such loadings can be accomplished with the bolted clamping method. It is important for the designer to verify that the clamping mechanism of the commercial housing being considered

Figure 4.25: Turned Angle, Gasket Sealing Filter Surface for a Commercial Housing

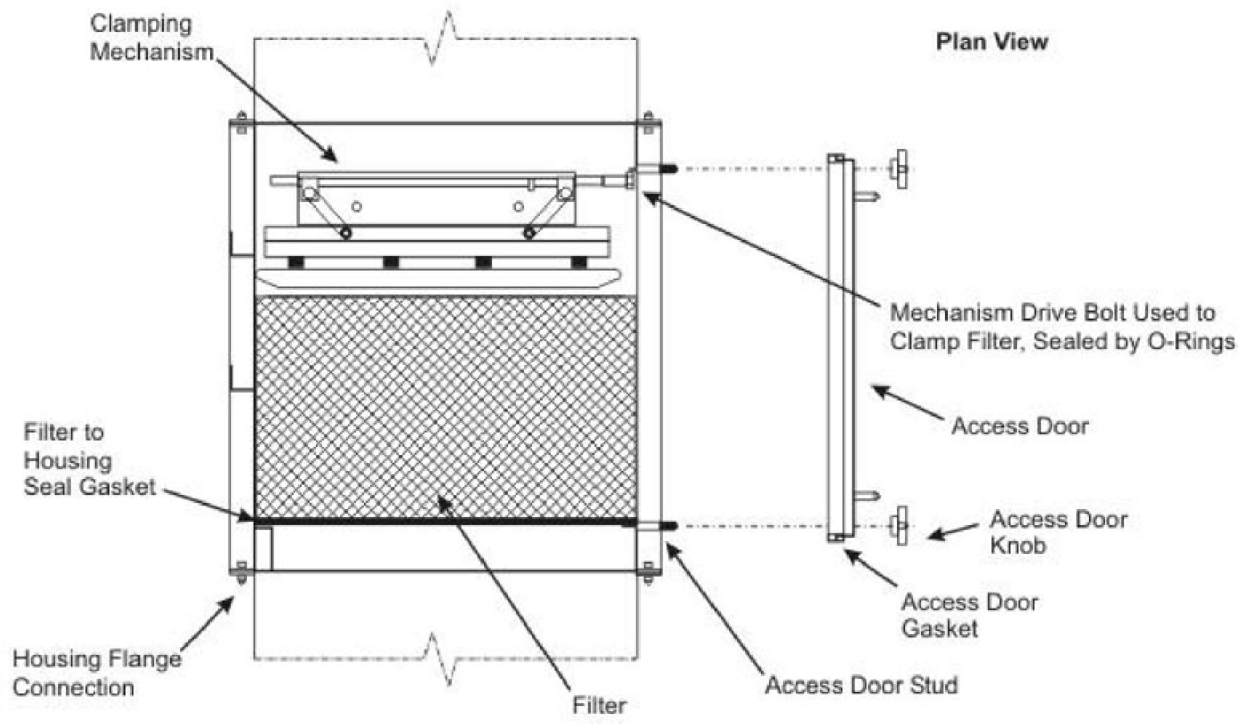

Figure 4.26: Four-Bar-Linkage Gasket Seal Clamping Mechanism

Figure 4.27: Using Wrench to Operate Four-Bar-Linkage Gasket Seal Clamping Mechanism

can develop the loading required and is adjustable. All parts of the mechanism should be stainless steel to prevent rusting and seizing under operational conditions (including springs, which tend to break when rusted). The only exception to this rule is that, if nuts are used, they should be brass, bronze, or another material that will not gall in contact with the stainless-steel male-threaded part. Clamping mechanisms should be on the clean side of the filter, and operator shafts, when required, should be sealed by O-rings or glands. A rest or guides, stops, or some other means for aligning the filter prior to clamping should be provided within the housing.

For gel seal housings, the knife-edge sealing surface should be seal-welded into the housing so that warping of the filter (component) sealing surface will not result. There should be a right angle all around the knife-edge sealing surface to provide reinforcement and ensure alignment. **Figure 4.28** shows a portion of the knife-edged filter sealing surface of a commercial housing. The gel seal housing clamping mechanism is operated by hand from the side of the housing. All parts of the mechanism should be 300 series stainless steel to prevent rusting and seizing under operational conditions.

The clamping pressure required to properly seal a gasket-sealed HEPA filter or adsorber cell needs to be both high and uniform. However, this requirement is substantially relaxed when gel seal systems are used. As shown in **Figure 4.29**, the filter element has a groove filled with a non-Newtonian (i.e., nonflowing) gel. The filter is pushed against the knife-edged flange of the mounting frame so that the gel envelops the knife-edge, forming an airtight seal. The clamping pressure only needs to be enough to prevent the filter from backing away from the knife-edge (which would break the seal) under any foreseeable differential pressure across the filter in either normal operating or system upset conditions. The gel, a silicone compound, has been tested and found to be capable of maintaining an adequate seal under the fire and hot air conditions of UL-586, Standard for High Efficiency, Particulate, Air Filter Units, and the radiation exposure requirement of ASME AG-1, Code on Nuclear Air and Gas Treatment, Section FC. Either the flat-gasket to flat-flange or the gel seal are recommended.

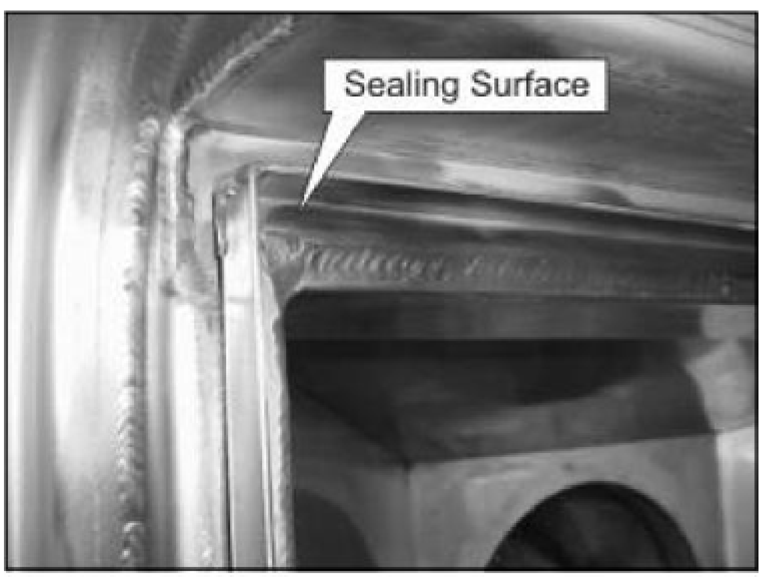

Figure 4.28: Gel Seal Commercial Housing Filter Sealing Surface

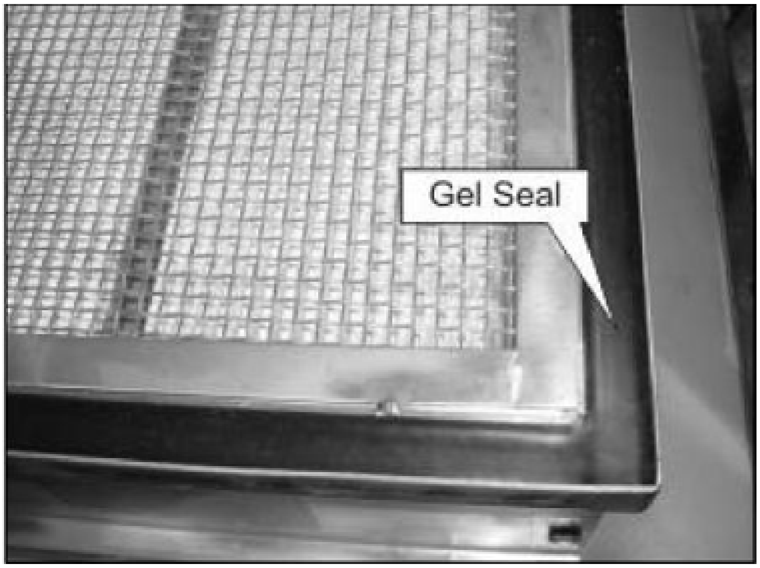

Figure 4.29: Gel Seal System

4.3.4 Housing Construction

The walls of the housing should be sufficiently strong to prevent overstressing under an alternating positive and negative pressure equal to at least 1.5 times the maximum gauge pressure to which the housing will be subjected under the most severe conditions for which it is intended. A minimum design pressure of 10 in. wg is generally recommended. In purchasing commercial housings, the designer should check the details of construction to verify that the design proposed is fully adequate for the intended application that stresses in the walls or clamping mechanism will not exceed a value of 0.7 times the yield strength of the material from which they are made under a housing pressure of 1.5 times the design pressure.

Many failures of commercial housings can be traced to corrosion. The filter housing is a common point where corrosives tend to condense, collect, and concentrate. When the filter housing is to be installed in a line that, under either normal or abnormal conditions, may contain corrosive fumes or vapors, stainless steel construction should be employed. In any event, all parts of the clamping device (including springs, but not nuts) should be stainless steel. Whenever housings are painted, the coating should comply with American Society for Testing and Materials D5144, *Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants*.

Hand knobs of the type shown in **Figure 4.30** should attach to the housing access door. Attachment of covers with machine bolts or nuts may be cheaper but will be a constant problem to the user. Nuts get lost and threaded bolts get damaged under service conditions. The result is often an inability to seal the housing properly, and the need to remove and replace a large number of nuts or bolts inhibits access and proper service. For access door clamping, the door should have a 2-inch-deep lip or flange all around for stiffening (**Figure 4.25** above). The cover should also be stiff enough or sufficiently reinforced so that it will not collapse under the pressure variations to which it may be subjected. The cover and the cover-clamping mechanism should be capable of sealing the cover opening whether or not a bag is in place.

4.3.5 Bagging

Most commercially manufactured and some one-of-a-kind shop-built housings are designed for bag-in bag-out filter replacement. **Figure 4.31** describes this procedure step-by-step. Shutoff dampers are needed upstream and downstream of the filter (or other component being replaced) to permit isolation of the housing during the change and to limit ballooning or collapsing in of the bag when the access door is opened due to a pressure differential between the inside and outside of the bag. A small, valve, breather vent can be specified on the clean side of the filter to control pressure in the housing; a slight negative pressure (0.25- to 0.5-in.wg) helps ensure inward leakage in case the housing becomes pressurized due to pumping of the bag. When sealing change-out bags, two seals about 0.25-inch apart are usually made so that, when the bag is cut between them, both the housing opening and the enclosed filter are sealed from the room environment. The end user's safety officer will determine the method of sealing the change-out bag that best suits the facility.

Bags should be clear plastic, typically polyvinyl chloride (PVC), to permit the worker to see what he is doing. In some housing designs, the worker has to manipulate the filter clamping mechanism through the bag as shown in **Figure 4.32**. Radiation levels may limit the use of PVC. Bags should be a minimum of 0.008-inch thick. Thinner bags could tear, particularly when used with metal-cased filters or adsorbers. Care should be taken when carrying out the procedure with larger (24- by 24- by 11.5-inch) items. Housings should be installed in a location that can be isolated as a contamination or radiation zone in the event of a bag tear and resulting spill. The excess bag material that remains after a new filter is placed into the housing is folded carefully against the side of the filter element (shown in **Figure 4.32** below) to prevent

Figure 4.30: Access Door Hand Knobs

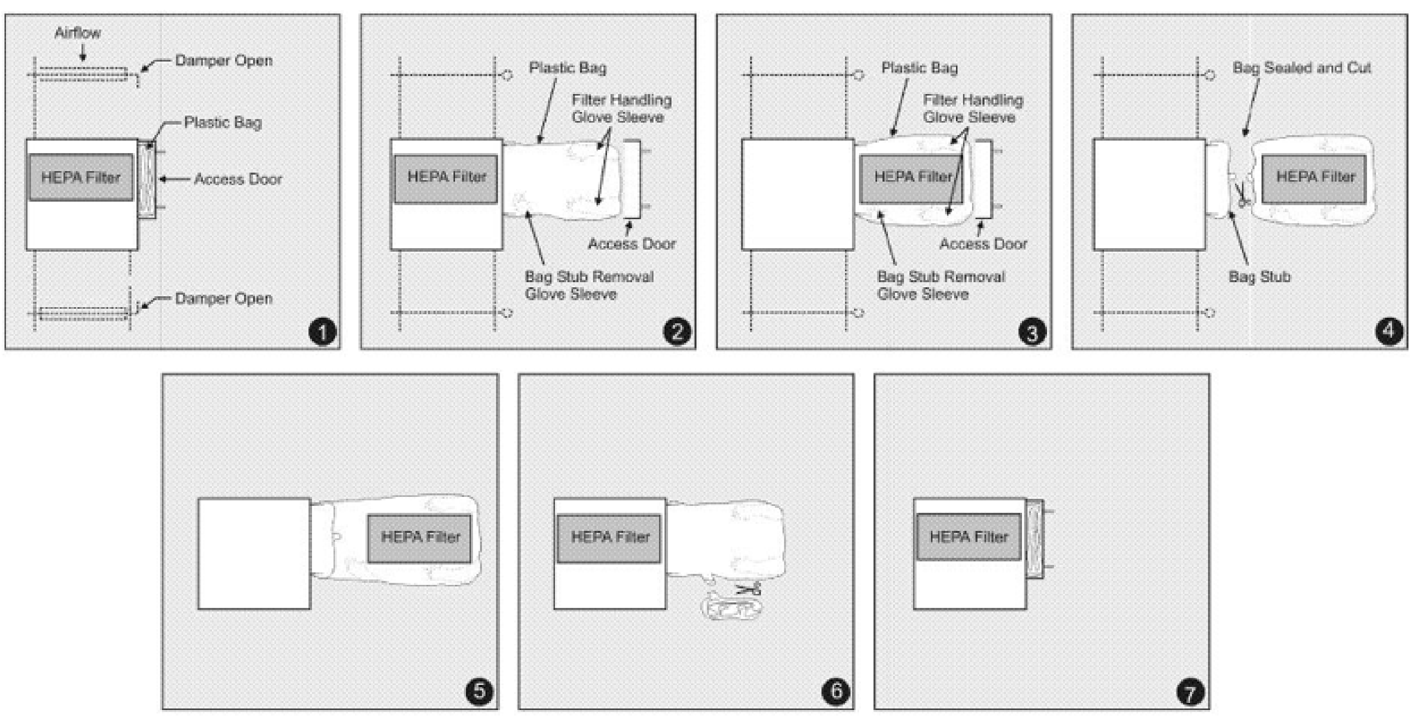

Figure 4.31: Bag-In Bag-Out Filter Replacement

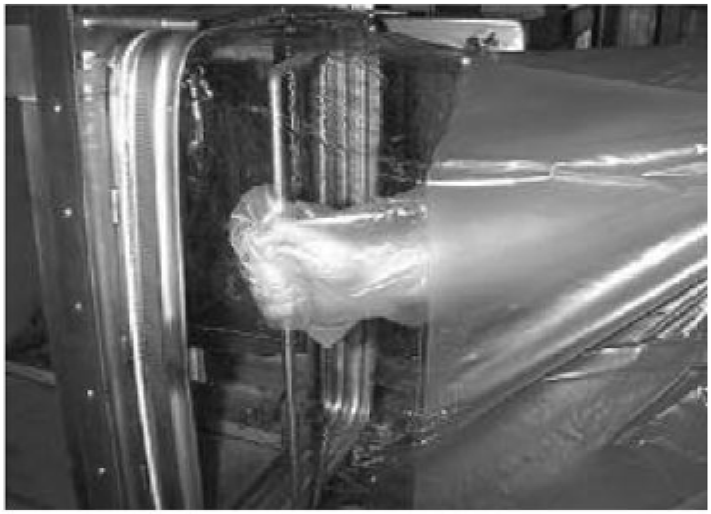

Figure 4.32: Use of Clear Bags

any portion from getting into the airstream or being pinched between the housing cover and bagging ring.

After folding the bag within the filter housing, it should be isolated from system airflow on the clean side of the filter because the plastic can be damaged from continued exposure to the airstream. The covers of bag-out housings should be capable of sealing the housing with and without the bag installed and should be kept closed when the system is in operation to protect the bag that remains in the housing. Bagging should not be considered an automatic solution to the contamination hazard, and the user is cautioned to take proper precautions during filter changes.

4.3.6 Housing Installation

Horizontal airflow with filter faces in a vertical position is recommended for large (24- by 24-inch face dimensions) HEPA filters. This recommendation is not so important for smaller filters designed with media support that is inherently sufficient to resist gravitational pull-on filter core and collected dust. When vertical airflow (filter face in a horizontal position) is unavoidable, up flow design is recommended over downflow design because filter media sagging is offset to some extent by air pressure and because there is less chance of cross-contamination from the dirty side to the clean side of the system. With the downflow design, contaminated dust dislodged during a filter change can fall into the clean side of the system.

A downflow design should be avoided where there is a potential for liquid to collect in the system. Liquid collected in the filter pleats of a downflow system will eventually seep through the media and carry dissolved contaminants into the clean side of the system. On the other hand, up flow systems may require withdrawal of contaminated filters into the clean zone. When horizontal installations should be used, filters should be designed to seal on the upper side of the mounting frame so that their weight will load rather than unload on the gasket or gel-sealing surface. Installation of the filter on the clean side (i.e., downstream) of the mounting frame is always recommended for single-filter installations.

For multistage installation, components may be grouped as one assembly (**Figure 4.33**). Although bolted, gasketed joints are recommended, flexible connections (see **Figures 4.34 and 4.35**) are suitable for housings connected directly to a fan. Duct-taped seals between housings and ductwork are not acceptable. Multistage installations can create problems related to periodic surveillance testing of HEPA filters and adsorber cells. Even though a flange-to-flange installation (**Figure 4.36**) is undoubtedly the least expensive option when considering materials and space occupancy, sufficient room should exist between components to introduce a well-mixed test agent, to obtain a satisfactory upstream sample, or to probe for leaks on the downstream faces of the components.

4.3.7 Cylindrical Filter Elements

Cylindrical filters may be either axial or radial flow. The cylindrical axial flow HEPA filter configuration frequently offers an ideal solution to certain installation requirements. The core is slipped into a molded or welded-seam cylinder (**Figure 4.37**) and sealed by catalyst-activated plastic foam or urethane. Cylindrical flow HEPA filters can be obtained with or without flanges on one or both ends. Radial flow filters as shown in **Figure 4.38** are used in push-through (i.e., incessant) installations. The filters are sealed into a cylindrical opening with one or more half-round circumferential gaskets (fixed to the filter) that make a slight interference fit with the receiver. Flanged axial flow HEPA filters (**Figure 4.39**) can be installed in pipe openings by bolting them to a flange on the pipe or by clamping the filter flange between mating pipe flanges. Conventional neoprene sponge gaskets are used for sealing. Because filter flanges and cases are characteristically made from light-gauge sheet metal with the flange seal-welded to the cylinder, these filters often leak at the flange-to-case weld. The flange often becomes deformed. Either condition results in an installation that is difficult to seal.

There are two methods of installing cylindrical filters, one a duct-entrance design and the other a hot-cell exhaust design. In the hot-cell exhaust design, the mounting is sloped to permit runoff of any liquid accidentally spilled on the shield that protects the filter and to facilitate handling by the cell electromechanical manipulators. Where cylindrical HEPA filters are used, liberal clearance (at least 1/8-inch all around) between the case and receiver is necessary to accommodate the characteristic out-of-roundness (see **Figure 4.40**). The advantage of cylindrical filters is close conformance to round ducts and pipes, which can both permit the use of smaller, cheaper duct transitions and require less space. For inline installations, however, except where the filter has flanges on both faces and is installed as a spool piece, provision should be made to extract the filter from the duct or pipe after the connection is broken, thus risking loss of the space advantage over an equivalent open-faced rectangular filter. Spool-piece filters should have flanges and withstand the forces imposed by the duct or piping system and the flange bolting.

Cylindrical filters are often used in radioactive vacuum cleaners and portable air purifiers. The air purifier shown in **Figure 4.41** is a single-use device that is discarded when the contamination level or pressure drop of the collectors becomes greater than the pre-established design level.

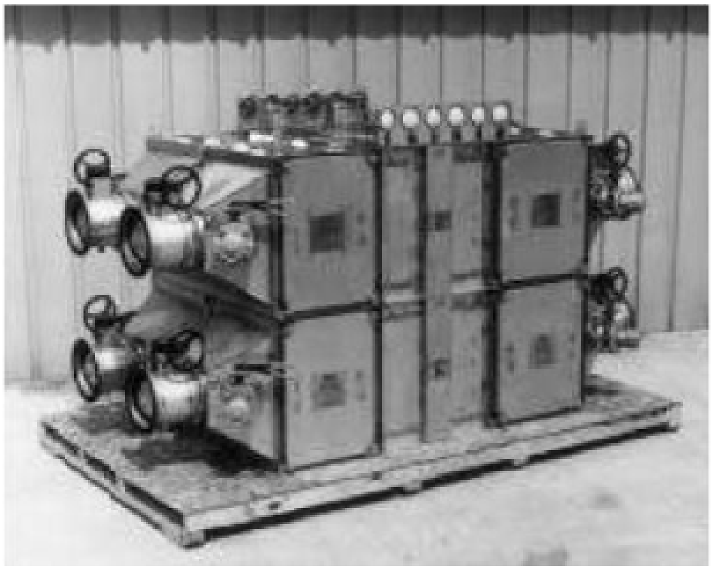

Figure 4.33: Four Individual Housing Units Grouped as One Assembly

Figure 4.34: Flexible Connection

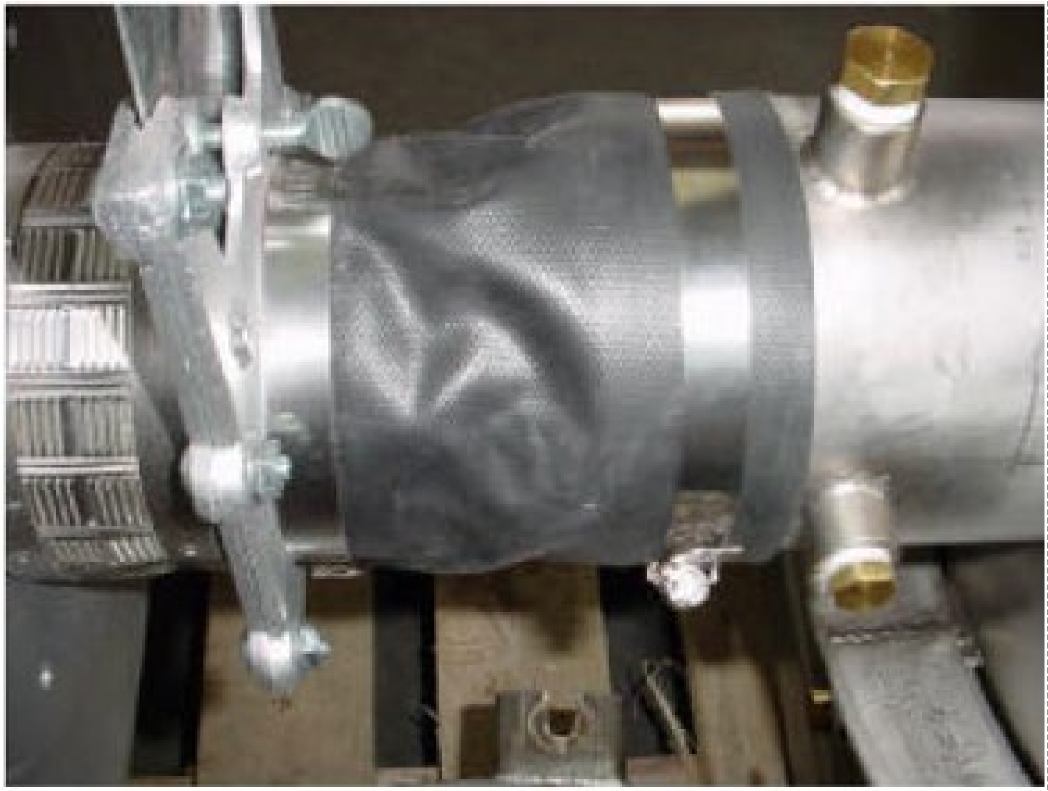

Figure 4.35: Flexible Connection

Figure 4.36: In-Place Filter Test Section

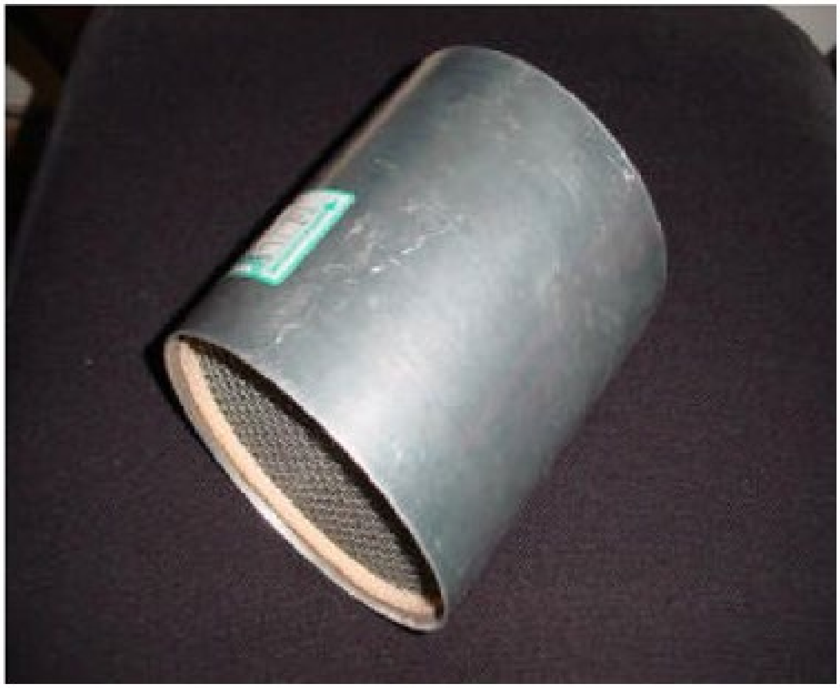

Figure 4.37: Open-Faced Axial Flow Cylindrical HEPA Filter

Figure 4.38: Radial Flow HEPA Filter

Figure 4.39: Open-Faced Axial Flow Cycloidal HEPA Filter with Flange

Figure 4.40: Clearance Between Radial Flow Filter and Housing

Figure 4.41: Cylindrical Filter Air Purifier

4.3.8 Installation and Human Factors

When practicable, single-filter installations should be located where they can be reached for service and testing without workers having to climb ladders or scaffolding. This requires consideration of human engineering factors. Analysis of the recommended weight limits indicates that handling a 1,000-cfm HEPA filter in the body positions often encountered in filter-change operations is at the upper range of personnel capability, and that handling of adsorber cells is well beyond the limits for one person.

Consideration should be given to the positions that a worker should assume to perform the required task. If the worker should hold his hands overhead for any length of time, fatigue may result. If crouching, bending, or squatting is required, the worker will soon become stiff, which will contribute to loss of efficiency. If a worker has to hold a heavy weight while performing a precision operation, such as supporting the weight of a filter or adsorber cell while trying to fit it between duct transitions or into a restricted opening, the stress of the combined task will become fatiguing and a mistake could occur. All of these factors are compounded when the worker should wear protective clothing and respiratory protection. In addition, protective clothing adds to the worker's spatial requirements and limits mobility. For HEPA filter and adsorber cell installations, location of the filter or housing at an elevation between knee and shoulder height is recommended.

4.3.9 Fume Hoods

The wide, often unpredictable variety of chemical operations conducted in laboratory fume hoods makes selection and installation of HEPA filters difficult and uncertain. Corrosive fumes may damage the filter and its mounting, and moisture and heat from hood operations may accelerate that damage.

Some facilities install fume hood filters in the attic, usually directly above the hood served. Where this design is employed, the attic space should be designed as a confinement zone for easy cleanup in the event of a spill and should not be used for extraneous purposes such as storage and experimental work when radioactive materials are handled in the hood.

Hood installations in which perchloric acid and certain other chemicals are handled should be provided with washdown facilities to permit periodic decontamination of the hood and ductwork (perchloric acid hoods should not be used for handling other materials because of the explosion hazard. Off gas scrubbers are often provided in hoods. Both washdown facilities and scrubbers generate substantial quantities of water droplets. Demisters should be considered to protect the filters and their mountings. Moisture collected in the demister should be conducted to a hood drain rather than permitted to fall into the workspace of the hood. Demisters should have adequate handling space and be easily accessible for cleaning, inspection, and replacement. Where incandescent particles or flaming trash can be released to the hood exhaust stream, a spark arrester should be installed to protect the HEPA filter. This arrester can be either a commercial flame arrester, a metal-mesh graded-density demister, or at minimum, a piece of 40-mesh metal cloth. In any event, it is recommended that the arrester be located at least one foot ahead of the HEPA filter and should have easily accessible for cleaning, inspection, and replacement.

Heat sources such as heating mantles, furnaces, and Bunsen burners are common equipment in laboratory fume hoods and should be planned for in the initial hood and exhaust system design. Designers should control heat-producing operations by limiting the size of heat sources such as furnaces or using air cooling methods.

4.3.10 Portable Air Cleaning Units

The use of portable HEPA filtration systems has become quite prevalent within the nuclear industry. Radiation protection standards stress the use of engineered controls, principal localized ventilation, and confinement as the primary means of controlling occupational exposure to airborne contaminants. Decontamination and decommissioning activities utilize supplemental ventilation to control the large amounts of dust generated by demolition activities, especially as existing facility ventilation systems are decommissioned. Portable air filtration systems pose their own unique challenges to both the designer and the end user. As with commercial side-access housing, well-designed portable filtration systems (shown in **Figure 4.42**) are much more than “black boxes.” Careful evaluation of system requirements, selection and integration of components, and attention to construction methods are all required to ensure a functional, effective, user-friendly system. This process has been made somewhat more difficult, however, due to a lack of industry standards that specifically address portable HEPA filtration units.

Procurement specifications for portable HEPA filtration systems should be developed by using ASME AG-1. These standards address the in-place safety systems for nuclear facility ventilation. While many aspects of these standards are applicable to portable systems, wholesale application without consideration of the unique features and functionality of portable systems may result in unrealistic specifications that are difficult, costly, or impossible to meet. Compromises need to be made, but without sacrificing the overall functionality and safety of the equipment.

Figure 4.42: Portable Filter Unit

4.3.10.1 Operational Considerations

Certain operational considerations should be addressed when selecting or specifying portable HEPA ventilation units for use in environments where nuclear or another hazardous contaminant is present. Like any other ventilation system, a portable HEPA filtration system should be designed to move and effectively clean the appropriate amount of air, required to maintain adequate environmental conditions within the workspace. Unlike permanently installed facility systems, however, the ultimate applications of portable systems are rarely known. They may be used for ventilating confined spaces, providing general area air exchanging, or providing high, localized, capture velocity in support of cutting, burning, grinding, or other mechanical and maintenance processes. Unless the system is intended for "one time, one application" use, it should be designed and constructed with sufficient flexibility to perform well under a variety of operating conditions. Thought should be given to the anticipated use of the equipment, and some basic operational questions should be asked to better define the required features. Examples include:

- Is particulate the only contaminate of concern, or will gas adsorption also be required?
- Is the expected operating environment or contaminant corrosive, or does it contain other contaminants that might affect the construction materials?
- Will the unit be used indoors or outdoors?

- What will be the ambient and process air temperature extremes?
- Will the unit be used in areas where there is high relative humidity or entrained water?
- Will the unit be used in areas where potentially explosive concentrations of gases or dust will be present, requiring special hazard class electrical components?
- Does the process or contaminant warrant redundant (series) HEPA filtration for added protection?
- Will the unit be subjected to high system losses due to using long lengths of temporary, flexible ducting and/or multiple filtration stages?
- Is heavy dirt loading expected that might require larger, more robust prefiltration capacity?
- Does the relative hazard of the contaminant require the added protection of bag-in/bag-out filter changing?
- What power is available to run the equipment? (Low voltage and amperage as well as single-phase power supplies can severely limit the capacity of the ventilation system.)
- How much space is available to stage the equipment? Is a single larger unit supporting multiple exhaust points more workable, or are smaller units placed local to the work more appropriate?
- What is the duration of the project or operation that will be supported by the portable system? Is the unit intended for reuse many times over years, or is it a one-time application? (Durability and ruggedness of construction can be greatly affected.)
- What sampling is expected from the unit?

4.3.10.2 Component Considerations

Fan Assemblies

Portable systems typically use centrifugal fans. Cast aluminum housing and wheels are common, as well as fabricated steel. Fiberglass, PVC, and other nonmetallic fans are available for processing air with corrosive contaminants. Regardless of the type of fan used, it’s performance should be matched with the intended application. A fan with high static capabilities at the required flow rate is needed for a portable system that will be expected to operate with high system losses (e.g., large amounts of flexible ducting on the inlet or discharge; periods of high filter loading). Likewise, if the unit is only intended to provide local recirculation without high system losses, a fan with lower static pressure capabilities is acceptable. Fan performance should be developed using Standard 5110 published by the Air Movement and Control Association (AMCA) and ASHRAE.

Fans are typically direct-drive systems. Motors with appropriate hazard class ratings should be specified to protect them from internal contamination. If frequent washdown with high-pressure water is expected, appropriate duty motors should be specified. Likewise, motors with appropriate hazard class ratings should be used in hazardous locations in accordance with NFPA-70, the *National Electrical Code*.

Motor starters should be mounted on the unit. National Electrical Manufacturers Association (NEMA) enclosures should be selected for the intended service, and NEMA enclosures and liquid-tight conduit should be specified for units intended for outdoor application or where direct water wash of the unit is expected. Reference NEMA Publication 250, *Enclosures for Electrical Equipment (1000 Volts Maximum)*, for electrical enclosure testing requirements. Alternate enclosure testing standards such as International Electrotechnical Commission (IEC) Publication 60529, *Degrees of Protection Provided by Enclosures*, are equally acceptable. The important point is that the electrical enclosures and wiring should be suitable for the intended operating environment, including any special NEC[19] hazard class requirements. Overload protection is suggested for all electrical starters. Special attention should be paid to using three-phase motors and starters. Due to differences in wiring methods between the power supply and the portable systems, starter fan rotation can be easily reversed with three-phase motors.

Fan and motor assemblies should not be rigidly mounted to the system's cart or the filter housing/transitions. Vibration isolation should be used for the motor, and a flexible boot or other vibration-isolating connection should be placed between the filter bank and the fan. Vibration isolation will reduce noise significantly. The fan always should be mounted on the downstream side of the filters to ensure the filters and ductwork are at negative pressure with respect to the environment. All motor fan assemblies should have appropriate safety guards, including the fan inlet and outlet (if normally accessible), the shaft, the pulley, and the belts (if used).

Filters and Filter Housings

Any single, standard-sized, HEPA filter can be readily incorporated into a portable filtration system rated 1,500 cfm or less. Gasketed and gel seal filters can both be used in portable systems, provided the clamping/holding mechanism stays engaged as the unit is moved.

The fan curve will indicate the system's maximum potential flow rate. The free airflow, or the flow at zero in. wg static pressure, is the maximum flow that most fans can develop. Since the fan is connected to a filter bank, some system losses are present, so the free air rate is not a good indication of maximum flow. The flow rate at the expected operating pressure is a better indication of the maximum flow that the fan/filter system can be expected to deliver.

A housing with bag-in/bag-out features provides added protection from high-risk contaminants or for units used outside. **Figure 4.43** depicts several portable system arrangements. Whichever method is used, the filter frame and clamping method should meet the recommendations in this handbook. Since portable systems are designed to be moved, the chosen clamping or housing method should adequately protect the filters and prevent unclamping or dislodging of the filter due to cart movement. The system's cart should be sufficiently rigid in construction to limit the amount of flexing seen in and by the filter frame and housing. When the filter is exposed, only metal-cased HEPA filters should be used.

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[19] National Electrical Code

Prefiltration should be integral to the portable system. Prefilters should be accessible independent of the HEPA filter and should not require unclamping of the HEPA filter during change-out. Additional inline prefiltration may be needed for heavy dirt loading applications such as concrete-cutting and abrasive blasting. A spark arrester should be added to the medium efficiency filter for plasma arc cutting or any other type of spark producing activity. Moisture separation also may be required. This can be addressed using either demisting pads that are integral to the portable system or supplemental dehumidifiers in line.

Adsorber beds can be configured on portable carts as well. The carbon cells can be adapted as part of the portable filter system or as a separate stand-alone assembly that is interconnected with the filter unit on an as-needed basis.

Figure 4.43: Portable Systems

4.3.10.3 Construction

Portable equipment used in an industrial setting is subject to abuse. As such, construction of a portable filtration system needs to be rugged and suitable to a harsh industrial environment. Transitions and housing pressure boundaries should be fully welded. Properly designed gasketed and bolted connections, especially on transition to and from the filter, are necessary to avoid loosening over time. Assembly should allow access for decontamination purposes. Construction materials should be compatible with the operating environment. Stainless steel is highly recommended, especially for those components that come directly in contact with the contaminated airstream.

Quality wheels and casters should be used on wheeled equipment. At least one set should have a brake or some other means of securing the cart in place. Wheels should be compatible with the surface where the equipment will be used. Hard wheels are suitable for indoor use and are more readily decontaminated, while large pneumatic wheels may be more appropriate for outdoor applications. Wheel design should allow replacement if the wheel becomes contaminated or damaged. On larger units, channels for fork truck lifting or lifting eyes will facilitate handling. Lifting points should be conspicuously marked. A stout push handle is a desirable feature. Tow bars can be used for larger skids, allowing the cart to be pulled like a trailer.

Flow control dampers should be incorporated into the unit, especially on systems with multiple connection points. Dampers located in the ductwork close to the work area may be advantageous if frequent flow adjustments are necessary. Dampers should include a positive lock to ensure that the damper will not move once the desired flow balance is achieved. Blast gates, quadrant control, and butterfly styles are all suitable for flow control dampers on portable systems. If possible, dampers should be installed so that in the event of a failure, they fail in place or open, thus preventing a sudden loss of flow in the event of damper failure.

Tapered transitions add considerable length to a portable system, so abrupt transitions are frequently used on portable systems where size is a concern. If abrupt transitions (i.e., no taper) are used, a plenum space of at least 4 inches should be left in front of and behind the HEPA filter. This space will allow for airflow expansion, thereby reducing air velocity prior to entering the filter.

Duct connection points should be undersized to allow connection of flexible ducting. Allow 1/8 inch less than the nominal size of the flex ducting used. A roll bead, round bar, or other protrusion fabricated into the duct connection point will help secure the duct when a hose clamp is installed behind it.

Differential pressure (DP) gauges should be installed to monitor dirt loading on the HEPA and medium efficiency filter. Individual gauges for both stages of filtration are desirable. Since the flow rate through a portable system can change significantly depending on ductwork routing and damper adjustments, observed changes on the DP gauge may not be due to dirt only but may instead reflect a change in the air velocity through the filter element. For this reason, it is necessary to ensure that, when assessing dirt loading on the filters over time, DP readings are taken under the same flow conditions. Alarms that indicate high filter DP, as well of loss of airflow (which can be indicated by a very low filter DP), are also good features. The same general caution about the effect of air velocity on filter DP would apply to these alarms as well.

4.3.10.4 Testing and Inspection

Portable air cleaning units require a periodic inspection and in-place leak testing. The rough handling and shock they can be expected to experience during transport makes careful inspections and functional tests, including in-place leak testing, mandatory prior to each use at installation. Also, anytime these units are moved or jarred after they are put into service, careful inspections and functional tests including in-place leak testing should again be performed. Temporary, portable ductwork is fragile and may be subject to degradation, especially if exposed to sunlight, chemical vapors, or heat. It should be inspected and checked for leakage frequently, depending on the application, a daily or weekly schedule may be appropriate.

4.3.10.5 Vacuum Cleaning Systems

HEPA-Vacs are most commonly used to control friable particulate before it becomes airborne. They are also used to control airborne particles and liquids in and around work areas and to locally control loose debris when work operations could potentially spread contamination. When used in the nuclear industry, HEPA-Vacs are commonly referred to as nuclear or radiological vacuum cleaners.

Additional information on radiological vacuum cleaners is contained in Section 4.1.14 of this Handbook.

4.3.11 References

1. ANSI/AMCA Standard 210-16/ASHRAE 51-16, *Laboratory Methods of Testing Fans for Certified Aerodynamic Performance Rating*, Atlanta, GA.
2. ASME, 2018, Quality Assurance Program Requirements for Nuclear Facilities, ASME NQA-1 New York, NY.
3. ASME, 2019, Code on Nuclear Air and Gas Treatment, ASME AG-1, New York, NY.
4. ASTM, 2018, *Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants*, Standard D5144, West Conshohocken, PA.
5. DOE, 2007, *Quality Assurance Inspection and Testing of HEPA Filters*, DOE-STD-3025.
6. DOE, 2015, *Specification for HEPA Filters used by DOE Contractors*, DOE-STD-3020.
7. IEC (International Electrotechnical Commission), 2013, *Degrees of Protection Provided by Enclosures*, IEC 60529 ED2.2 B:2013, Geneva, Switzerland.
8. IEST (Institute of Environmental Sciences & Technology), 2016, *HEPA and ULPA Filters*, IEST-RP-CC001, Mt. Prospect, IL.
9. NEMA (National Electrical Manufacturers Association), 2014, *Enclosures for Electrical Equipment (1000 volts Maximum)*, Publication 250-2014, Rosslyn, VA.
10. NFPA, 2018, Standard for the Installation of Air Conditioning and Ventilating Systems, NFPA 90A, Boston, MA.
11. NFPA, 2020, *National Electrical Code*, NFPA-70, Boston, MA.
12. UL, 2013, *Standard for Closure Systems for Use with Flexible Air Ducts and Air Connectors*, UL-181B, Northbrook, IL.

13. UL, 2013, *Standard for Closure Systems for Use with Rigid Air Ducts and Air Connectors*, UL-181A, Northbrook, IL.
14. UL, 2017, *Standard for High Efficiency, Particulate, Air Filter Units*, UL-586, Northbrook, IL.

4.4 Housing Design and System Layout

4.4.1 Introduction

The two basic housing designs are man-entry and side-access (**Figures 4.47 and 4.48**). Two side-access housing types are square filters and the other radial flow/round filters (**Figure 4.49**). Both side-access designs are for housings with two or more filters and for system capacities greater than 2,000 cfm.

4.4.2 Housing System Design

Large-volume air supply and exhaust requirements may be met by side-access or man-entry filter housing installations operating in parallel, or in a single central system. Parallel housings have the advantages of: (1) greater flexibility for system modification; (2) minimum interference with operations during filter replacement because individual units can be shut down without affecting the remaining systems; (3) good overall ventilation control in the event of malfunction, fire, or accident to one or a few individual units; and (4) easy system testing and balancing.

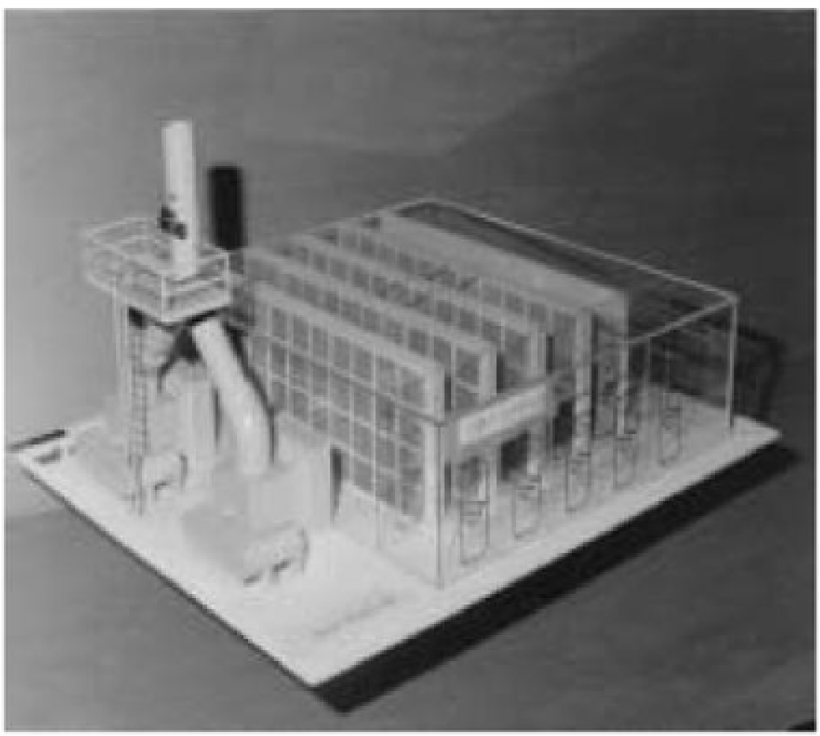

Figure 4.47: Model of Man-Entry Plenum

Figure 4.48: Side-Access Design (Square)

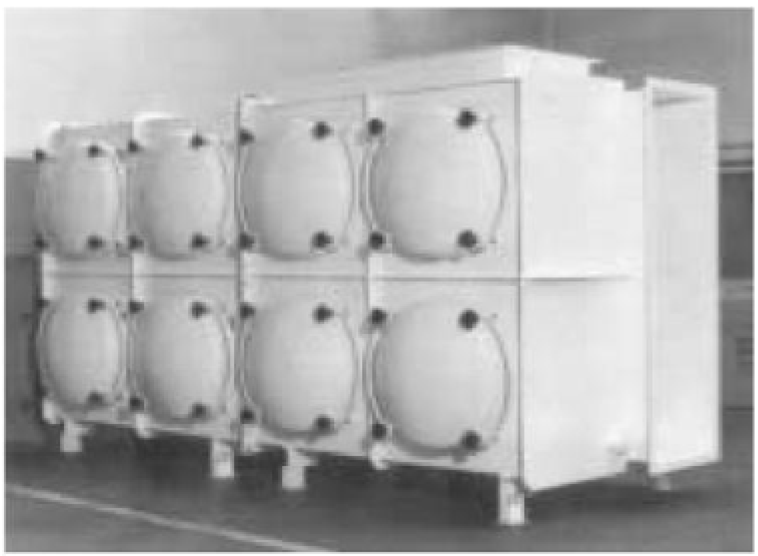

Figure 4.49: Side-Access Design (Cylindrical)

4.4.2.1 Man-entry Housing System Design

The man-entry filter housing consists of a fabricated steel confinement room with one or more walls seal-welded in place. The walls have holes and hardware to mount HEPA filters or absorbers. The room has access doors providing entry. Air is ducted into one end of the room, passed through the filters/absorbers mounted on the wall, and exhausted from the other end of the room. A wall with filters/absorbers mounted on it is considered a “stage” or “bank.” The man-entry design is best used for housings with stages of 15 filters (5 across, 3 high) or more.

As the number of filters/absorbers increases, consideration should be given to the ability to test the filters/absorbers and to the distribution of airflow. Isolation valves, recommended on each housing, result in convenient system control, isolation of individual units during an emergency, and maintenance or testing activities.

4.4.2.2 Arrangement and Location

Maintainability is a major consideration when laying out filter housings. Although some systems may have only a single bank of HEPA filters, most will have at least one additional bank of medium efficiency filters, and many will have multiple banks of HEPA filters. Those systems in which contaminated gaseous and aerosol releases should be controlled will also require one or more banks of adsorbers. Often a bank of moisture separators is required, resulting in as many as six or more banks of components in a single housing. There should be sufficient clear corridor space adjacent to the housing for handling filters during filter changes, as well as an adequate number of corridors to and from the housing. Dollies are often used to transport filters to and from the housing area. This practice results in safer operations that reduce the risk of both injury to personnel and spread of contamination from dropped filters. When dollies are used, space is required to move the dollies in and out, and for loading and unloading. Additional space is desirable for stacking new filters adjacent to the work area during the filter change-out process. Recommended clearances for housings and adjacent aisles or airlocks are given in **Figure 4.50.**

Proper access to the filter housing is sometimes overlooked. Too frequently, housings are situated among machinery, equipment, and ductwork where workmen are required to climb between, over, or under obstructions to get to the housing door, where they still have inadequate workspace. In some installations, it is necessary to carry filters one at a time over ductwork and then rely on rope slings to transfer them up to the floor above where the air cleaning system is located. It is essential to preplan the route for getting filters and adsorbers to and from the housing, and to provide elevators or cranes when hoisting to an upper level in required. Gallery stairways are also recommended in lieu of ladders.

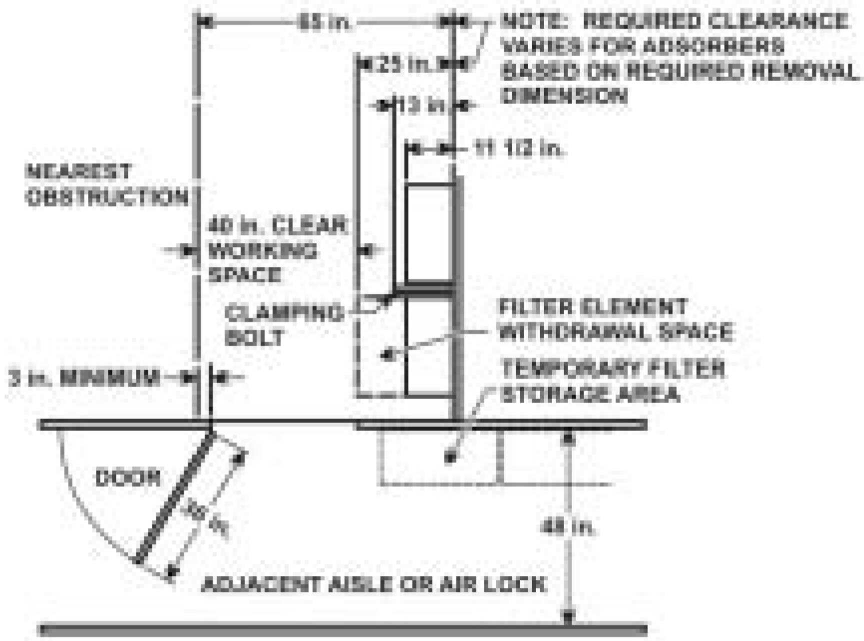

Figure 4.50: Recommended Clearances

High-risk operations often require segmented systems with two or more housings ducted in parallel that exhaust from the same area and vent to the same stack. Housings with inlet and outlet isolation dampers permit one housing to be held in standby or, when both are normally operated simultaneously, to allow one housing to be shut down for maintenance, testing, and emergencies.

Another important consideration in housing layout is uniformity of airflow through the installed components. This is especially important for adsorbers, since flow through those components should achieve the gas residence time required for efficient adsorption of gaseous contaminants. For large, multiple-filter housings that should operate in parallel, equalizing screens may be required in each filter unit to ensure uniform flow in housings. Long transitions are difficult, particularly in large housings. Nevertheless, every effort should be made to locate and design inlets and outlets to avoid stratification and to enhance the uniformity of airflow through components.

Special care should be taken in designing side-access housings to ensure uniform flow through all filter elements. It is recommended that manufacturers performance-test prototype side-access filter units in accordance with ASME AG-1, Section TA, to document uniformity of flow through side-access filter units before fabrication of production units. When high-activity alpha-emitters such as plutonium or transuranic elements are handled, it may also be desirable to compartmentalize the system, both in series, with separate housings for medium efficiency filters and HEPA filters, and in parallel for extra safety.

4.4.3 Component Installation

4.4.3.1 General

Proper installation of HEPA filters, adsorber cells, and demisters is critical to the reliable operation of a high-efficiency air cleaning system. HEPA filter and adsorber frames should be designed in accordance with the requirements of ASME AG-1, Section FG. Considerations include:

- Structural rigidity of mounting frames;
- Rigid and positive clamping of components to the mounting frame;
- Careful specification of and strict adherence to close tolerances on alignment, flatness, and the surface condition of component seating surfaces;
- Welded-frame construction and the welded seal between the mounting frame and housing;
- Ability to inspect the interface between components and the mounting frame during installation (man-entry);
- Adequate spacing between components in the bank (man-entry); and
- Adequate spacing in the housing for men to work (man-entry).

4.4.3.2 Housing Construction

The components and mounting frame should form a continuous barrier between the contaminated and clean zones of the system. Any hole, crack, or defect in the mounting frame or in the seal between components and the frame that permits bypassing will result in leakage of contaminated air into the clean zone and reduced system effectiveness. A mounting frame that is not sufficiently rigid can flex so much during operation, particularly under abnormal conditions, that leaks may develop in the HEPA filters clamped to the frame (due to differential flexing of the filter case relative to the mounting frame). Cracks may also open between the filters and the frame, between frame members (due to weld cracking or fatigue), or between the frame and the housing. Insufficient attention to maintenance provisions in the original design can increase operating costs and reduce reliability of the system.

Once the system is installed, defects are difficult to locate, costly to repair, and may even require rebuilding the system. Mounting frames for HEPA filters and other critical components should be all-welded structures of carbon or stainless-steel structural shapes. Carbon steel frames should be painted or coated for corrosion resistance. Galvanized steel is not recommended because of welding difficulties and because the zinc coating does not give adequate protection in the environments that may be encountered in a contaminated exhaust system. Aluminum is not recommended because of the high cost of surface preparation. Stainless steel is often the best and most economic choice for radiochemical plant applications.

ASME AG-1 Section HA contains information on suitable housing and mounting frame materials and on fabrication.

4.4.3.3 Potential Housing Leakage

The design of nuclear air cleaning system housings should consider the potential for leakage to prevent contamination of adjacent service and operating areas. By locating the filter unit in an appropriate plant location and locating the fan relative to the filter housing, leakage amounts (especially leakage of contaminated air) can be minimized.

A once-through contaminated exhaust filter housing may be designed with the exhaust fan located after the filter housing and the housing located in a space that is “cleaner” than the air entering the housing. The benefit of this system configuration is that the air cleaning system up to the fan is under a negative pressure. Leakage is into the housing, thereby minimizing the potential impact of contaminated leakage on plant personnel during system operation. This system configuration does not mean leakage should not be considered. It means that the leakage potential can be reduced by component location and that further reductions in personnel dose to levels ALARA are possible via housing construction.

If the space where an air cleaning system housing is located is more contaminated than the air entering the housing, it would be better to locate the fan on the inlet side of the housing. This arrangement would eliminate in-leakage of more contaminated air downstream of the filters. For a habitability system where the housing is located within a protected space, the fan should be located downstream of the filter unit to ensure any potential in-leakage is “cleaner” air. If the housing in a habitability system is located in an area outside the protected space, then the fan should be located upstream of the filter unit to ensure potentially contaminated air does not bypass the filter unit.

The first step in determining housing leak-tightness is to assess the relative contamination potential between the air entering the housing and the space where the housing is situated. Locate the fan accordingly, then determine the allowable leak rate to maintain: (1) the personnel dose within the requirements of 10 CFR Part 835 for in-plant personnel, (2) the offsite dose per the Documented Safety Analysis, and (3) the ability of the system to maintain performance [e.g., direction of airflow, required pressure differential, air exchange (dilution) rates]. The latter item depends on the system design and margin. ASME AG-1, Section HA, “Housings,” provides guidance on determining allowable leakage. The allowable leakage should be considered when determining construction requirements. However, for filter housings, the structural design requirements for pressure and dynamic forces dictate that the housing fabricated of heavy platework (10-gauge to 3/16-inch-thick) can be seal-welded to join the transverse and longitudinal joints, instead of using bolts, without significantly increasing cost. This will result in a low-leakage installation.

4.4.3.4 Paints and Protective Coatings

Coatings and paint requirements should be consistent with the corrosion expected in a particular application. Corrosion and radiation-resistant paints and coatings should, at a minimum, meet the requirements of ASTM D5144, *Standard Guide for Use of Protective Coatings in Nuclear Power Plants*.

Carbon steel housing interiors and mounting frames should be painted to protect against corrosion and to facilitate cleaning and decontamination. Surfaces should be properly prepared, and primer and topcoats should be applied in strict accordance with the coating manufacturer's instructions in order to obtain the necessary wet-film and dry-film thicknesses. Film thicknesses should be tested during and after application. Surfaces to be coated should be abrasive blasted to a profile of 1 to 2 mils in accordance with the Society of Protective Coating (SPC) SSPC-SP-5/NACE No. 1, *Near White Metal Blast Cleaning.* The prime coat should be applied within 2 to 3 hours, but in no case more than 8 hours, after surface preparation.

For exterior carbon steel surfaces, either hand or power tool cleaning (SSPC-SP-2 or SSPC-SP-3) is usually sufficient. For certain conditions, such as humid atmospheres, exterior carbon steel surfaces should be prepared in accordance with SSPC-SP-5/NACE No. 1 instead. Both ambient and metal surface temperatures should be 10 to 20 degrees Fahrenheit (6.6 to 12.2 degrees Celsius) above the dew point before starting to paint and there should be adequate drying time (recommended by the coating manufacturer) between coats.

QA for nuclear grade coatings is discussed in ASME AG-1, Section AA and ASTM D3843, *Practice for Quality Assurance for Protective Coatings Applied to Nuclear Facilities*. Other standards applicable to painting of nuclear facilities include ASTM D3911, *Standard Test Method for Evaluating Coatings Used in Light Water Nuclear Power Plants at Simulated Design Basis Accident (DBA) Conditions* and ASTM D3912-95, *Standard Test Method for Chemical Resistance of Coatings Used in Light Water Nuclear Power Plants*.

Because the difficulty in applying nuclear grade coatings to carbon steel surfaces often results in unsatisfactory performance of the coatings in service, designers should seriously consider use of stainless steel for mounting frames and housings in corrosive environments or where frequent decontamination is required. While there are some special handling and fabrication rules associated in working with stainless steel (particularly the highly polished surface finishes that should be protected from scratches during fabrication), the overall costs of painted carbon steel versus stainless are similar.

4.4.4 Man Entry Housing

4.4.4.1 General

Steel man-entry housings may be shop built or field fabricated. Stainless steel is the most common material of construction; however, carbon steel also may be used. Aluminum and galvanized steel are not suitable.

4.4.4.2 Structural

The mounting frame is a statically indeterminate lattice that generally consists of a set of full-length members spanning the height or width of the bank (whichever is shorter), connected by cross members that are slightly shorter than the width of individual filter (adsorber) units. For design purposes, the frame may be considered as an array of simply supported, uniformly loaded beams. Experience has shown that, to obtain adequate frame rigidity, these beams (frame members) should deflect no more than 0.1 percent of their length under a loading equivalent to 1.5 times the maximum dirty filter pressure drop across the bank.

4.4.4.3 Structural Design

Structural design of housings for both ESF air cleaning units and non-ESF units should consider the service conditions the housing may experience during normal, abnormal, and accident plant conditions. The design requirements for determining housing plate thickness, stiffness, spacing, and size are presented in ASME AG-1, Section AA. Housing design should consider the following load criteria. Key considerations for proper installation include:

- Additional dynamic loads,
- Constraint of free end displacement loads,
- Dead weight,
- Design pressure differential,
- Design wind speed,
- External loads,
- Fluid momentum loads,
- Live load,
- Normal loads,
- Normal operating pressure differential,
- Seismic load, and
- System operational pressure transient.

Stress criteria limits are given in ASME AG-1, Section AA. The maximum deflection for panels, flanges, and stiffeners for the load combination should be the lesser of the two values derived as shown below.

Criterion 1

- Plate or sheet: 1/8 inch per foot of the maximum unsupported panel span in direction of airflow, but not more than 3/4 inch;
- Stiffeners and flange connections: not to exceed 1/8 inch per foot of span, but not more than 3/4 inch; or
- Flange connection to dampers and fans: 1/360th of the span, but not to exceed 1/8 inch.

Criterion 2

Deflections are limited to values that will not cause:

- Distortion of the airflow path cross-section, resulting in unacceptable increase in system pressure;

- Damage to safety-related items such as instrumentation or other safety-related equipment or accessories;
- Impingement of deflected elements on adjacent services such as equipment, pipe, cables, tubing;
- Loss of leak-tightness (in excess of leakage limit);
- Buckling (refer to ASME AG-1, Section AA-4000); or
- Functional failure of components attached to ductwork (e.g., instrument lines).

4.4.4.4 Mounting Frame Configuration

The basic type of mounting frame construction is face-sealed (i.e., the filter seals to the outermost surfaces of the frame members by means of gaskets glued to the front surface or to the flange around the face of the filter unit) as shown in **Figure 4.51.**

A minimum face width of 4 inches is recommended for major and cross members of face-sealed HEPA filter frames. This allows 1-inch-wide filter-seating surfaces to compensate for any misalignment of the filter during installation and a 2-inch space between filters, horizontally and vertically. It also provides adequate room for handling (personnel replacing contaminated filters will probably have to wear double gloves), using power tools or torque wrenches during filter change, and manipulating a test probe between units.

Face widths of frame members for installing Type I (pleated-bed) adsorber cells are the same as those for HEPA filters. Face widths of frame members for installing Type II (tray-type) adsorber cells may be narrower since handles are provided on the front of the trays to facilitate installation. Satisfactory mounting frames may be made from rolled structural shapes or rectangular structural tubing. **Figure 4.52** shows a HEPA filter frame made from 4 × 4 inch structural tubing that meets all structural requirements. Rolled structural shapes for building mounting frames are given in **Table 4.10.** Square structural tubing frames for HEPA filters should be made from rectangular tubing with a face width of at least 4 inches; structural tubing frames for Type II adsorber cells may have narrower face widths.

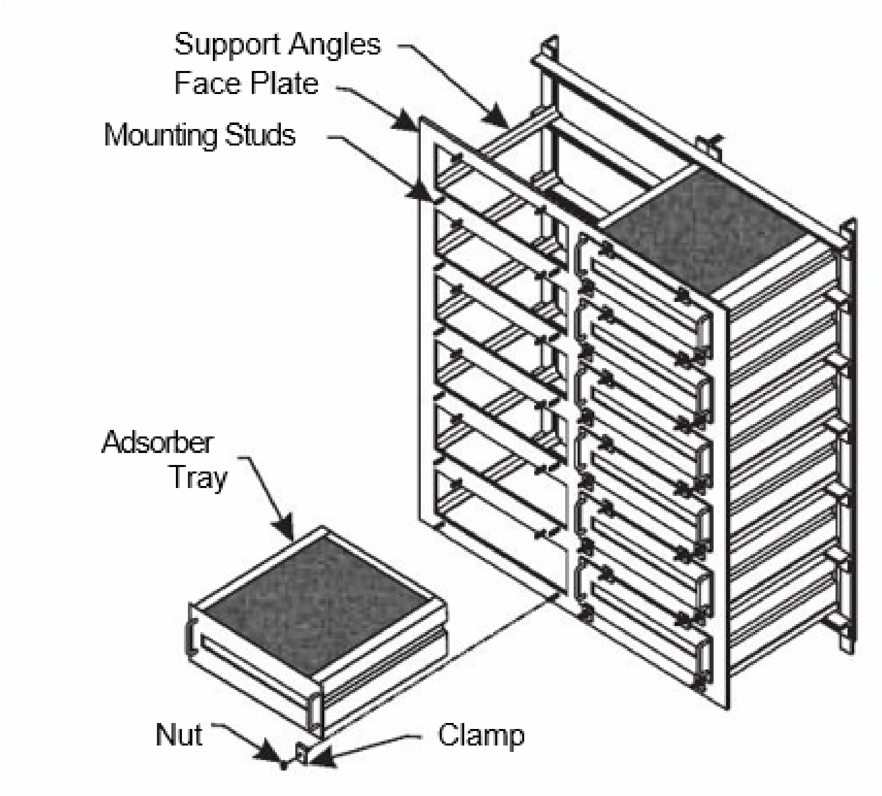

Figure 4.51: Adsorber Gasket Seals Against Mounting Frame Face Plate

Figure 4.52: Filter Mount

Table 4.10: Minimum-Cost Structural Members for 24-by-24 HEPA Filter and Type I Adsorber Mounting Frames (maximum pressure drop to 12 in. wg)

Number of 1,000 cfm Units High	*Principal Member I-beam* a			*Cross Member Channel (span = 22)*	
	Span b	*Size (in.)*	*lb./ft.*	*Size (in.)*	*lb./ft.*
2	4 ft. 8 in.	4 X 4 M	13	4 x 13/4	5.4
3	6 ft. 10 in.	4 x 4 M	13	4 x 13/4	5.4
4	9 ft. 0 in.	4 x 4 M	13	4 x 13/4	5.4
6	13 ft. 4 in.	6 X 4 B	16	4 x 13/4	5.4
8	17 ft. 8 in.	8 X 4 B	10	4 x 13/4	5.4
10	22 ft. 0 in.	10 X 4 5/8	25.4	4 x 13/4	5.4

a Principal members should span the shortest dimension of the bank.
b Span = (number of filters X 26) + 4 (inches).

4.4.4.5 Frame Fabrication

Filter mounting frames should be shop-fabricated if practicable because it is nearly impossible to avoid misalignment, warping, and distortion in field fabrication. Shop fabrication is less costly than field fabrication and permits better control over assembly, welding, and dimensional tolerances. Care should be taken to avoid twisting or bending the completed frame during handling, shipping, and field installation. For proper performance and maintenance of installed filters, dimensional and surface-finish tolerances should be tight and rigidly enforced. Welds on the filter-seating side of the frame should be ground flat, smooth, and flush.

Only welders qualified in accordance with the American Welding Society (AWS) D1.1, *Structural Welding Code-Steel* or Section IX of the ASME *Boiler and Pressure Vessel Code* should be permitted to make welds on HEPA filter and adsorber mounting frames. Both seal and strength welds should be visually inspected by a qualified inspector under a light level of at least 100-foot candles on the surface being inspected. In addition, liquid penetrant (ASTM E165) or magnetic particle inspection (whichever is applicable for the base material being inspected) of the seal welds between frame members is recommended.

4.4.4.6 Clamping and Sealing

HEPA filters and adsorber cells should be carefully sealed to the mounting frame **(Figures 4.53 and 4.54)** to achieve the required low penetration leakage rates and to allow easy replacement. Except for the fluid-seal design described at the end of this section, sealants are not a satisfactory substitute for gaskets. Experience in clean rooms and contaminated exhaust and air cleanup applications has shown that flat, closed-cell, neoprene gaskets, ASTM D1056 grade 2C3, give the most satisfactory seal for high-efficiency filters, adsorbers, and moisture separators.

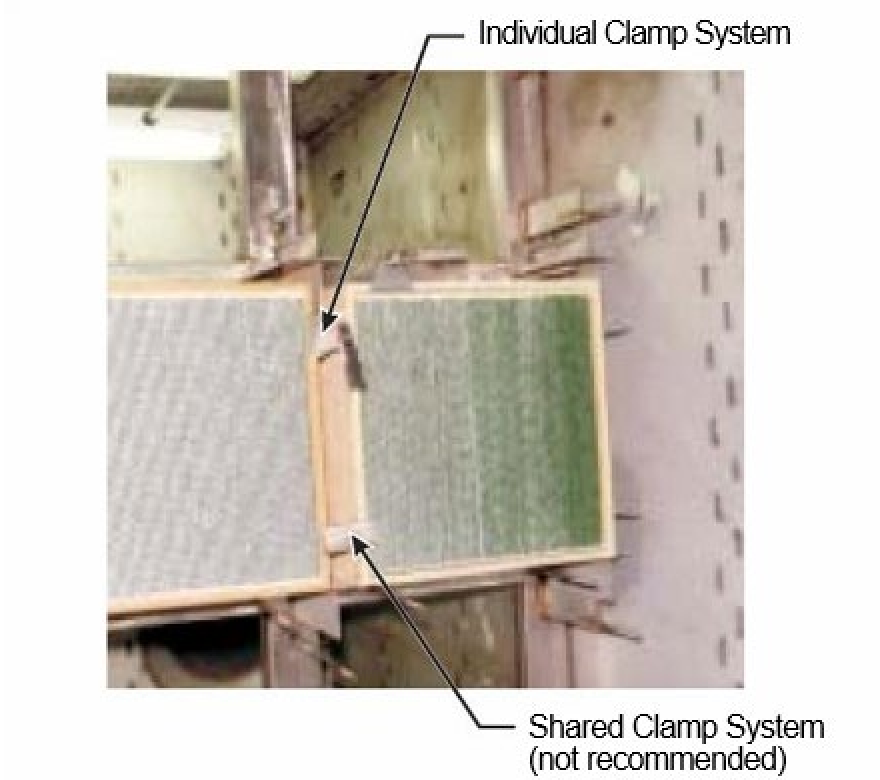

Figure 4.53: HEPA Filter Mounting Frame (Showing Two Clamp Designs)

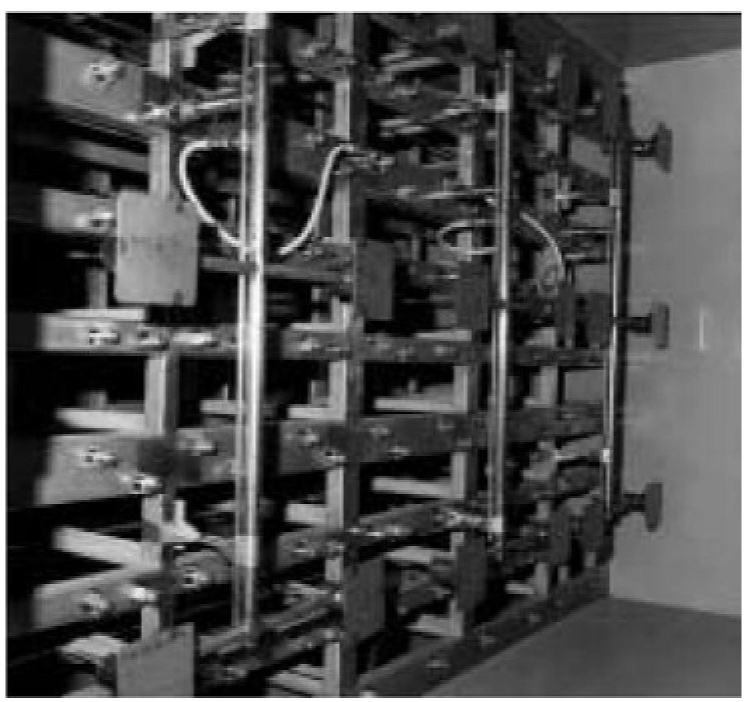

Figure 4.54: Absorber Mounting Frame with Test Section Manifold

Gaskets that are too soft (i.e., are less than grade 2C3) take an excessive compression set that may permit leakage when there is relaxation of the clamping bolts. Gaskets that are too hard (i.e., harder than grade 2C4) require such high clamping loads to effect proper scaling that the filter itself can be distorted or damaged. As little as 20 percent gasket compression is needed to affect a reliable seal when the thickness of the gasket is uniform to within ±0.01 inches and the seating surface of the mounting frame is plane to within ±0.01 inches.

However, these tolerances are much too restrictive for economical construction, and experience has shown that it is usually necessary to compress a 2C3 gasket at least 80 percent to affect a reliable seal over long periods. Eighty-percent compression requires a loading of approximately 20 psi of gasket area, or a total clamping load of about 1,400 pounds for a 24- by 24-inch filter unit. The recommended procedure for installing filters under nonhazardous conditions is to initially torque the clamping bolts to produce 50 percent gasket compression and then retorque them 1 or 2 weeks later to a total compression of about 80 percent. In a radioactively contaminated filter system, replacement can be a hazard to personnel and to the filters and/or adsorbers installed in the system. Under such conditions, one entry is advised. One option is to manually compress the filter gasket to an estimated 50 to 80 percent. A spring-loaded hold-down (**Figure 4.55)** is another option used at some DOE sites. Torsion bar clamps designed to exert the proper clamping forces are a third option.

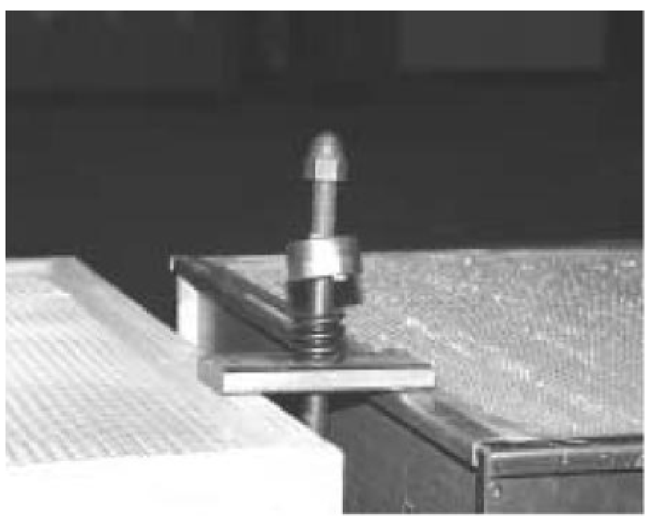

Figure 4.55: Filter Hold-Down (Spring Design)

Gaskets that are too thin may not give a reliable seal, whereas those that are too thick may be unstable and tend to roll or pull off the flange of the filter case as they are compressed, perhaps to the extent that sections may be extruded between the case and mounting frame and produce a serious air leak. Recommended gasket sizes are 1/4 to 3/8 inch thick by 3/4 inch wide and 1/4 to 3/8 inch thick by 5/8 inch wide. Gaskets should be glued to the filter element rather than to the mounting frame because they should be replaced with each filter change. A sealant such as silicone could be applied lightly to the filter gasket. Residue should be removed before installing new filters as the sealant may be contaminated, making disposal more difficult. Gaskets should have cut surfaces on both faces because the "natural skin" produced by molding sometimes tends to bridge discontinuities or defects in the seating surface, and because the silicone mold-release compounds used in the manufacture of sheet neoprene prevent proper adhesion of the gasket to the filter case.

Clamping devices should function easily and reliably after long exposure to hostile environments. In addition, they should be capable of easy operation by personnel dressed in bulky protective clothing, gloves, and respirators (or full-face gas masks) while working in close quarters. Experience has shown that a simple nut-and-bolt system gives satisfactory service under these conditions. Nut-and-bolt clamping, however, entails removal and handling of a large number of nuts, and this procedure can be a problem during a filter change in a highly radioactive system. However, clamping systems that provide the required torque and gasket compression without loose parts are highly recommended. Any system that achieves the desired clamping torque is acceptable. **Figure 4.56** shows four pressure clamping points as recommended for HEPA filters and provides an example of clamping a blanking plate for filter change.

Eccentric, cam-operated, over-center, or spring-loaded latches, and other quick-opening latches, such as the window latch design, are not recommended for clamping high-integrity components such as HEPA filters and adsorber cells. Because of their weight, eight pressure points are desirable for clamping Type I (pleated-bed) adsorber cells. For clamping Type II (tray-type) cells, two pressure points on the top and two on the bottom edges of the front plate are needed for proper sealing, with individual clamping.

The minimum bolt size recommended for individually clamped filters is 3/8-16-UNC, but 1/2-11-UNC or 5/8-11-UNC bolts are less prone to damage. For Type I adsorbers, 5/8-11-UNC bolts are necessary. The nuts and bolts of the clamping system should be made of dissimilar materials to prevent galling and seizing. Bolting materials and clips should be corrosion resistant. Stainless steel (300 series) bolts with brass nuts are frequently used. Springs, if used, should also be made from a PPH grade of stainless steel if they are to resist corrosion and relaxation over a period of service.

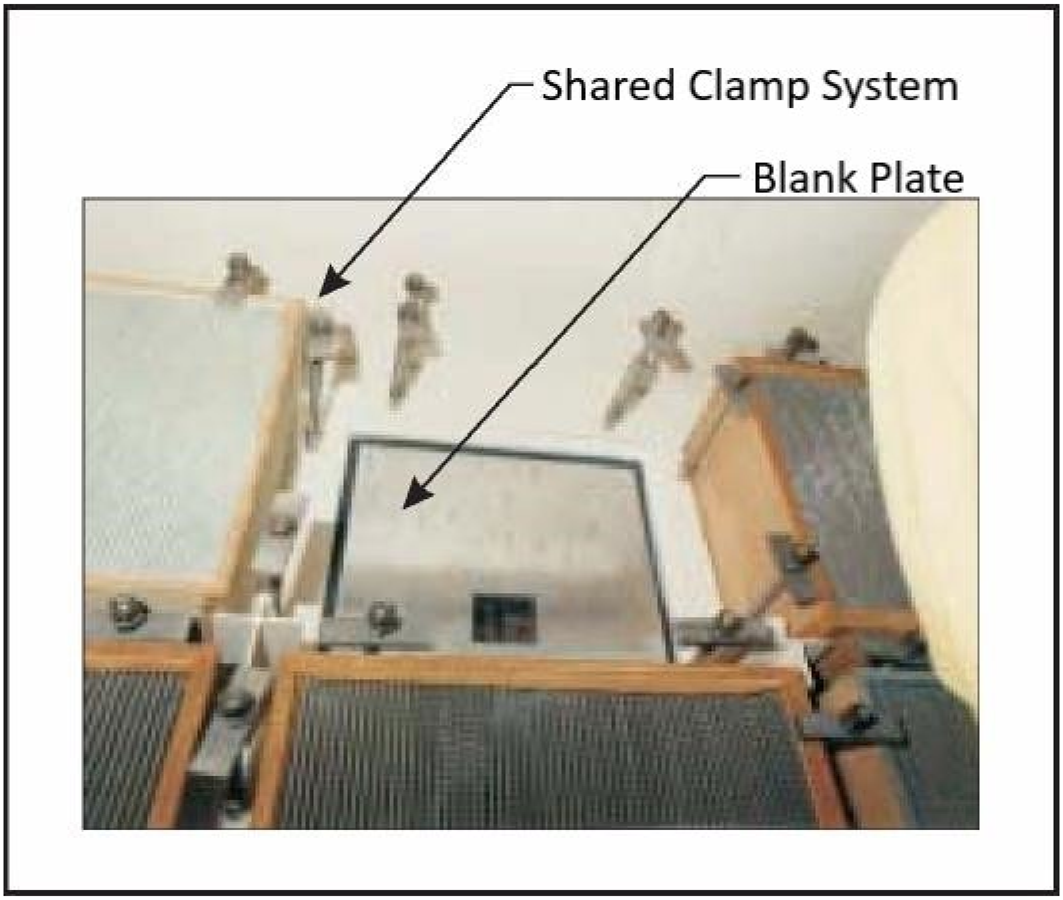

Figure 4.56: HEPA Filters Mounting Frame with Blanking Plate Installed for Filter Change

4.4.4.7 Filter Support

A cradle or other support for the filter element as it is moved into position on the frame is a desirable feature from a maintenance standpoint. The cradle should not obscure any more of the filter-to-frame interface than necessary to avoid interference with inspection as the filter is installed. The support shown in **Figure 4.57** is a good choice because it obscures less of the gasket-frame interface. In some installations, filters have been supported on the bottom clamping bolts, a practice that risks damage to the threads of the clamping bolts and is not recommended.

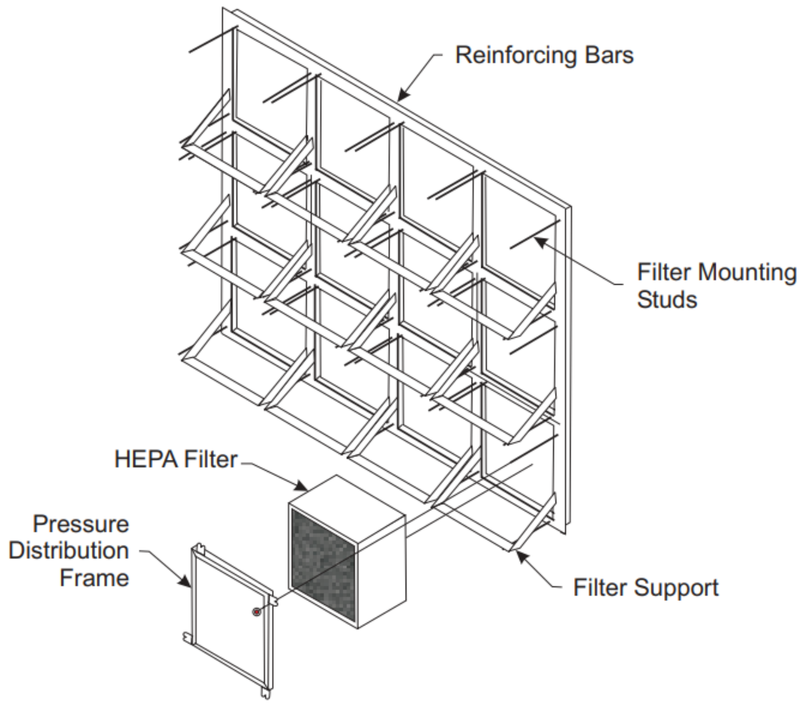

Figure 4.57: HEPA Filter Mounting Using Pressure Distribution Frame Design Filter Hold Down

4.4.4.8 Size and Arrangement of Filter and Adsorber Banks

The size (nominal airflow capacity) and orientation of filter banks (vertical or horizontal), the location of filters on the bank (upstream or downstream side), and the floor plan and height of the bank all affect the reliability, performance, maintainability, and testability of the air cleaning system. Savings gained by designing for minimum space and materials can be wiped out many times over by the higher operational, maintenance, and testing costs that will result from higher pressure drop and cramped working space in the filter housing. See Section 4.4.4.11 for additional guidance on the size of filter banks and system capacity.

4.4.4.9 Vertical Filter Banks

Vertical banks with horizontal airflow are preferred in contaminated exhaust systems because the filters are more favorably oriented with respect to ease of handling, mechanical strength of the filters, and collection of condensate. The pleats of Type I adsorber cells and the beds of Type II cells should be installed horizontally to avoid adsorbent settling in the cells. Before designing a horizontal filter bank with vertical airflow, filter/adsorber components should be validated for performance in this application/design. In addition, the design should include provisions for filter installation and removal.

4.4.4.10 Location of Filters on Mounting Frame

No clear-cut preference can be justified for mounting filters on either the upstream or the downstream side of the mounting frame. Both methods have been used successfully and the advantages and disadvantages of each are listed below.

Upstream Mounting

Advantages:

- The filters are withdrawn into and handled within the contaminated side of the system during a filter change.
- No contaminated materials are brought into the clean side of the system, so there is more complete separation of the clean and dirty sides of the system.

Disadvantages:

- Personnel have to work within a potentially contaminated zone during a filter change.
- It is possible that contamination can be tracked or carried out of the contaminated zone by workmen, unless the filter change is carefully planned and executed.
- The filter clamping devices are located in the dirty side of the system where they are most exposed to corrosion and dirt.
- Contaminated material may accumulate on the horizontal surfaces of the filter case and may dislodge during removal.

Downstream Mounting

Advantages:

- Filters are withdrawn into and handled within the clean side of the system, thereby reducing the likelihood of tracking or carrying contamination into the building during a filter change.
- Filter clamping devices are located on the clean side of the system where they are less subject to corrosion.
- Leak-scanning of installed filters is more sensitive: if there are gasket or casing leaks, the driving force of air entering the filter forces the test aerosol through the leak, and they are readily detected.
- With upstream mounting, on the other hand, any test aerosol that goes through a leak in a gasket or filter case mixes with the air and test aerosol passing through the opening in the mounting frame, thus obscuring the leaks. Although the existence of a leak may be disclosed by a test, the location of the leak cannot be easily determined by probing.
- Only the upstream face of the filter is contaminated during operation. The outer surfaces of the filter case and the downstream face of the filter pack are not usually contaminated.

Disadvantages:

- The contaminated filters should be withdrawn into the clean side of the system in a filter change. This disadvantage can be offset by "fixing" (locking down) the contaminated dust by spraying the upstream side of the filter pack with paint or acrylic spray or by taping cardboard over the upstream face of the filter. However, this procedure requires personnel to enter the contaminated chamber of the housing, and the possibility still exists of dislodging contaminated dust into the clean side of the system, either from the filter itself or from the edges of the frame opening (which is exposed to contaminated air during operation).
- Filters have been mounted on both sides of a mounting frame in some installations. This is not recommended. A cardinal rule in contaminated exhaust systems is that no credit is granted for untested and untestable filters. Such mounting precludes testing of both filters. Therefore, although double mounting may provide two sets of filters, the operator cannot take credit for two-stage filtration or series redundancy. This design has been shown to fail in a fire. The upstream filter blows out when plugged with smoke particles and impacts the filter downstream, causing it to blow out also.

4.4.4.11 Size of Banks

Previously, a nominal system capacity of 30,000 cfm has been recommended by DOE and NRC for any filter or adsorber bank. This recommendation has been modified to account for the larger capacity components now in use. Thus, the maximum size of a safety class or safety significant filtration housing not exceeding 30 filtration components (e.g., medium efficiency filter, moisture separator, HEPA filter or adsorber cell) per stage, allows for meaningful in place testing. When significantly greater air flow than this is needed, multiple systems can be installed in parallel. The purpose of this requirement is to facilitate maintenance and in-place testing, to improve control in the event of a system upset, and to enhance the reliability of the total system.

By breaking the system into two or more air cleaning units, testing and filter replacement can be conducted in one unit while the other unit remains online. NRC RG 1.52 recommends such redundancy for ESF air cleaning systems in reactors. The designer may also choose to segment a system into units of substantially less than 30,000 cfm or 30 filtration components when redundancy is desired to achieve advantages of control, maintainability, and testability. The use of 1,500-cfm filters allows higher-capacity systems without increasing the physical size of the bank. In-place testing and maintenance is the determining factor.

4.4.4.12 Arrangement of Banks

Arrangement of filters on a mounting frame influences operating performance and maintenance. Where possible, banks should be laid out in an array of three filters high or nine Type II adsorber cells high. When floor space is at a premium, the bank may be arranged with one 3-high array above another, with a service gallery between. Thus, an 18,000-cfm bank might be arranged in an array 6-wide by 3-high or 3-wide by 6-high, with a service gallery between the third and fourth tiers. The arrangement of a 24,000-cfm bank in a 6-wide by 4-high array would be undesirable. A better arrangement is an array 8-wide by 3-high or, if floor space is at a premium, two 4-wide by 3-high arrays, one above the other, separated by a service gallery. In no case should filter changing require the use of temporary ladders or scaffolding.

Based on the 95th-percentile man, the maximum height at which a man can operate hand tools effectively is 78 inches, and the maximum load he can handle at a height of 5 feet or more is 40 pounds, which is the approximate weight of a clean HEPA filter. Therefore, provision for access to the higher tiers of filters is necessary. In fact, ASME AG-1, Subsection HA, requires that a permanent platform be installed to access filters above 6 feet.

Filter banks should be rectangular. The use of odd-shaped banks to limit installed filter capacity to calculated system airflow requirements increases construction costs significantly. Operating costs may also be reduced because the additional filters permit operation at a lower flow rate per unit resulting in longer filter life and reduced filter-change frequency. For the purposes of laying out adsorber banks, three Type II (tray) adsorbers will fit vertically into the space occupied by one 24- by 24-inch HEPA filter.

4.4.4.13 Floor Plan of Filter Banks

The plenum floor plan of a vertical filter bank varies with the application of the system. Judicious configuration of banks can often reduce pressure losses in the system and bring about more uniform dust loading of filters, thereby equalizing the utilization of the filters installed in the banks.

The procedures required for construction and operational maintenance should be considered early in the planning stages. Adequate clearances for access should be maintained at turning points and between the bank and the nearest obstruction. Passageways both between the banks and between the banks and the housing wall should be wide enough for welders to operate effectively and for workmen, dressed in bulky clothing, to get in to change filters (see **Figures 4.58 and 4.59).** Both welders and workmen will have to kneel or stoop to get to the bottom tier. A 95th-percentile man in a kneeling position requires a minimum clearance of 36 inches from the face of the filters to the nearest obstruction, excluding withdrawal space for the filter unit itself. A minimum clearance of 40 inches is therefore recommended between the face of one bank and the nearest obstruction.

4.4.4.14 Steel Housings

Design practices used for conventional air conditioning and ventilation system ductwork and equipment casings are not adequate for high-reliability, high-efficiency contaminated exhaust and air cleanup systems. Experience has shown that, under system upset and shutdown conditions, housing leaks can result in the escape of contamination to clean areas. Even with fans operating, reverse leakage of particles from the low-pressure side of a system (i.e., the interior of the housing or duct) to the high-pressure side (i.e., the occupied area of the building) can sometimes occur because of dynamic and aspiration effects. Out-leakage may also occur when the system is shut down. Filter housings for contaminated exhaust service should be able to withstand negative pressures without damage or permanent deformation at least up to fan cutoff, which may be equal to 20 in. wg. in many systems. A pressure differential of 2 in. wg. between the inside and outside of a housing produces a load of more than 1,000 pounds over every 10 square feet of the housing wall. If the filters are operated to economical pressure drops, the housing may have to withstand 10 or more times this load without appreciable deflection. Pulsation and vibration may aggravate the condition. In addition, the housing should be able to withstand design shock loads without damage.

Figure 4.58: HEPA Filter Mounted on Upstream Side of Mounting Frame Filter Replacement

Figure 4.59: Blanking Plate Being Installed on Downstream Side of Mounting Frame

Housings should be of all-welded construction, with bolted flange or welded inlet and outlet connections to the ducts and fans. **Table 4.11** gives minimum sheet metal thicknesses for sheet steel housings, and **Table 4.12** gives minimum moments of inertia for steel reinforcing members. Sheet metal thicknesses in **Table 4.11** are based on a maximum deflection of 1/4 inch per linear foot at a pressure differential between the interior of the housing and atmosphere equivalent to 1.5 times the maximum pressure at fan cutoff. The moments of inertia for reinforcing members listed in **Table 4.12** were selected to avoid exceeding the allowable stress of the steel. Members up to 20 inches long were considered to be uniformly loaded beams with fixed ends, whereas members longer than 20 inches were considered to be uniformly loaded beams with simply supported ends. The sheet-metal thicknesses in **Table 4.11** are given in U.S. gauge numbers for sheet and fractional inches for plate.

Table 4.11 – Minimum Sheet-Metal Thicknesses [a] for Welded Steel [b] Filter Housings under Negative Pressure

Dimensions of Largest Unsupported Panel (in.)		Thickness [c] (U.S. gauge for sheet, fractional in. for plate) for negative pressure					
Long Side [d]	Short Side	4 in. wg.	8 in. wg.	12 in. wg.	20 in. wg.	1 psi	2 psi
54 (2)	12	18	18	14	16	14	11
	24	18	14	11	12	8	1/4
	36	16	12	8	11	1/4	3/8
	48	14	12	6	8	1/4	3/8
80 (3)	12	18	16	14	16	14	11
	24	18	14	11	12	8	1/4
	36	16	12	6	11	1/4	3/8
	48	14	12	6	8	1/4	3/8
106 (4)	12	18	16	16	14	14	11
	24	18	14	12	11	8	1/4
	36	16	12	8	6	1/4	3/8
	48	16	10	6	1/4	3/8	3/8

[a] Based on flat plate edges held but not fixed (*Roark's Formulas for Stress and Strain*), and maximum deflection of 0.25 inch per foot between reinforcements.
[b] 30,000 to 38,000 psi yield strength.
[c] Metal thickness less than No. 18 U.S. gauge are not recommended because of welding problems.
[d] Length based on 2-inch spacing between 24- × 24-inch filter units; the numbers within parentheses denote number of filter units. The metal thicknesses are adequate for panel lengths within ±10 inches of the length shown.

Table 4.12– Recommended Minimum Moments of Inertia for Selecting Reinforcing Members for Steel Filter Housings under Negative Pressure a, b

Reinforcement		Moment of inertia (in.) [c] for negative pressure (relative to outside)					
Length [d] (in.)	Spacing (in.)	4 in. wg.	8 in. wg.	12 in. wg.	20 in. wg.	1 psi	2 psi
54 (2)	12	0.04	0.04	0.04	0.04	0.04	0.08
	24	0.04	0.04	0.04	0.06	0.08	0.16
	36	0.04	0.04	0.05	0.09	0.12	0.24
	48	0.04	0.05	0.07	0.12	0.16	0.32
80 (3)	12	0.04	0.04	0.05	0.08	0.11	0.21
	24	0.04	0.06	0.09	0.16	0.21	0.43
	36	0.05	0.10	0.14	0.24	0.32	0.63
	48	0.06	0.13	0.19	0.32	0.42	0.86
106 (4)	12	0.04	0.09	0.13	0.22	0.30	0.60
	24	0.09	0.18	0.26	0.44	0.60	1.19
	36	0.13	0.27	0.39	0.66	0.90	1.79
	48	0.18	0.36	0.52	0.88	1.19	2.38
132 (5)	12	0.09	0.17	0.26	0.51	0.69	1.39
	24	0.18	0.34	0.52	1.02	1.39	2.78
	36	0.27	0.51	0.78	1.53	2.08	4.17
	48	0.36	0.68	1.04	2.04	2.76	5.55
158 (6)	12	0.15	0.29	0.44	0.73	1.0	2.0
	24	0.29	0.59	0.88	1.46	2.0	4.0
	36	0.44	0.87	1.32	2.19	3.0	6.0
	48	0.58	1.16	1.76	2.19	4.0	8.0

[a] Based on permissible deflection of 1/8 inch per foot.
[b] Uniformly loaded beam, 50 percent simply supported and 50 percent fixed end assumed.
[c] Structural angles can be chosen from the tables given in the AISC *Manual of Steel Construction*.
[d] Length based on 2-inch spacing between 24- x 24-inch filter units; the numbers within parentheses denote number of filter units. The metal thicknesses are adequate for panel lengths within ±10 inches of the length shown.

Housings installed inside a reactor confinement may experience a pressure lag during rapid pressurization of the confinement following a major accident. Unless the housings are equipped with pressure-relief dampers, this lag could result in a pressure differential between the housing and confinement substantial enough to collapse the housing.

Reinforcing members should be spaced to minimize vibration and audible drumming of the housing walls, which can be transmitted through the system. Reinforcements should be installed on the outside of the housing, when possible, to eliminate interior ledges and projections that collect dust and constitute hazards to personnel working in the housing (**Figure 4.60**).

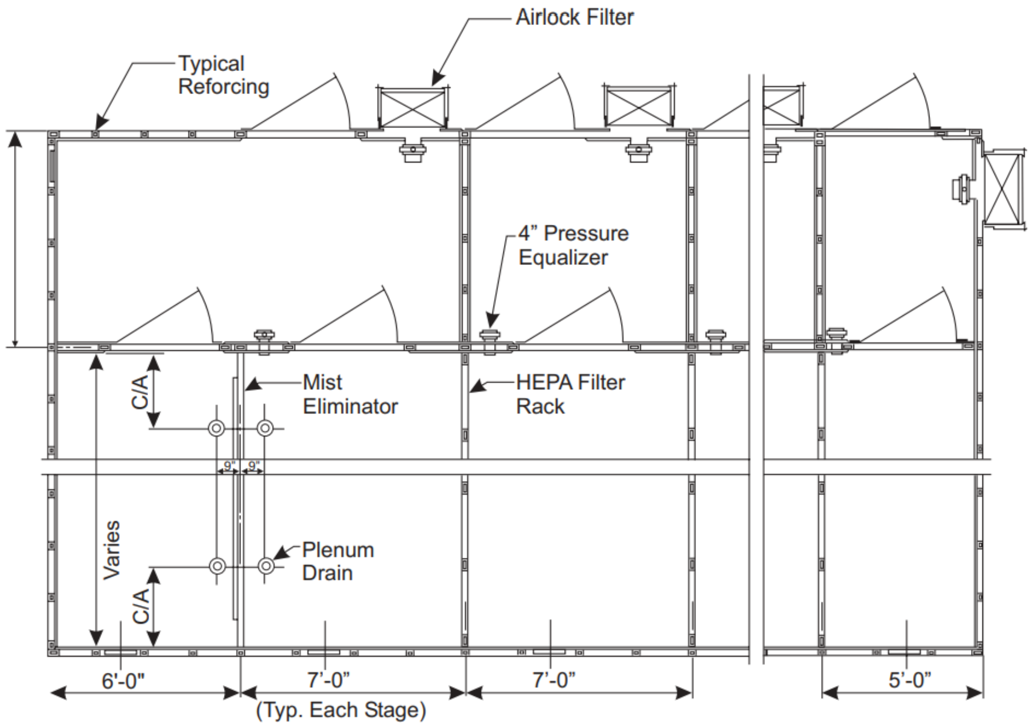

Figure 4.60: Filter Plenum Floor Plan

All sharp corners, welds, weld spatter, and projections inside the housing should be ground smooth. The housing design should minimize cracks and crevices that are difficult to clean and that may collect moisture that can cause corrosion.

Mastics and caulking compounds, including silicone-based, room-temperature vulcanizing (RTV) sealants, deteriorate in service and should not be used for sealing between panels and sections of a contaminated exhaust housing. Lock seams, rivets, and bolts used in conventional construction for joining panels do not produce leak-tight joints. When bolted flange joints are used between the housing and ducts, 1.5- × 1.5- × 0.25-inch-angle flanges with ASTM D1056, grade 2C5 or 30-40 Shore-A durometer neoprene gaskets are minimum requirements. A maximum bolt spacing of 4 inches is recommended for flanges.

4.4.4.15 Masonry and Concrete Housings

Filter housings for low-gamma-activity systems and vaults for high- (or potentially high-) gamma-activity systems sometimes have been built as an integral part of the building structure utilizing the same concrete building walls for HEPA housing walls. This construction is not recommended.

4.4.4.16 Housing Floor

Steel housings should have steel floors welded continuously to the walls of the housing. Housings should not be installed on a wood floor or on a floor having less than a 3-hour fire rating. A steel curb, welded to the floor, is recommended to raise the filter-mounting frame off the floor. The section of flooring between two banks of components should be considered a separate floor to be drained independently. Floors should be free of obstructions or raised items that could be hazardous to workmen.

4.4.4.17 Housing Doors

Easily opened doors are essential on large housings, and more than one door is generally needed. A door should be provided to each compartment (space between banks) where maintenance, testing, or inspection may take place. The use of bolted-on removable panels for access to filter compartments should be avoided for even the smallest filter housings when human entry is required. Sliding doors are not recommended for filter housings, because they cannot be sealed and because they jam after any distortion of the housing.

Sturdy double-pin-hinged doors with rigid, close-fitting casings and positive latches should be provided on man-entry housings, particularly those for ESF and other high-hazard service. Doors and gaskets should be designed to maintain a hermetic seal under positive and negative pressures equal to at least the fan cut-off pressure. Doors of negative pressure systems should open outward and, since they may have to be opened against the negative pressure, a means for breaking the vacuum or for mechanically assisted opening is desirable. Doors should have heavy-duty hinges and positive-latching devices that are operable from inside and outside. Means for locking, such as a padlock, may be provided to prevent unauthorized entry. Door stiffness is important because flexible doors can be sprung when opened against negative pressure or allowed to slam shut under load. An airlock at the entry to the housing will eliminate problems with opening doors against negative pressure and slamming, and, if large enough, will provide an intermediate work area for personnel during a filter change.

Housing doors of the type shown in **Figure 4.61** require a minimum of two latching dogs on each side. Lighter-construction doors require additional latches to achieve a satisfactory seal. Latching dogs should be operable from inside and outside the housing, and shafts should be fitted with O-rings, glands, or stuffing boxes to prevent leakage. Door hinges should be of the double-pin, loose-pin, or other type that will permit the full plane of the door to move perpendicular to the plane of the doorframe during the last fraction of an inch of closure. Single-pin hinges, which result in angular motion throughout the door closing arc, do not permit the door to seal properly and may cause the gasket to be rolled out of its groove after a period of use, thus resulting in the loss of housing leak-tightness. If door gaskets are too hard, they will be incompressible, and the door cannot be sealed properly even with lever-and-wedge latching dogs. If too soft, the gasket will rapidly take a compression set and lose its ability to seal. Solid neoprene or silicone rubber of about 30 to 40 Shore-A durometer hardness is recommended.

Figure 4.61: Filter Plenum Entry Door (No Airlock Type-Test Manifold with Valves Shown)

The door should be large enough for easy access to personnel dressed in bulky protective clothing, wearing gas masks or respirators, and carrying (a) 24x24x11.5-inch filters weighing up to 40 pounds, or (b) 26x6x30 inch adsorber cells weighing up to 130 pounds. However, the larger the door, the more difficult it is to seal and the more likely that it or its frame can be damaged if allowed to slam under load. The door should be as large as possible for easy access, but in no event should it be any less than 26 inches wide and 48 inches high. A coaming (2-inch-high minimum to 6-inch-high maximum) should be provided at all doors to prevent the outflow of contaminated water should the housing become flooded.

4.4.4.18 Housing Drains

Floor drains are essential in contaminated-exhaust filter housings, particularly when sprinkler protection is provided. Even if moisture or condensation is not expected under normal conditions, occasional wash-down may be required for decontamination and water will be needed in the event of a fire. When the housing is above grade, the minimum provision for drainage is a Chicago half-coupling that is sealed with a bronze pipe plug using tetrafluoroethylene (Teflon®) plastic "ribbon dope" so the plug can be easily removed when needed.[20] When the filter is at or below grade, drains should be piped to an underground contaminated waste system during initial construction, since later drainage system installation is likely to be costly. Drains from contaminated systems should be piped to the radioactive waste system. In cold climates, water seats, traps, and drain lines should be protected against freezing if they are above the frost line. In hot climates, water seats/seals may dry out. When fire sprinklers are installed in the filter house, the drains should be sized to carry away the maximum sprinkler flow without water backup in the housing. Design of housing drains and the loop seals need to consider that the negative pressure within the system, caused by the vacuum created by the downstream fans, may impact the ability of the housing to drain water.

If a separate drain is needed for each chamber of the filter house, then each drain should have its own water/loop seal or trap **(Figure 4.62**). The raised drain (shown) takes into consideration criticality concerns while minimizing wastewater. The spaces between two banks of components in series are considered separate chambers. When piped to a common drain system, drain lines from the individual chambers of the housing should have a valve or be sealed, or otherwise protected to prevent bypassing of contaminated air around filters or adsorbers through the drain system. The drain system should be tested for leakage as part of the housing leak test, as well as part of system bypass testing of the HEPA and adsorbent filters.

Provision should be made for those seals or traps to ensure they are filled with water during the plant life (**Figure 4.63**). Water seals should be periodically checked to ensure they do not dry out. If the seal does dry out, there is a possibility that air from the contaminated drain system will be drawn into the filters. A manual or automatic fill system may be utilized to ensure water seals do not evaporate for systems that do not experience moisture conditions continuously. **Figure 4.64** shows alternate methods of drain connection.

[20] Use of Teflon in radiation areas needs to be specifically considered for radiolytic decomposition on a case-by-case basis.

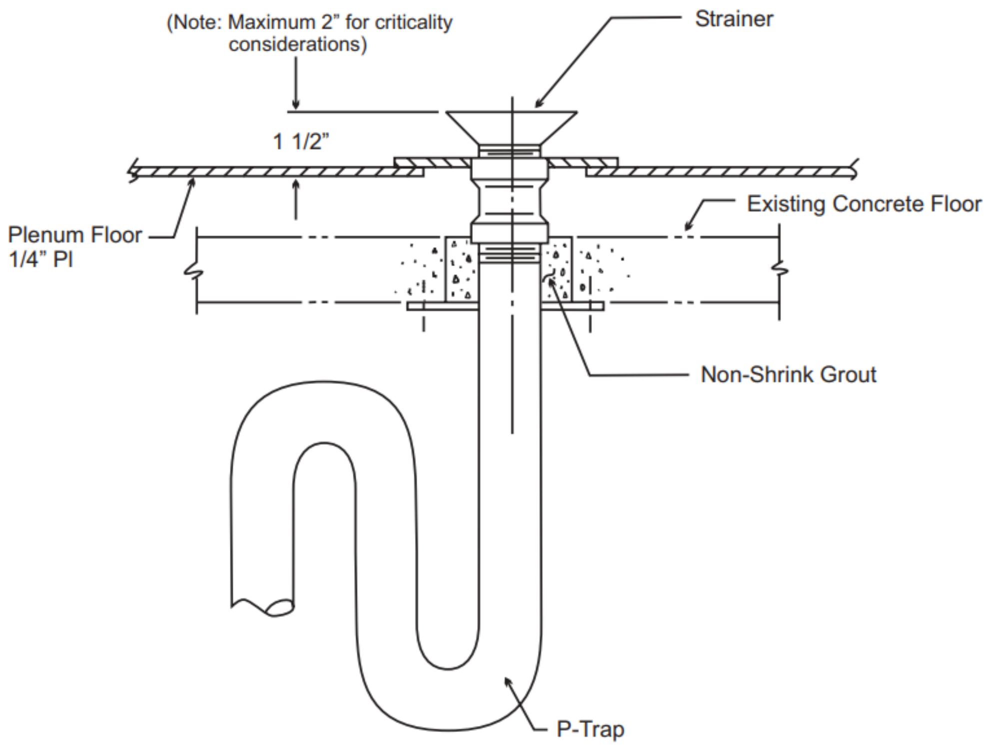

Figure 4.62: Plenum Drain Detail

Figure 4.63: Filter Plenum Drain P-Trap Fill Tube

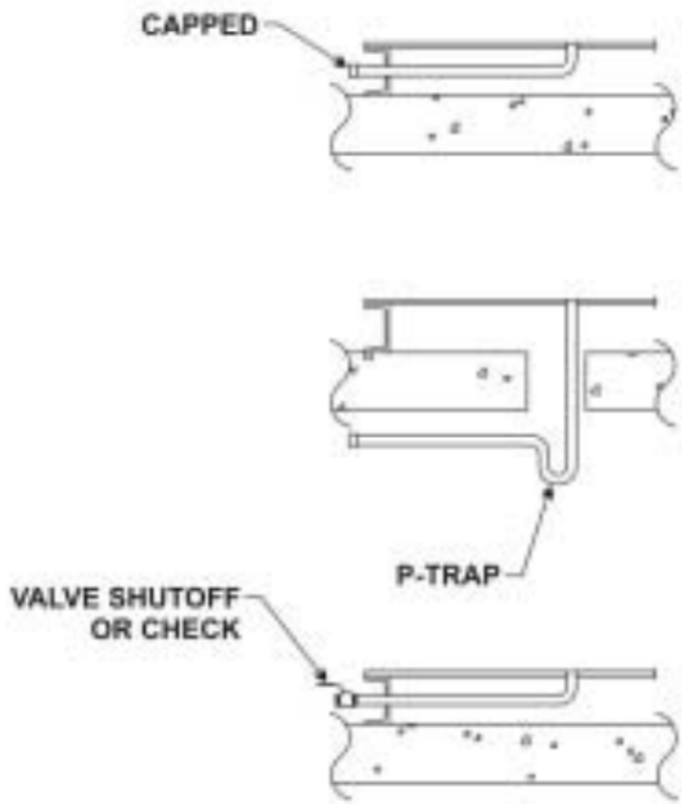

Figure 4.64: Plenum Drain Designs

4.4.4.19 Other Housing Requirements

Figures 4.65 and 4.66 illustrate features that are desirable in an air cleaning housing. The housing is all-welded construction. This housing consists of the moisture separator, medium efficiency filter, HEPA filter, carbon adsorber, and downstream HEPA filter. The housing is a 9,000-cfm capacity system and includes the following features.

- Shop fabrication.
- Wired-glass viewports on each side of the filter bank for visual inspection without entering the housing (**Figure 4.67**).
- Permanently installed lights in vapor-tight globes that are replaceable from outside of the housing.
- Wiring installed on the outside of the housing (penetrations for wiring are a common source of leakage).
- Shock-mounted instruments with a pressure-drop manometer across each bank of filters and inlet and outlet temperature indicators (**Figures 4.68 and 4.69**).

- A large marine bulkhead door that is operable from both inside and outside the housing (**Figure 4.70**).
- Ample space (approximately 4 × 7 feet) inside the housing to allow personnel to work during a filter change.
- All reinforcements located on the outside of the housing.
- A housing opening on the aisle that can be controlled and that serves as a workspace during filter change-out.
- All-welded construction to eliminate leaks to occupied areas.
- All penetrations sealed by either continuous seal welding or adjustable compression-gland-type seals rated and qualified for the environmental conditions.
- Housing drains located in each compartment.
- Permanently installed test aerosol and Freon injection and sample ports (highly recommended).

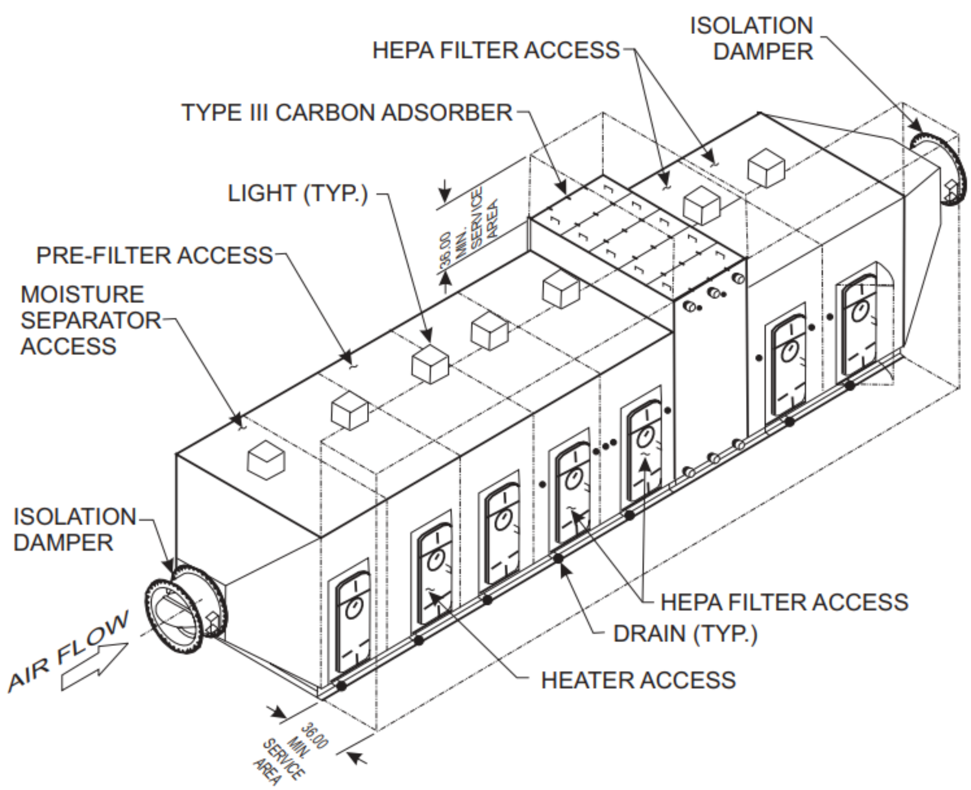

Figure 4.65: Desirable Air Cleaning Housing Features (a)

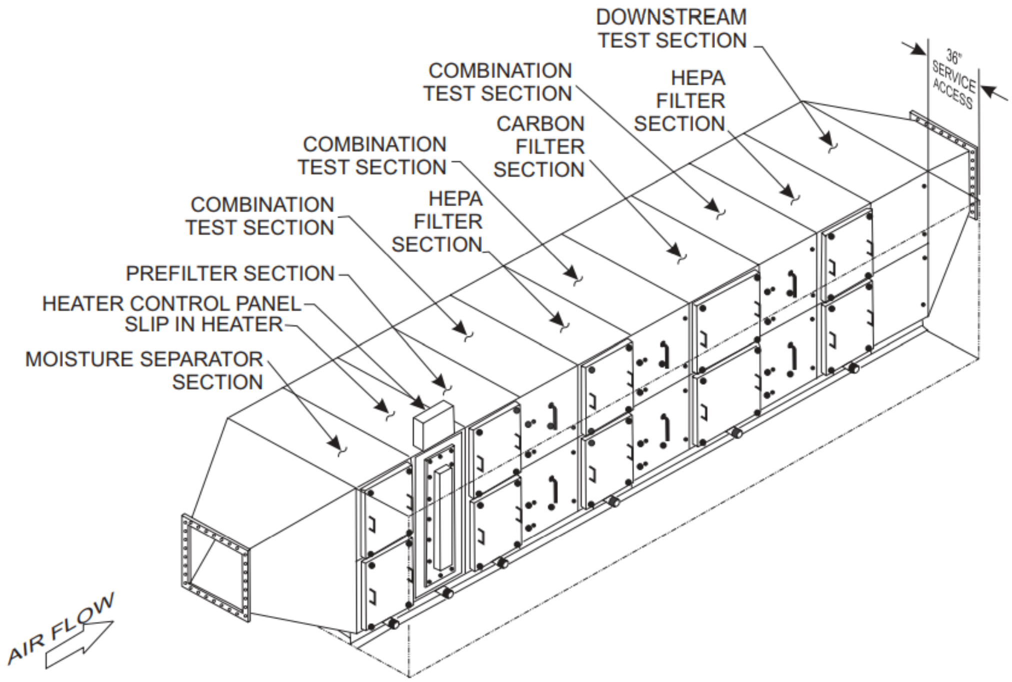

Figure 4.66: Desirable Air Cleaning Housing Features (b)

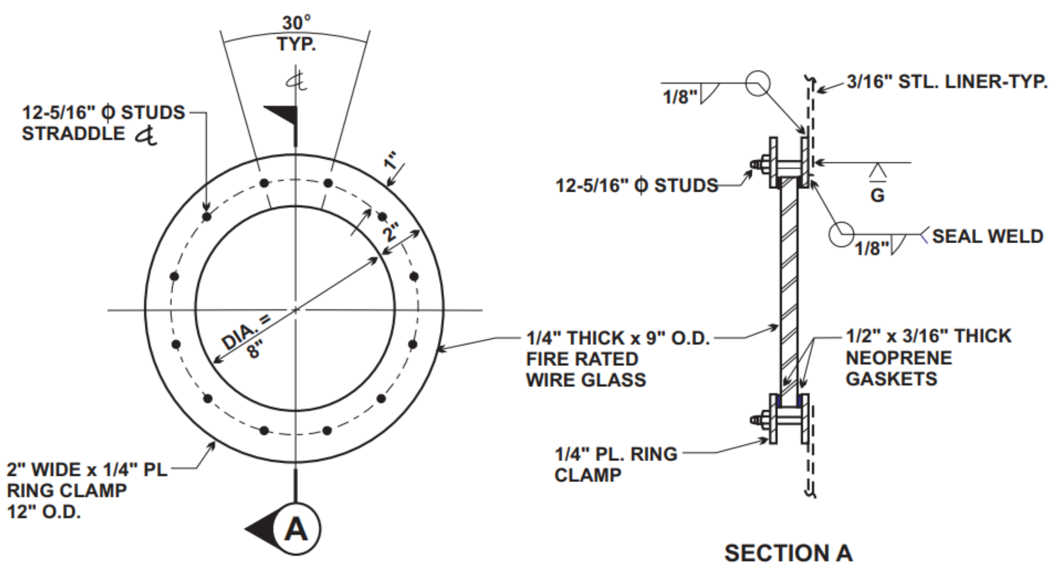

Figure 4.67: Viewport

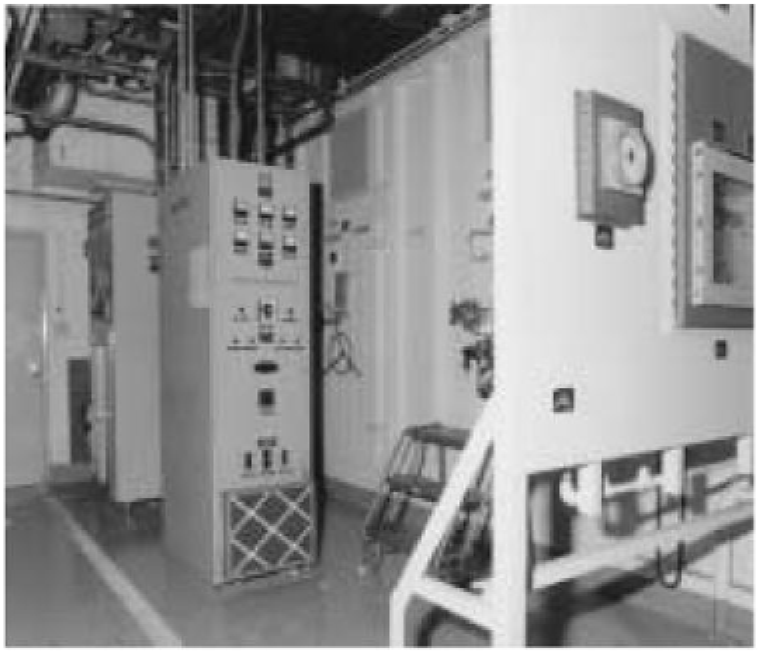

Figure 4.68: Manual Control and Instrument Panel

Figure 4.69: Air Monitor in Exhaust Duct from Plenum

Figure 4.70: Plenum Door (Wheel-Type Inside Plenum Access)

4.4.5 Design of Side-Access Housings

The recommended capacity range for side-access housings is 2 filters (24 × 24 × 11 1/2 inches) per stage to 12 filters per stage (4 across × 3 high). Single filter units are also available. Units may be stacked 3 high or higher if platforms are provided. Housings may be provided with or without bag-in/bag-out features. Bag-in/bag-out side-access housings feature a ribbed bagging ring inside the side-access door. A specially designed polyvinyl chloride change-out bag is secured around the bagging ring after initial filter loading. All subsequent filter changes are accomplished through change-out bags. Contaminants are isolated to the inside of the bag to protect site personnel and permit safe handling and disposal of spent filters. A self-adjusting filter seal mechanism prevents filter bypass and maintains a positive seal during normal system operation. The housing can also be utilized without the use of change-out bags, which may be specified where future hazardous contaminants are unknown.

4.4.6 Recommended Design Features

Housing Material: Standard 14-gauge stainless steel.

Unit Construction:

- All pressure boundary joints and seams seal welded,
- Surfaces free of burrs and sharp edges, and

- Reinforced to withstand up to 30 in. wg.

Access Panel:

- Completely hand-removable,
- Handles retained in access panel after removal, and
- Protected panel gasket seal covers entire inner panel surface.

Bagging Ring:

- Two continuous ribs for optimum bag seal,
- Ring depth designed to contain bag during operations, and
- Smooth outer surface and hammed outer edge.

Filter Clamping Mechanism:

- Spring-loaded pressure bars exert uniform clamping force on filed frame;
- Spring loading compensated for any loss of filter gasket memory;
- Positive displacement screw-drive clamping mechanism;
- Leak-tight connection for clamping mechanism on outside of housing;
- Stainless steel clamping mechanism; and
- Over 1/2-inch travel to prevent filter binding.

Filter-to-Housing Seal

- Standard full perimeter flat mounting frame mates to filter gasket; and
- Full seal weld around filter frame.

Filter Removal Rod

- Standard mechanical assist on all multiple wide housings; and
- Operated through bagging ring.

Pressure Taps

- Welded in housing, upstream and downstream of filter,
- 1/2-inch National Pipe Thread half-coupling with plug.

Seals and Gaskets

Seals and gaskets should be installed on panels, and a “knife-edge” gasket sealing surface should be provided. The gasket should be installed in as few pieces as possible to minimize the number of joints and designed to prevent leakage due to miss fitting butt joints. Side-access, bag-out access panels often use gaskets that accommodate the panel to the housing seals. Latches or bolts should be of sufficient quantity and strength to compress the gasket and ensure that the housing leakage criteria are met. Panels should allow access for testing and component inspection. The drawings for each type and size panel should be submitted to the owner for review before fabrication. Panel drawings should show the location and details concerning the hinges, latching lugs, and gaskets.

4.4.7 Differences Between Nuclear Filtration Systems and Commercial/Industrial Filtration Systems

1. The standard design pressure for nuclear systems is 10 to 15 in. wg. compared to 3 in. wg. or less for commercial/industrial systems. In addition, confinement systems can be built to higher pressures, such as 30 to 40 in. wg. without significant cost increases.
2. Nuclear systems are designed, manufactured, and tested to a higher level of QA, such as ASME NQA-1. This includes certified welders, in-process inspections, and material traceability. Several factory tests are standard, such as filter fit, operability of filter locking mechanisms, flatness of filter sealing surfaces or alignment of knife edges and leak testing of each filter sealing surface and overall pressure boundary of each housing and/or system. Test reports are available to the customer for their files.
3. Nuclear systems are designed and built with all-weld construction. All pressure-boundary welds are continuously welded. These systems are built for long life, and RTV sealants are not allowed.
4. Stainless steel is the material of construction for confinement systems versus galvanized construction for commercial/industrial systems.
5. Most nuclear systems incorporate the bag-in/bag-out feature which allows the user to protect their maintenance personnel and the surrounding environment during filter change-out.
6. Nuclear filter housings incorporate filter locking mechanisms that are designed to achieve a filter-to-frame seal that will last throughout the life of the filter, not just when the filter gasket is new.
7. Nuclear systems are designed so that each tier of filters has its own access door. This is needed when the bag-in/bag-out feature is used and is desirable even without the bag-in/bag-out feature.
8. Nuclear systems offer optional in-place test sections.
9. Nuclear systems offer optional separate access panels for medium efficiency filters, which allows the seal of the HEPA filters to be on the upstream side.
10. Nuclear systems now incorporate isolation dampers in many cases. These dampers are now readily available in both “bubble-tight” and “low-leakage” designs.
11. These dampers are designed, manufactured, and tested in the same manner as the filter housings.

4.4.8 Advantages of Stainless Steel Over Heavy Carbon Steel Construction

- Nuclear filtration systems are usually constructed of 14- and 11-gauge stainless steel reinforced externally. The cost of this design is very nearly the same as manufacturing from heavy steel plates and priming/painting for corrosion protection.
- Stainless steel offers much better corrosion protection during installation and use than painted steel.
- Decontamination and cleaning of systems is much easier with stainless steel.
- Modification of systems in the field is much easier with stainless steel. Changes, including welding, can be made without ruining the corrosion protection of the system.
- Stainless steel systems typically weigh less than carbon steel systems.

4.4.9 Side-Access Housings For Radial Flow Cylindrical HEPA Filters

Side-access housings for radial flow cylindrical filters have been designed for the installation of up to 12 plug-in, 2000-cfm filters, for a total of 24000 cfm. Larger installations are possible (**Figures 4.71 through 4.73**). A ring is provided around the filter access to facilitate fitting of the change bag (**Figure 4.74**). An access cover is positioned over the filter. A locator fitted in the cover ensures correct positioning of the filter in the module.

Figure 4.71: Side-Access Housing

Figure 4.72: Side Access Housing

Figure 4.73: Side Access Housing

Figure 4.74: Radial Flow Filter Bag-Out

4.4.10 References

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4.5 External Components

4.5.1 Introduction

External components of an air cleaning system include fans, ductwork, dampers, louvers, stacks, instruments, and other miscellaneous accessories that are associated with the movement, control, conveying, and monitoring of the air or gas flow. This section contains information on the design, fabrication, materials, and codes and standards requirements/ considerations for air cleaning system external components for nuclear facilities.

4.5.2 Ductwork

This section will address the functional design, mechanical design, materials, coatings, supports, acoustic considerations, leakage, vibration considerations, and applicable codes and standards for ductwork for nuclear facilities.

4.5.2.1 Functional Design

The sizing and layout of ductwork to provide desired air distribution, ventilation rates, transport velocities, and other functional requirements of the ventilation system are covered by the standard Z9.2-2018, *Fundamentals Governing the Design and Operation of Local Exhaust Ventilation (LEV) Systems*, published by ASHRAE, ACGIH, and ANSI. The least expensive first-cost duct layout may not be the most economical when the total annual cost of operating the system is considered. Short-radius elbows and other shortcuts in ductwork may seriously increase system resistance, which could require, for example, the use of a larger fan and/or fan motor with resulting higher operating costs, or conversely, they could make it impossible for the system, as installed, to operate at the desired level of performance.

The physical layout of ductwork in a building is often compromised to conform to the confines of a building structure or design. This may be unavoidable when installing new ducts in an existing building. In new construction, consideration should be given to providing adequate space and optimizing the duct layout configuration in the earliest phases of building layout, long before the building design has been finalized. Adequate access to filter housings, fans, dampers, and other components is vital to maintainability and testability. Allowance of adequate space is necessary to achieve well-designed elbows, transitions, and fan inlets.

4.5.2.2 Mechanical Design

The mechanical design of the ventilation system is influenced by the size and quantities of ductwork, construction materials, coatings used for protection against corrosion, construction methods (seams, joints), air-tightness requirements, erection sequence (including consideration of space limitations, post-erection cleaning requirements), and the number and type of field connections and supports (hangers, anchors) required. Consideration should be given to future modification, dismantling, and disposal of contaminated ductwork, particularly in the design of systems for DOE facilities, nuclear power plants, laboratories, experimental facilities, and other operations where change-out of the ductwork or removal for maintenance can be expected. Provision for adding on or changing ductwork is a consideration that is often overlooked in initial design.

Where space permits, a round duct is generally preferred to a rectangular duct because it is stronger (particularly under negative or collapsing pressure); is more economical for the high-pressure construction often required for nuclear applications; provides more uniform airflow; and is easier to join and seal than a rectangular duct. The principal disadvantages of round duct are that it makes less efficient use of building space, and it is sometimes difficult to make satisfactory branch connections. Specific requirements for the performance, design, structural load combinations, construction, inspection, and shop and field fabrication acceptance testing for ductwork, ductwork accessories, and ductwork supports can be found in ASME AG-1, Sections SA and TA.

It is sometimes assumed that all leakage in negative pressure ductwork will be in-leakage, this is not necessarily true. In the event of fire or explosion in a contained space (room, enclosure, hot cell, glovebox, or confinement structure) served by the system, ductwork can become positively pressured, resulting in out-leakage. Out-leakage can also be caused by a rapidly closing damper or by dynamic effects (in a poorly laid-out system) under normal operating conditions.

Under system shutdown conditions or during maintenance, the possibility of out-leakage from normally negative-pressure ductwork also exists. The engineer should consider these possibilities in the design and specification of permissible leak rates for negative-pressure portions of systems.

Ducts should be sized for the transport velocities needed to convey all particulate contaminants without settling. Recommended transport velocities are given in Section 5 of *Industrial Ventilation*. Ducts for most nuclear exhaust and post-accident air cleanup systems should be sized for a minimum duct velocity of 2,500 feet per minute (fpm). ASME AG-1, Section SA, contains requirements for ductwork construction standards. Article SA-4000 contains specific details for the design requirements and methods for calculating ductwork specifications and acceptance criteria. SMACNA and ACGIH provide guidance for duct fittings. Pressure loss due to duct fittings is a design consideration and can be determined by laboratory testing. A uniform velocity profile is important to maintain and can be established by using straight duct 3 to 10 diameters in length both upstream and downstream of the duct fitting in the laboratory. If fittings are closely spaced, the total pressure loss will be higher than the sum of the losses of the individual fittings, due to the nonuniform velocity entering the fittings combined with the loss of any static pressure that may be regained due to the preceding fitting.

For ducts that are fabricated by welding, a minimum of No. 16 U.S. gauge sheet metal is recommended because of the difficulty of making reliable welds in thinner material. Because a nuclear facility may contain spaces of widely differing potential hazard levels, the type of duct construction required may vary from one part of the plant to another. The following questions, as a minimum, should be answered to establish the type of duct construction needed for a particular application.

- Is the system nuclear safety related?
- If the system is nuclear safety related, is the level of radiation that exists in the duct, or the level that could exist in the duct in the event of a system upset, low, intermediate, or high?
- Should the air cleaning system remain operable in the event of a system upset (power outage, accident, malfunction) or can it be shut down?
- Where will the ductwork be located in relation to: (1) the contained space served by the system, and (2) the occupied spaces of the building?[21]
- Is the system once-through or recirculating?
- Is it a safety-related feature system that is intended to mitigate the consequences of an accident?
- What are the environmental considerations (e.g., pressure, temperature, corrosion)?

Depending on the answers to these questions, the duct should be constructed to conform to one of the several grades outlined in **Table 4.13.** Recommended construction requirements are categorized as described below.

[21] Building spaces that are not normally occupied but are occasionally entered for repair or service of equipment, are considered “occupied.”

Level 1. In accordance with SMACNA's "HVAC – Systems-Duct Design*,*" (with the exceptions that button-punch and snap-lock seam and joint construction are not permitted), these constructions are considered unsuitable even for low-pressure construction. Companion-angle or bolted (or screwed) standing-seam transverse joints are recommended. Standing edges of seams or joints and reinforcement should be on the outside of the duct (**Figure 4.75**). Use of Level 1 ductwork is limited to systems serving administrative areas and other non-safety-related applications in which maximum static pressure does not exceed 2 in. wg.

Level 2. In accordance with SMACNA's "HVAC Systems-Duct Design*,*" the use of Level 2 ductwork is limited to systems serving administrative areas, as well as Secondary and Tertiary Confinement Zones in which the radiotoxicity of materials that are handled or could be released to the ductwork does not exceed hazard class 2 (see **Tables 3.3 through 3.5**), and in which negative pressure does not exceed 10 in. wg. The following exceptions apply: (1) button-punch and snap-lock construction are not permitted; (2) only bolted flanged joints, companion-angle flanged joints, welded-flanged joints, or welded joints are permitted for transverse connections; (3) tie rods and cross-braking are not permitted on negative-pressure ducts; (4) standing edges and reinforcement of seams and joints should be on the outside of ducts only; (5) sheet-metal thickness and reinforcement of negative-pressure ducts should be in accordance with ASME AG-1, Section SA-4000, and (6) radiation-resistant sealants (e.g., silicone room-temperature vulcanizing) are used as required in the makeup of nonwelded seams and in penetrations of safety-related ductwork.

Table 4.13: Guide for Selecting Recommended Duct Construction Levels for Various Applications in Nuclear Facilities

Contamination Level and/or Function [b]	*Operating Mode* [c]	*System Type, Duct Location Outside Contained Space, All Systems, Duct Located in–*				*HVAC,* [d] *Supply,* [e] *Recirculating Portion within Contained Space*
		Zone IV	*Zone III*	*Zone II*	*Zone I*	
None, supply, HVAC	A	1	1	2	2	2
	B	1	1	1	1	1
Low (class 4)	A	3	2	2	2	2
	B	1	1	2	2	1
Moderate (class 3)	A	4	3	2	2	2
	B	4	2	2	2	1
High (class 2)	A	4	4	4	4	2
	B	4	4	4	4	2
Very high (class 1)	A	4	4	4	4	2
	B	4	4	4	4	2
Process off-gas	A	5	5	5	4	2
	B	5	5	4	4	2
Controlled atmosphere [f]	A	5	5	5	5	5
	B	5	5	5	5	5

[a] Duct construction level: 1, SMACNA low velocity; 2, SMACNA, high velocity; 3, SMACNA high velocity; 4, welded; 5, pipe or welded duct, zero leak.

[b] Contamination levels from Tables 2.3 for classes 2, 3, and 4.

[c] Operating mode: (A) system to operate following upset or accident; (B) system shutdown in event of upset or accident.

[d] HVAC, building enclosure zones from Section 2.2.9.

[e] Contained space: The building area or enclosure served by the system.

[f] Inert gas, desiccated air, or other controlled medium.

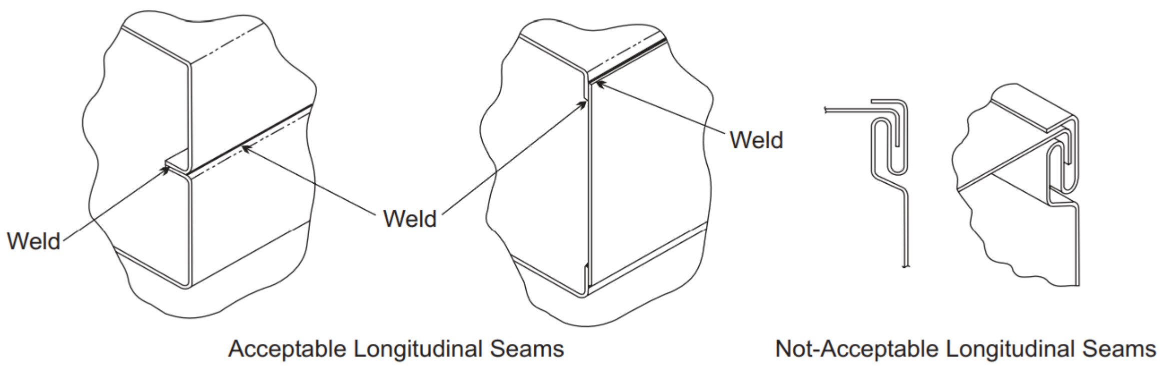


Figure 4.75: Leakage Class 1 Duct Seams

Level 3. This is the same as Level 2, with the exception that: (1) transverse joints are required to have a full-flanged face width and use 1/4-in.-thick gaskets made of ASTM D1056 grade 2C2 or 2C3 cellular neoprene; grade 2C3 or 2C4, 30 to 40 durometer, Shore-A, solid neoprene; or an equivalent silicone elastomer with interlocking notched corners; and (2) nonwelded longitudinal seams, transverse joints, or the entire exterior may have hard-cast treatment (polyvinyl acetate and gypsum tape system) or comparable fire-resistant, corrosion-resistant, radiation-resistant, non-peeling, leak-tight treatment.

Level 4. This level requires all-welded construction with sufficient mechanical transverse joints to facilitate coating (painting), erection, and future modification and/or dismantling. Mechanical transverse joints should conform to **Figure 4.76**. For sheet-metal thickness and reinforcement, see ASME AG-1, Section SA. Specific guidance is provided in nonmandatory Appendix SA-C, Section C-1300.

Level 5. Level 5 ductwork meets requirements for leak-tightness as determined in ASME AG-1, Section SA, Nonmandatory Appendix SA-B or the requirements of the *American National Standard for Pressure Piping*, ASME B31.1, or the ASME Boiler and Pressure Vessel Code.

Methodologies to calculate leak tightness are provided in ASME AG-1 Section SA. Table 4.14 specifies the recommended leakage criteria for each of the duct classes defined in Table 4.13.

See **Figures 4.77 and 4.78** for examples of seams, joints, gaskets, and sealing of companion angle joint corners.

Table 4.14: Recommended Maximum Permissible Duct Leak Rates [a] at 2 in. wg Negative (by methods of ASME N510)

Duct Class	*Maximum Permissible Leak Rate*
Level 1	5 percent of system airflow per minute
Level 2	1 percent of system airflow per minute
Level 3	0.2 percent of volume per minute [b]
Level 4	0.1 percent of volume per minute [b]
Level 5	Zero detectable leak at any test pressure up to 20 in. wg
Recirculating	Leak test not required if totally within contained space served by air cleaning system

[a] Maximum permissible leak rate at pressure greater than 2 in. wg is found from the equation.

$$L_p \times L_2 \sqrt{(P' / 2)}$$

where

L_p = permissible leak at higher pressure,

L_2 = permissible leak at 2 in.wg from table,

P' = higher pressure.

[b] Based on volume of portion of system under test.

Figure 4.76: Acceptable Transverse Joints

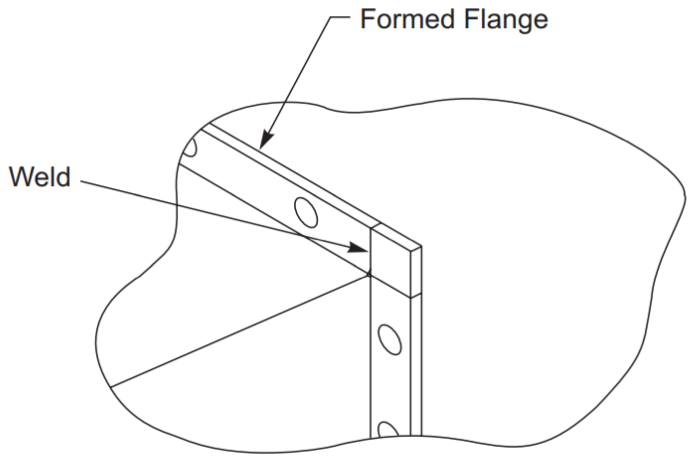


Figure 4.77: Acceptable Formed Flange

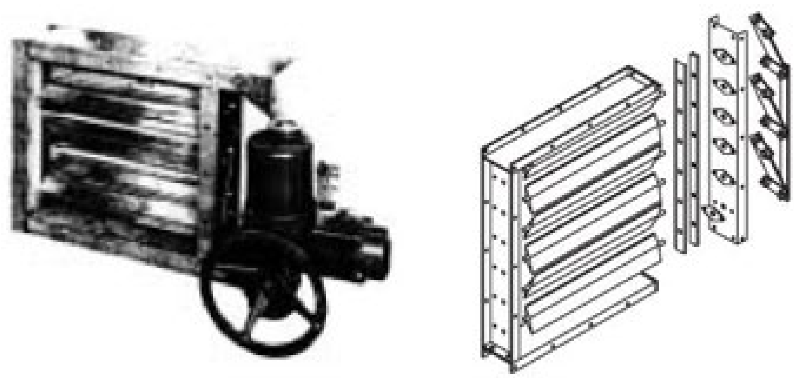


Figure 4.78: Control Dampers

4.5.2.3 Engineering Analysis

When sheet-metal thickness and reinforcements are established from engineering analysis, a design pressure of at least 1.25 times the normal operating pressure is necessary for level 1, 2, and 3 construction. A design pressure of 1.5 times the maximum negative pressure that can exist in the particular run of duct, under the most adverse conditions to which it can be subjected under any conceivable conditions, including the DBA and safe shutdown earthquake, is recommended. The maximum negative pressure is generally the fan shutoff pressure. In the engineering analysis, the following loadings should be considered as applicable to the particular system under consideration:

1. DP across the duct wall, as affected by maximum internal and external pressures that could prevail during testing and under normal and abnormal operating conditions, and any increase or decrease in the pressure due to inadvertent closure of a damper or plugging of an internal component. For ductwork located within the containment vessel of a reactor, the external

pressure under DBA conditions, due to the lag of pressure rise within the ductwork during the pressure transient in the containment vessel, should also be considered (such overpressures may be alleviated through the use of pressure-relief dampers that discharge to the containment space).

2. Effects of extreme natural phenomena on safety class-ductwork.
3. Thermal expansion.
4. Weight of the ductwork, including all attachments.
5. Weight of personnel walking on large ductwork only. Where this situation is likely to occur, duct sections with exposed top surfaces should be capable of supporting a 250-pound weight concentrated midway between the hangers or reinforcement, without permanent deformation. The out-of-roundness produced by such loading could lead to a sudden collapse of round duct when operating under negative pressure.

A maximum allowable stress of 0.7 times the elastic limit is recommended for the design of ductwork maximum deflections under normal operating conditions and should be:

Rectangular duct: 0.125 inch per foot of maximum unsupported panel span in the direction of airflow, but not greater than 0.75 inches. Defection of reinforcement -0.125 inch per foot of span, but not more than 0.75 inches across total span.

Round duct: 0.025 inch per foot of diameter, but not more than 0.5 inch at any point.

4.5.2.4 Engineered Ductwork

When sheet metal or piping thicknesses and reinforcement are established from analysis other than as required by ASME AG-1 for safety systems and nuclear applications, SMACNA standards for commercial grade applications, or other referenced documents, the design should be in accordance with the criterion found in ASME AG-1, Sections AA and SA. In the engineering analysis, the following are examples of loads that should be considered potentially applicable to the system under consideration:

- **Additional Dynamic Loads.** These loads result from system excitation caused by structural motion such as relief valve actuation and hydrodynamic loads due to DBAs.
- **Constraint of Free End Displacement Loads.** These loads are caused by the constraint of free-end displacement and are caused by thermal or other displacements.
- **Dead Weight.** These loads are the weight of equipment and ductwork, including supports, stiffeners, insulation, internally mounted components, externally mounted components and accessories, and any contained fluids.
- **Design Pressure Differential.** These loads are dynamic pressures caused by the DBAs, and intermediate or small break accidents.
- **Design Wind Speed.** These loads are produced by design extreme straight-line winds, hurricanes, tornadoes, or other abnormal, infrequently occurring meteorological conditions.
- **External Loads.** These are applied loads caused by piping, accessories, or other equipment.

- **Fluid Momentum Loads.** These are loads other than those previously listed, such as the momentum and pressure loads caused by fluid flow.
    - **Live Load (L).** Such loads occur during construction and maintenance and other loads due to snow, ponded water, and ice.
    - **Normal Loads (N).** These loads include normal operating pressure differential, system operating pressure transients, dead weight, external loads, and inertia loads.
    - **Normal Operating Pressure Differential.** This is the maximum positive or negative pressure differential that may occur during normal system operation, including startup and testing. These include the pressures resulting from normal airflow and damper or valve closure.
    - **Seismic Load.** These loads result from the operating basis earthquake or the safe shutdown earthquake (SSE). These seismic forces are applied in the direction that produces the worst-case stresses and deflections.
    - **System Operating Pressure Transient.** These overpressure transient loads are caused by events such as rapid damper or valve closure, rapid plenum or housing door closure, or other loads of this type that result in a short duration pressure differential (spike).

Additional information concerning the structural design and supports for ductwork and supports can be found in ASME AG-1, Section AA.

4.5.2.5 Materials of Construction

Ductwork may be constructed from painted or coated carbon steel, galvanized steel, aluminum, stainless steel, or any combination of these materials as required to resist corrosion in the service environment. Glass-fiber reinforced plastic (GFRP) and epoxy ducts have been used in corrosive environments where fire and safety requirements permit, and may be less expensive than stainless steel, lined carbon steel, or epoxy- or vinyl-coated carbon steel. Although the GFRP duct has been approved by the NFPA and UL for commercial and industrial use, even high-temperature resins will soften under brief exposure to temperatures of 350 to 450 $^{\circ}$ F. Softening of the GFRP duct can lead to rapid collapse or distortion, followed by loss of air cleaning function. GFRP and other plastic ductwork should not be used for Level 3, 4, or 5 construction and should be used with caution for Levels 1 and 2.

4.5.2.6 Paints and Protective Coatings

Coating and paint criteria for ductwork are required to be consistent with the corrosion that can be expected in the particular application and with the size of the duct. Corrosion- and radiation-resistant paints and coatings should, as a minimum, meet the requirements of ASME AG-1, and ASTM D5144, *Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants*. Unless special spray heads are used, spray coating of the interior of ducts smaller than 12 inches in diameter is often unreliable because it is difficult to obtain satisfactory coating and to inspect for defects. The interior of a duct sized 8 inches and smaller cannot be satisfactorily brush-painted; therefore, dip coating is recommended. Ducts to be brush-painted should be no longer than 5 or 6 feet to ensure proper coverage.

When special coatings such as high-build vinyls and epoxies are specified, the designer should keep in mind that difficulties in surface preparation, application, and inspection may increase the cost of coated carbon steel to the point that stainless or galvanized steel may be more economical. In addition, stainless or galvanized steel may provide better protection. Note that high-build coatings and paints can be damaged during handling and shipping (as well as during construction, maintenance, repair, and testing/surveillance). Corrosion can begin under such damaged areas without the user's knowledge. Painted and coated ductwork should be inspected carefully during the painting (coating) operation, as well as on receipt. Galvanized coatings and plates should also be carefully inspected, particularly on sheared edges and welds.

4.5.2.7 Supports

Non-safety class ductwork can be hung, supported, and anchored in accordance with the recommendations of Chapter 5 of the SMACNA's *HVAC—Duct Design*, with the following exception: anchors and attachments which rely on an interference-fit between, or deformation of, the base material (concrete roof deck, beam) and the attachment device (as is the case for power-actuated drive bolts and studs and for concrete anchors) should not be used for safety-related ductwork. Support requirements for safety class ducts and other ductwork that should remain in place in the event of an earthquake or major accident should be established by modeling or engineering analysis. Such analysis should be based on the inputs (forces, accelerations) to the building element to which the duct is fastened or from which it is hung (floor, wall, roof deck) that will be produced by the DBA or SSE, or both. Non-Engineered Safeguard Feature ductwork located above or adjacent to other safety class equipment of the facility, which could damage such equipment if it fell, is also subject to this restriction.

4.5.2.8 Thermal Insulation and Acoustic Considerations

Acoustic linings and silencers are not permitted in safety-related ducts or ducts which carry, or may carry, moisture. Acoustic treatment, if required, should be attached to the exterior of the duct.

Thermal insulation, acoustic linings, and duct silencers are not permitted in ducts that carry or may carry moisture, corrosive fumes, or radioactive air or gas. Thermal insulation and acoustic treatment, if required, should be attached to the exterior of the duct and secured in such a manner that it cannot fall off during applicable DBAs.

4.5.2.9 Ductwork Leakage

The leaktightness of ductwork is extremely important, particularly in systems that carry or could potentially carry radioactive material. Duct leakage wastes power and thermal energy (the energy required to heat, cool, or dehumidify air), causes noise, prevents correct airflow to outlets from inlets, makes system balancing and temperature and humidity control difficult, and produces dirt collections and radioactive contamination at leakage sites. Guidance on ductwork leakage is defined in ASME AG-1 Non-Mandatory Appendix SA-B.

Even one percent is excessive for systems that carry or could potentially carry intermediate- to high-level radioactivity. Duct tightness is generally tested by sealing off sections of the system and individually testing them by either the direct-measurement or pressure decay method of

ASME AG-1. With such procedures, a leakage criterion based simply on percentage of airflow can produce anomalous results. By such a criterion, two duct systems build to the same construction standards and having the same volume and surface area, but different airflow could have widely differing permissible leakages. Conversely, if the airflow is the same but the volumes differ, they could have widely differing permissible leakages. For this reason, a permissible leakage based on duct volume or a permissible leakage based on the surface area of the pressure boundary of the section under test is recommended.

Vibration and Flexible Connections

Vibration and pulsation can be produced in an air or gas cleaning installation by turbulence generated in poorly designed ducts, transitions, dampers, and fan inlets, and by improperly installed or balanced fans and motors. Apart from discomfort to personnel, excessive vibration or pulsation can result in eventual mechanical damage to system components when vibrational forces become high or when acceleration forces (e.g., from an earthquake or tornado) coincide with the resonant frequencies of those components. Weld cracks in ducts, fan housings, and component mounting frames may be produced by even low-level local vibration if sustained, and vibrations or pulsations that produce no apparent short-term effects may cause serious damage after long duration.

Vibration produces noise that can range from unpleasant to intolerable. An important factor in preventing excessive vibration and noise is planning at the stage of initial building layout and space allocation to ensure adequate space is provided for good aerodynamic design of ductwork and fan connections. Spatial conflicts with the process and with piping, electrical, and architectural requirements should also be resolved during early design so that the compromises that are so often made during construction, which often lead to poor duct layout and resulting noise and vibration, can be avoided. Ducts should be sized to avoid excessive velocities while maintaining the necessary transport velocities to prevent the settling out of particulate matter during operation.

Fan vibration can be minimized via vibration isolators and inertial mountings. It should be noted that use of these devices should be carefully coordinated with the structural designers because seismic design requirements sometimes prohibit their use. Some structural designers require hard-mounting of fans where continued operation during and after an earthquake should be considered.

To minimize transmission of vibration from fans, flexible connections between fans and ductwork may be employed. These should be designed to resist the high static pressures often incurred in HVAC systems, particularly in those parts of the system under negative pressure, e.g., near the inlet of large exhaust fans. In addition, consideration should be given to the leakage and potential failure that can occur with flexible connections. Commercial applications commonly use heavy-duty canvas. Canvas is not suitable for nuclear facility applications. Consideration should be given to using at least two layers of a leak-proof material (e.g., rubber or neoprene). Finally, the ductwork system should be balanced after installation, not only to ensure the desired airflows and resistances, but also to “tune out” any objectionable noise or vibration that may be inadvertently introduced during construction.

4.5.3 Dampers and Louvers

4.5.3.1 Damper Descriptions

By definition, a damper[22] is a device used to control pressure, flow, or flow direction in an air or gas system. (See ASME N509 and AG-1, Section DA) Different types of dampers can be used, depending on specific functional requirements. **Table 4.15** lists the types of dampers and their functions, and **Table 4.16** lists the damper configurations. **Figures 4.79 through 4.81** are examples of industrial-quality dampers. Selection of the proper damper type and blade configuration is important to achieve the required damper performance. The type and configuration of damper can significantly impact pressure drop, leakage rates, and controllability.

[22] For more information on dampers, see reference document ERDA 76-21, pages 118=120.

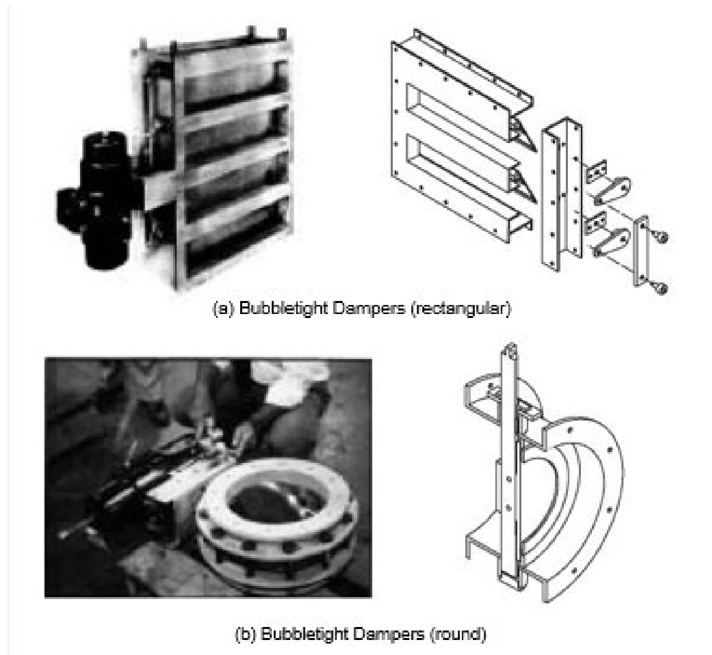
Table 4.15 – Classification of Dampers by Function

Designation	Function
Flow control damper	A damper that can be continuously modulated to vary or maintain a given level of airflow in the system in response to a feedback signal from the system, or from a signal fed to the damper operator via a manually actuated control or switch.
Pressure control damper	A damper that can be continuously modulated to vary or maintain a given pressure or pressure differential in the air cleaning system or in a building space served by the system in response to a pressure signal.
Balancing damper	A damper set (usually manually) in a fixed position to establish a baseline flow or pressure relationship in the air cleaning system or in building spaces served by the system.
Shutoff damper	A damper that can be completely closed to stop airflow through some portion of the system or opened partially or fully to permit airflow (the flow control damper may also serve this function).
Isolation damper	A high-integrity shutoff damper used to completely isolate a portion of a system from a contained space, or from the remainder of the system with a leaktight seal. In the case of confinement isolation, butterfly valves are used in lieu of dampers.
Back-draft or check damper	A damper that closes automatically or in response to a signal to prevent flow reversal.
Pressure-relief damper	A damper that is normally closed but will open in response to overpressure in the system or in the contained space served by the system to prevent damage to the system.
Fire and smoke damper	A damper that interrupts airflow automatically in the event of fire or smoke so as to restrict the passage of flame or smoke through the air system, in order to maintain the integrity of the fire-rated partition or other fire-rated separation.
Tornado damper	A damper that controls airflow automatically to prevent the transmission of wind-generated pressure surges.

Table 4.16 – Classification of Dampers by Configuration

Designation	Configuration
Parallel blade damper	A multi-blade damper with blades that rotate in the same direction (AMCA 500).[a]
Opposed blade damper	A multi-blade damper having adjacent blades that rotate in opposite directions (AMCA 500).[a]
Butterfly damper	A heavily constructed damper, often a valve, that is used in piping or duct systems and is usually round in cross-section and designed for high-pressure service (25 psi minimum pressure rating), with one centrally pivoted blade that can be sealed.
Single-blade balanced damper	A damper, usually round in cross-section, with one centrally pivoted blade.
Single-blade unbalanced damper	An accurately fabricated, often counterbalanced damper, usually rectangular in cross-section, with one eccentrically pivoted or edge-pivoted blade.
Folding blade, wing blade, or check damper	A damper with two blades pivoted from opposite sides of a central post that open in the direction of airflow.
Poppet damper	A weight or spring-loaded poppet device that opens when the pressure differential across it exceeds a predetermined value.
Slide or gate damper	A damper similar to a gate valve, with a single blade that can be retracted into a housing at the side of the damper to partially or fully open the damper.

[a] AMCA 500-D-1998, *Laboratory Methods of Testing Dampers for Rating,* Air Moving and Conditioning Association, Arlington Heights, IL, 1998. Also, AMCA 500-L-1999, *Laboratory Methods of Testing Louvers for Rating*, Air Moving and Conditioning Association, Arlington Heights, IL., Figures 4.80 through 4.82/5.5 through 5.7.



(a) Bubbletight Dampers (rectangular)

(b) Bubbletight Dampers (round)

Figure 4.79: Bubbletight Dampers

Figure 4.80: Backdraft Dampers

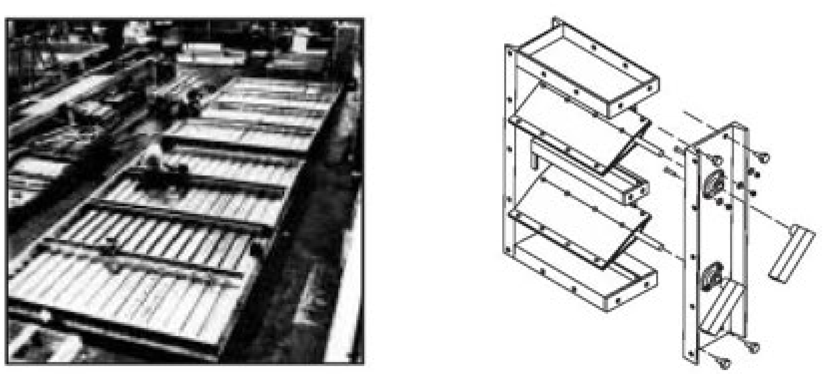


Figure 4.81: Tornado Dampers

The following factors should be considered in the selection or design of dampers for nuclear applications:

- Damper function.
- Construction type.
- Dimensions and space limitations.
- Pressure drop for open position and across closed damper.
- Normal blade operating position.
- Method of mounting damper.
- Blade orientation relative to damper frame.
- Operator type and power source.
- Seismic requirements.
- Requirements for position indicator.
- Limit switches and other appurtenances.
- Damper configuration.
- Permissible leakage through closed damper.
- Space required for service.
- Airstream environmental parameters (temperature pressure relative humidity).
- Damper orientation in duct.
- Airflow direction and velocity.
- Failure of mode and blade position.
- Maximum closing and opening times.
- Shaft sealing method.

4.5.3.2 Design and Fabrication

In conventional air conditioning and ventilating applications, damper procurement has been generally accomplished by specifying little more than the manufacturer's make and model number or “approved equal.” This is inadequate for nuclear and other potentially high-risk applications. Dampers for nuclear applications should be designed and constructed in accordance with ASME AG-1, Section DA.

Clear, concise specifications should be established for mechanical strength, for leakage rate at maximum (DBA) operating conditions, and for performance under required operational and emergency conditions. The operability of linkages should be assured through specification of, and requirement for, cycling at minimum torque requirements under full load. Static testing of the closed damper should be required, where applicable, for those to be used in critical applications to verify strength and leaktightness. All features important to proper operation should be stipulated in detail, including construction materials, permissible lubricants, bearings, blade design and edgings (if permitted), indicating and locking quadrants, supports, operator type and capability, and the accessibility of operators, linkages, blades, and bearings for maintenance. A checklist of the minimum requirements that should be included in a damper design specification is given in ASME AG-1, Section DA.

4.5.3.3 Structural Design

The structural design of dampers should be in accordance with Sections AA and DA of ASME AG-1 for the loading combinations and the service levels specified in the design specifications. The design should be verified by analysis, testing, or a combination of both for those dampers that should remain functional or retain their structural integrity during a DBE.

4.5.3.4 Design and Construction Considerations

A very important part of damper design is determination of damper torque and sizing and selection of damper actuator for the maximum torque. Actuator torque should be selected for a minimum of 1.5 times the damper maximum torque to provide margin and allow for degradation over the life of the damper. Actuators should be evaluated for damper blade movement in both directions, at the beginning of blade movement, and while stroking blades through the full cycle of movement.

The linkage mechanism is required to transmit actuator torque for the blades in order to achieve required leakage performance. Ganging of more than two damper sections for operation by one actuator is not recommended because of the potential problems in transmitting the torque equally to each section and blade. Experience has shown that ganging multiple damper sections has led to twisting of drive shafts and over-torquing of the blades closest to the actuator.

Conversely, ganging two or more actuators per damper can also cause operating problems if the actuators are not synchronized. Some blades may close tighter than others, since not all of the blades are linked together. Damper actuators should be factory-mounted whenever possible. Wherever actuators should be installed in the field or removed for maintenance, manufacturer's installation instructions should identify the necessary amount of retorquing required to achieve design leakage. The actuator shaft, coupling, and blade shaft should be “match-marked” for easy installation.

Seals are another important component of damper design. Dampers designed for low leakage rely heavily on blade and jamb seals to limit leakage. Seals typically are either metal (e.g., stainless steel) or elastomer. Design of seals should consider the required life of the damper assembly to minimize maintenance. For this reason, stainless steel seals are recommended for low leakage dampers in contaminated airstreams whenever possible (see Section DA of ASME AG-1). To control frame leakage, either stuffing boxes or frame cover plates are required.

4.5.3.5 Damper Operators

Damper operators can be one of three types: pneumatic, electric, or electrohydraulic, as described below.

Pneumatic. These damper operators are used whenever controls rely primarily on compressed air (pneumatic) for moving operators or transmitting control signals. Most nuclear facilities only use pneumatic control systems and operators for nonsafety-related applications, as the control air is not usually an assured source during DBAs.

Electric. These damper operators are used whenever controls rely primarily on low voltage electric circuits to transmit control signals and are usually two-position. That is, they are either open or shut and cannot modulate. Most nuclear facilities use electric control systems and operators for safety-related applications because power can be obtained from the emergency electric power and control system.

Electrohydraulic. These damper operators are the same as the electric type described above, except for capacity to modulate. Experience has shown that these operators require significant maintenance to keep them functional. They use an electric control signal to position a hydraulic system that, in turn, positions the damper.

4.5.3.6 Limit Switches

Limit switches are usually provided directly on the damper to detect the open and closed position of the damper blade. The switches are housed in enclosures defined by NEMA 250. The contact rating should be properly selected for the electrical load. The force required to operate the limit switches should be considered to properly size the damper actuator.

4.5.3.7 Performance Requirements

The dampers for nuclear air cleaning systems are required to meet the following performance criteria:

- Seat leakage.
- Frame leakage.
- Pressure drop.
- Closure (or opening) time.
- Fire rating and closure.

Seat and frame leakage is required to meet ASME AG-1, Section DA, for Leakage Class I (low leakage), II (moderate leakage), III (normal leakage), and IV (applications where leakage is of no consideration). Leakage class 0 (zero leakage or bubble tight dampers are typically used at filtration housing inlets and outlets. Seat leakage class should be determined by the engineer based on radiological and health physics analysis and known or estimated airborne concentrations within the duct system. Frame leakage is also based on radiological assessments of the effect of airborne concentrations inside and outside the ductwork, as well as the system configuration. For further guidance on leak class determination, refer to ASME AG-1 Code, Section DA.

Pressure drop of the damper has an important impact on proper system operation. Dampers with high-pressure drop, especially for counterbalanced pressure relief dampers, may restrict airflow and affect space pressurization. The pressure drop characteristics of dampers as a function of airflow rate or velocity indicates the ability of each particular type of damper to control airflow. Preferably, the pressure drop/airflow characteristic should be as close to linear as possible to achieve controllability. Opposed blade damper pressure drop characteristics make this type of damper well suited for flow or pressure control compared to parallel blade or butterfly dampers.

For fire dampers installed within duct systems where the airflow normally flows continuously and the damper is expected to isolate portions of the duct system in case of fire, the damper is required to close under airflow. This requirement has caused difficulties with past damper construction. Different manufacturers' dampers react differently based on their particular design. Some dampers are sensitive to air velocity, such as the shutoff dampers shown in **Figure 4.82**. **Figure 4.83** shows dampers with actuator options. These dampers are more sensitive to duct pressure upstream of the damper when they are closing.

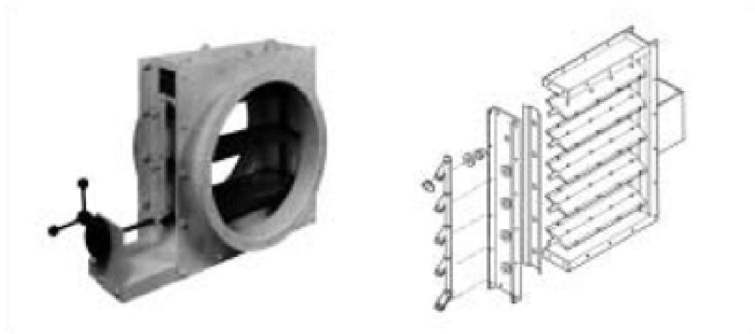


Figure 4.82: Shutoff Dampers

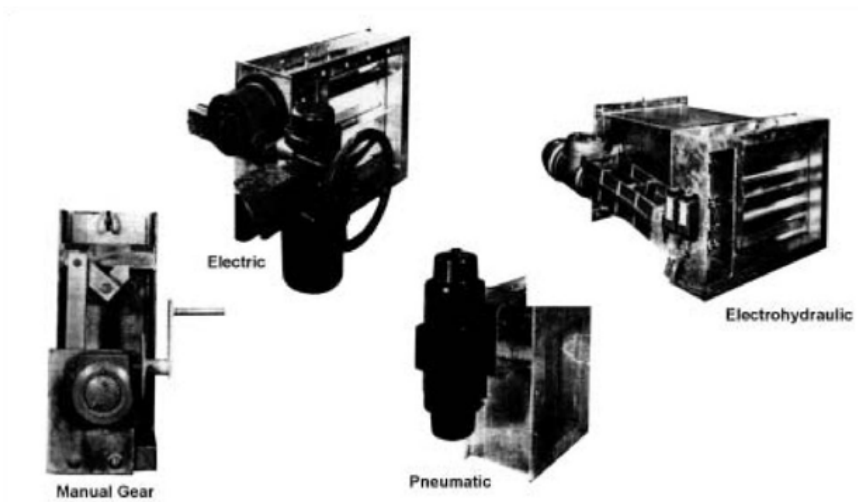


Figure 4.83: Actuator Options

4.5.3.8 Qualification Testing

Qualification consists of performing prototype or preproduction-model tests to verify the design, performance, and operational characteristics of the dampers. In the case of the AMCA-rated dampers, these tests essentially consist of pressure drop and airflow determinations at various degrees of blade opening. The AMCA rating is generally considered sufficient evidence that suitable qualification tests have been performed. For dampers not listed by AMCA, the manufacturer should be required to provide performance data obtained under conditions equivalent to those used in the AMCA 500-D test standard. One particularly important piece of information that can be obtained by qualification testing is the resistance of the fully open damper and the resistance versus blade-position curve from full open to full closed. Resistance should be included in the air cleaning system design calculations in the same manner as other system resistance. Qualification tests are required to be performed prior to fabrication and, if possible, prior to award of a contract.

Production units should be subjected to acceptance tests to verify that the units are in good operating condition and to document their ability to meet performance requirements such as leakage and closure time. Repetition of other qualification tests to demonstrate operational characteristics is generally unnecessary and unwarranted. Dampers should be cycled through the full range at least 10 times, with all accessories attached, to verify the free and correct operation of all parts and the correct adjustment, positioning, and seating of the blades. Maximum time for operation of any of the cycles should be not more than the specified cycle time. Limit switches, if used, should be checked for proper operation. Adjustments should be made as necessary during the test to correct deficiencies. Shop leakage tests for seat and frame leakage should be performed when applicable. Seat leakage testing should be performed after cycle testing is completed. Tests should be performed in accordance with ASME AG-1, Section DA. Because damper operators are generally furnished to the damper manufacturer as a purchased item, a test to verify the torque characteristics of the operator is desirable after installation of the damper in its service position, particularly for control, shutoff, and isolation dampers for all safety-related dampers.

Fire dampers should be qualified for closure under airflow by testing in accordance with AMCA 500-D for both plenum-mounted and duct-mounted configurations. The damper should close completely at maximum airflow rate for various sizes of dampers and for maximum static pressure. Fire and smoke dampers are required to be tested in accordance with UL-555 and UL-555S, respectively, when dampers are required in fire- or smoke-rated barriers.

4.5.3.9 Louvers

The function of louvers is to keep rain, snow, and trash from being drawn into outside air intakes of air handling systems. They can be either fixed-blade or movable-blade design. The vast majority of louvers are of the fixed-blade type. If shutoff or modulation of the airstream is necessary, dampers can be used downstream of the louvers. If operable louvers are used and shutoff or modulation is required, then an operator is required. Architects usually are consulted when specifying louvers because the louvers are located on outside walls or roofs and should blend in with the architectural features of the structure.

It is important to account for the size of the area that the louver blades take up when sizing the louvers. Blades typically take up 50 percent or more of the free area that affects the velocity of the air entering the intake. The usual maximum velocity to prevent water and snow entrainment in the airstream is less than 500 fpm. For louvers on exhaust openings, the velocity is not usually a primary concern, with the exception that the higher the velocity, the higher the pressure drop that has to be accounted for in the system pressure drop calculations.

Finally, louvers are required to meet the same structural requirements as the rest of the air cleaning system. That is, they should meet the seismic loading requirements if they are required to function during and after a DBA. Louver testing should conform to AMCA 500-L.

4.5.4 Fans and Motors

The selection of fans and motors for air treatment systems is a very important part of the design of the systems. An air cleaning unit may be properly designed and arranged, the duct system may be nearly leak-free, dampers may be properly constructed, and controls may be functioning correctly, but if the fan is not sized and selected properly, then the system will not perform its design function. For example, the system resistance should be correctly calculated, the effect of parallel or series fans should not result in surging, and the fan should be selected for the applicable range of airflow and pressure. ASME AG-1, Section BA, contains a list of the design parameters necessary to properly specify and/or select a fan and motor.

4.5.4.1 Fan Types and Applications

Fan types can be classified as centrifugal, vane-axial, and high-pressure blowers. Centrifugal fans can be further classified by blade type as airfoil, forward curve, radial, and backward inclined/backward curved. Vane-axial fans can be classified as either fixed or adjustable pitch. All fans can be furnished as either direct or belt drive. Note that, for nuclear power plant applications, fans located inside the confinement are usually direct drive to minimize the maintenance and adjustments associated with belt drives (because confinement entry is limited).

High-pressure blowers may be required when airflow rates are low (10,000 cfm or less) and pressure is high (10 to 15 in. wg). This may dictate a radial-bladed centrifugal fan selection.

Vane-axial fans are typically used in larger built-up systems when the fan is located as part of the duct system rather than part of the filter housing. Vane--axial fans are best suited for airflow rates greater than 30,000 cfm and pressures less than 10 in. wg. Whenever possible, vane-axial fans should be located downstream of filter units because the fan motor is in the airstream.

Fans should be selected such that fan power requirements are non-overloading (the fan brake horsepower does not increase with increasing airflow) unless provisions are made to prevent overloading the motor (e.g., airflow control and high limit trip). Radial-bladed and forward-curved centrifugal fan power increases with increasing airflow.

Belt drives should be used only in areas that are accessible for maintenance during normal and accident conditions. Multiple belts should be provided so that loss of one belt does not impair system function. For constant flow systems, variable pitch sheaves should be changed to fixed pitch sheaves after air balancing. Belt driven fans that should operate during and after dynamic events (e.g., seismic events) should be qualified for operation by testing.

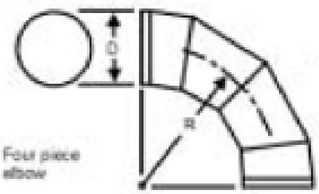
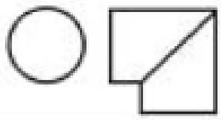
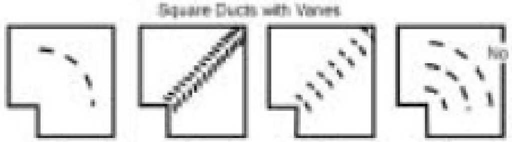
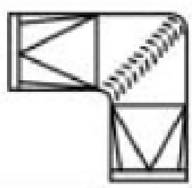
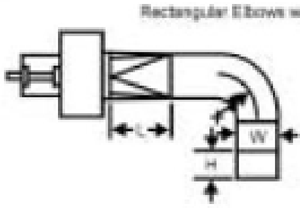
Fans for general heating, ventilating, and air conditioning (HVAC) duty (e.g., air supply systems and small exhaust systems), are selected using the guidance for such systems found in sources such as the ASHRAE *HVAC Applications Handbook*, and the ASHRAE *Systems and Equipment Handbook*. These systems can range in size from a few hundred cfm to over 100,000 cfm and are usually low-pressure systems (less than 5 in. wg).

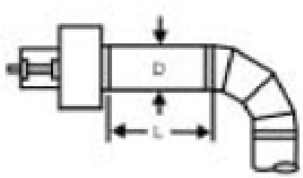
4.5.4.2 Fan Performance

The previous use of information in the ASHRAE *Handbook of Fundamentals* covered methods for designing industrial exhaust systems and balancing branch duct resistance either by utilizing balancing dampers or by sizing ductwork. For systems handling highly radioactive particulate, self-balancing is recommended to eliminate particulate accumulation in the duct system. This recommendation should be considered against the potential for changes to duct runs during installation. The development of computer aided design tools has replaced the preparation of design documents such as a total pressure grade line, summarizing the branch and main duct pressure drop for each fan system. Published guidance by ASHRAE and SMACNA provides guidance on how to determine system resistance and fan pressure requirements, such as Chapter 21, "Duct Design," in the ASHRAE Handbook.

System Effect Factors

Figure 4.84 shows the effects of various inlet conditions on fan performance and the resulting increase in fan capability (fan static pressure) to compensate for these effects. Too often, these effects are not considered when calculating fan requirements, with the result that neither the fan nor the filters can perform to the desired design levels. Outlet connections also affect fan performance, as indicated in **Figure 4.85**. Drastic transitions such as elbows should be avoided directly upstream and downstream of fans. Simply adding an evase **(**flow diffuser that converts kinetic energy into pressure energy) downstream of the fan can have significant impacts in terms of fan static pressure and energy efficiency over time.

DESCRIPTION		PERCENT LOSS IN CFM IF NOT CORRECTED	PERCENT INCRESE NEEDED IN FAN SP TO COMPENSATE
 Four piece elbow	Three piece elbow R/D = 0.5	12	30
	1.0	6	15
	2.0	5	11
	6.0	5	11
	Four piece elbow R/D = 1.0	6	13
	2.0	4	9
	6.0	4	9
	Five piece elbow R/D = 1.0	5	11
	2.0	4	9
	6.0	4	9
	Mitered elbow	18	42
Square Ducts with Vanes  A B C D	No Vanes	17	45
	A	8	18
	B	6	13
	C	5	11
	D	4	9
	Round to Square to Round	8	18
Rectangular Elbows without Vanes* 	In all cases use of three long, equally spaced vanes will reduce loss and needed sp increase to 1/3 the values for unvaned elbows.		
The maximum included angle of any element of the transition should never exceed 30°. If it does, additional losses will occur. If angle is less than 30° and L is not longer than the fan inlet diameter, the effect of the transition may be ignored. If it is longer, it will be beneficial because the elbow will be farther from the fan.	$\frac{H}{W}$ - 0.25, and $\frac{R}{W}$ = 0.5	7	15
	1.0	4	9
	2.0	4	9
	$\frac{H}{W}$ - 1.00, and $\frac{R}{W}$ = 0.5	12	30
	1.0	5	11
	2.0	4	9
	$\frac{H}{W}$ - 4.00, and $\frac{R}{W}$ = 0.6	15	39
	1.0	8	18
	2.0	4	9



Each 2 1/2 diameters of straight duct between fan and elbow or inlet box will reduce the adverse effect approximately 20%. For example, if an elbow that would cause a loss of 10% in CFM or an increase of 23% in fan SP, if on the fan inlet, is separated from the fan by straight duct, the effect of the duct may be tabulated thus:

No duct	Loss = 10% - SP needed = 23%
L D = 2 1/2	Loss = 8% - SP needed = 19%
5	Loss = 6% - SP needed = 13%
7 1/2	Loss = 4% - SP needed = 9%
10	Loss = 2% - SP needed = 4%

Figure 4.84: Effect of Fan Inlet on Performance

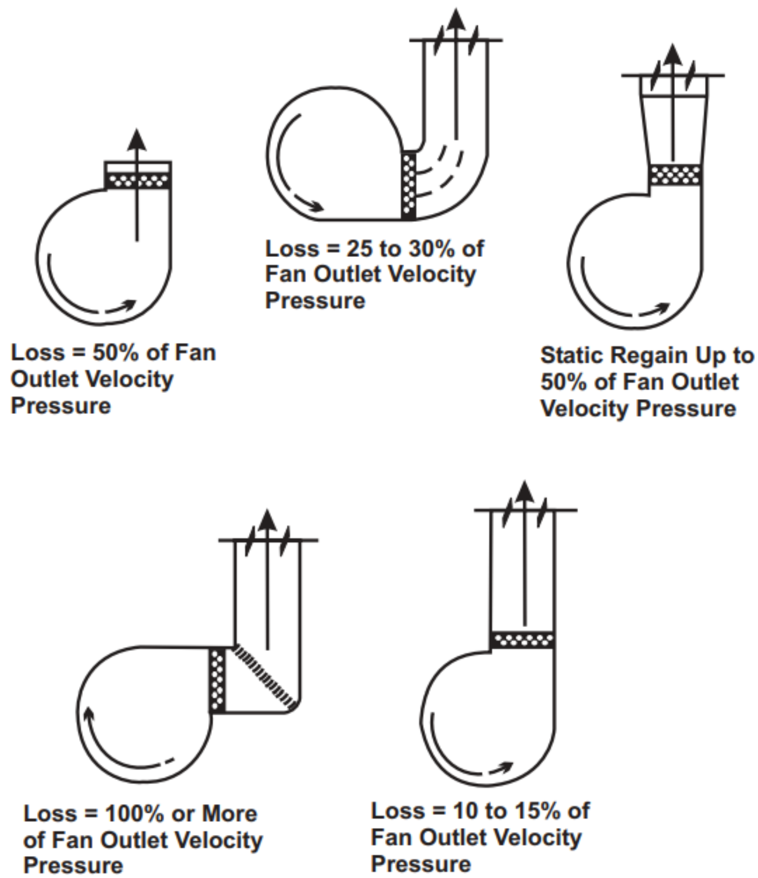


Figure 4.85: Effect of Fan Outlet Connection on Fan Performance

Figure 4.85 illustrates inlet and outlet conditions that will affect fan performance and are important factors in initial fan selection. System effects are the losses in fan performance that result in the fan being installed in a less than ideal configuration. These effects should be considered by the designer to obtain a realistic estimate of fan performance under actual operating conditions in the field. Publication 201, "Fans and Systems," contained in the AMCA Fans and Air Systems Application Manual," provides information on system effect factors that should be considered in the design calculations.

Figure 4.86 illustrates a deficient fan-system interaction resulting from one or more undesirable design conditions. It is assumed that pressure losses in the duct system were accurately estimated (point 1, curve A), and a suitable fan, based on published ratings, was selected for operation at that point. However, no allowance was made for the effect of the fan connections on fan performance (the interaction between the fan and the system as designed). To compensate for the system effect (capacity loss resulting from unfavorable interaction between the fan and its connections), a system effect factor should be added to the calculated system pressure losses to determine the actual system characteristic curve. It will then be possible to select the fan required to produce the required operating characteristics.

Testing to establish the capability of the fan in a nuclear air cleaning system, as originally installed, is recommended by ASME AG-1, Section TA. Planes of measurement, measurements to be made, average test readings, calculation of test results, and corrections to overcome deficiencies disclosed by the tests are all covered in detail. It is preferable to apply such system

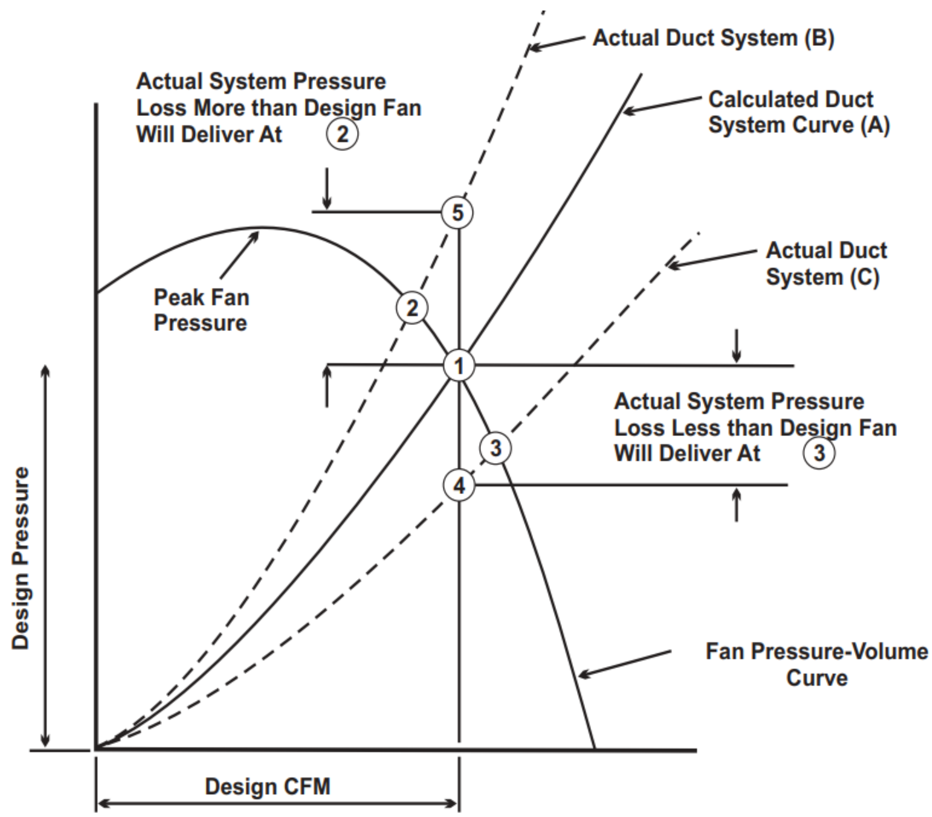


Figure 4.86: Deficient Fan-System Interaction

effect factors before selection, purchase, and installation of a fan to prevent the incorporation of unfavorable features into the system design. In applying system effect factors, it should be recognized that those factors given in the AMCA manual are only guidelines and general approximations, although many have been obtained from research studies. Fans of different types and fans of the same type that are made by different manufacturers will not necessarily interact with the system in the same way. It is necessary, therefore, to apply judgment based on experience using system effect factors.

Fans play an important role in establishing a well-mixed sampling location so that representative samples according to ANSI/HPS N31.1-2011 are obtained for qualification, in-place testing and in-service testing of the fans and ventilation systems.

Fan and System Curves

A major requirement for a fan operating in a high-efficiency air cleaning system is its ability to perform safely and efficiently over a much larger variation of resistance than more conventional ventilation systems. This variation of resistance is caused by dust loading of the HEPA filters and may double from the time of filter installation to the time of filter change or may increase as much as five times in some systems. The increase in resistance across the HEPA filters is usually the major factor influencing the pressure flow relationships of high- resistance versus airflow are represented by characteristic curves such as curves A, B, and C of **Figure 4.86**. The volume of air that can be delivered by the fan is determined by the intersection of the fan and system characteristic curves. The flow represented by this point of intersection is the only flow that can be delivered by the fan under the given operating conditions. In most cases, a fan with a steeply rising characteristic (curve A, **Figure 4.86**) is desirable to maintain reasonably constant airflow in the system over the entire life of the HEPA filters. If a fan with a broad, flat characteristic is chosen, it will be less capable of delivering the required airflow as the filters become dust-loaded (curve 1 to curve 2), and either system performance (airflow) or filter life will have to be sacrificed. Any decrease in filter life will, of course, be accompanied by higher change frequency and corresponding increases in operating and maintenance costs. If a pressure-equalizing device (damper) is installed to balance system pressure against filter pressure drop in order to maintain a constant pressure-airflow relationship in the system, a penalty in operating (power) costs will result.

4.5.4.3 Fan Leakage Flexible Connection Leakage

Vibration created by fans, motors, and drives can be isolated by using flexible connections between the fan and ductwork on both the fan discharge and suction. Where such connections are used, a frequent problem has been tearing and pulling-out of the fabric (from which the flexible connection is made) at the connector clamp and an associated increase in leakage. The flexible connection design shown in **Figure 4.87** can overcome these problems. The fabric shown consists of two layers of 30-ounce neoprene-impregnated fiberglass cloth, lapped so that the ends are displaced from one another, and glued. Flexible materials reinforced with fiberglass or other products are also available. Flexible connections should be periodically inspected (visually) to ensure the connection is intact (no tears or holes). Eliminating leakage at the flexible connection is important to the effective operation of the unit. With the fan located properly with respect to the contamination concentration, the leakage on the suction side should not impact personnel dose but could impact system effectiveness by reducing the flow rate of the discharge leakage through the connection at the point of contamination. This could affect the local derived air concentration (DAC) levels, depending on the relative concentration between the space and the duct.

Flexible connections should be qualified for the temperature, pressure, relative humidity, and contaminants that will be encountered. However, since the flexible connections are exposed to continuous stresses due to airflow turbulence and fan vibration, the flex connections should be replaced frequently throughout the life of the plant. A maintenance frequency should be planned based on the results of the periodic surveillance inspections for each specific fan.

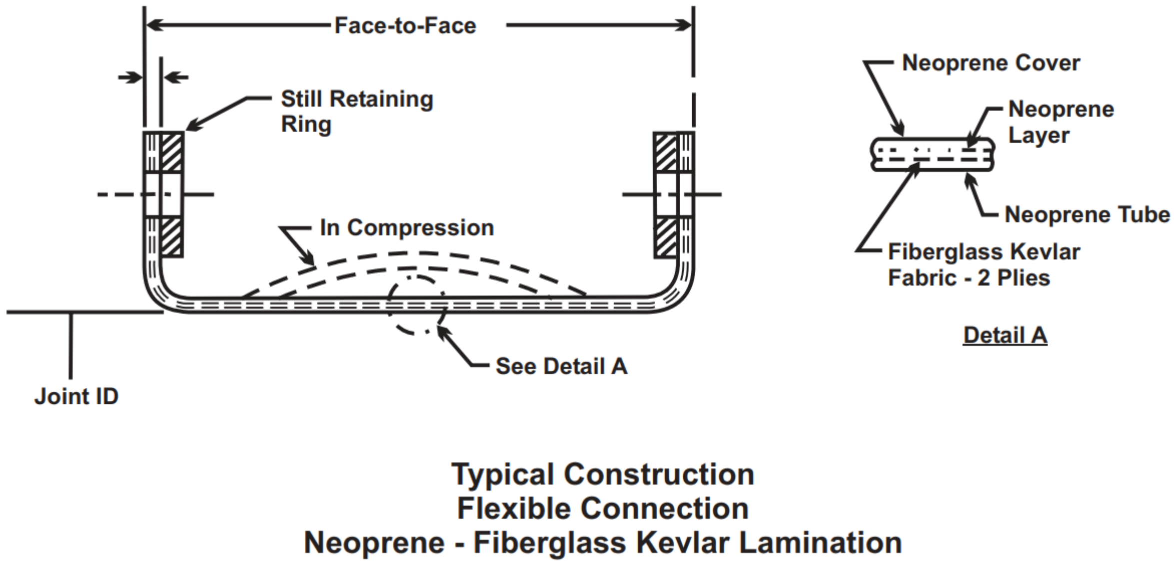


Figure 4.87: Flexible Connection Design

Shaft Leakage

Fan shaft penetration of fan housings should be designed to minimize leakage. When the fan is located properly so that leakage does not impose a contamination burden on the space, or the fan is located in the space supplied by air from the fan, then no special sealing is required. However, if there is a potential for a significant increase of DAC levels or a significant impact on airflow rate from the space the air is being induced from, then shaft seals should be installed. Shaft seals should limit leakage to 0.01 percent of design airflow rate per inch of fan operating pressure or 0.5 cfm, whichever is greater. The safety analyses should be consulted for allowable leakage for safety class designs, especially for systems with multiple HEPA filter banks. If the fans are located downstream of the HEPA banks, or if in a potentially contaminated area, extremely small levels of fan shaft in-leakage (< 0.001 cfm) may be unacceptable for maintaining the desired level of removal.

Multiple Fan Installation

Installation of two fans in series is sometimes desirable where a steeply rising pressure-airflow characteristic is needed. However, caution should be exercised in such a design. In theory, the combined pressure-volume characteristic of two fans operating in series is obtained by adding the fan pressures at the same volumetric airflow, as shown in **Figure 4.88**. Care should be taken in designing the connection between the fans, because a significant loss of efficiency can occur in the second-stage fan due to nonuniform airflow into its inlet, particularly if the two fans are closely coupled. Manufacturers may be able to install two fan wheels in series within a single housing, which is longer than a single-wheel fan. Fan manufacturers should provide certified fan performance curves for these multistage fans.

For fans installed in series and not in a common plenum, a bypass duct is recommended so that a failed fan can be isolated from the system for repair and to avoid additional system resistance due to the failed fan wheel. Two or more fans are often operated in parallel to move large volumes of air, to enhance the control of segmented air cleaning facilities, or to limit the installed capacity (filters, adsorbers) of any one unit of the air cleaning system. The combined volume-pressure curve in this case is obtained by adding the volumetric capacity of each fan at the same pressure (**Figure 4.89**).

One concern in parallel fan installations is that some fans have a positive slope in their characteristic curves to the left of the peak pressure point (**Figure 4.90**). If the fans are operated in the pressure-volume regime of this positive slope, unstable operation may result. This is shown by the closed loop to the left of the peak pressure point in **Figure 4.90** (this loop is obtained by plotting all of the possible combinations of flow at each pressure). If the system's characteristic curve intersects the fan characteristic in the area of this loop, more than one point of operation is possible; this may cause one of the fans to handle more of the system airflow than the other and result in a motor overload. The unbalanced flow conditions tend to shift rapidly so that the fans intermittently load and unload. The pulsing that results from such loading and unloading generates noise and vibration and may cause damage to the fans, motors, and ductwork. In addition, if more than two fans are operated in parallel, the designer and/or fan manufacturer should review the fan performance curves and system curves for possible combinations of fans, assuming one or more are out of operation for maintenance,

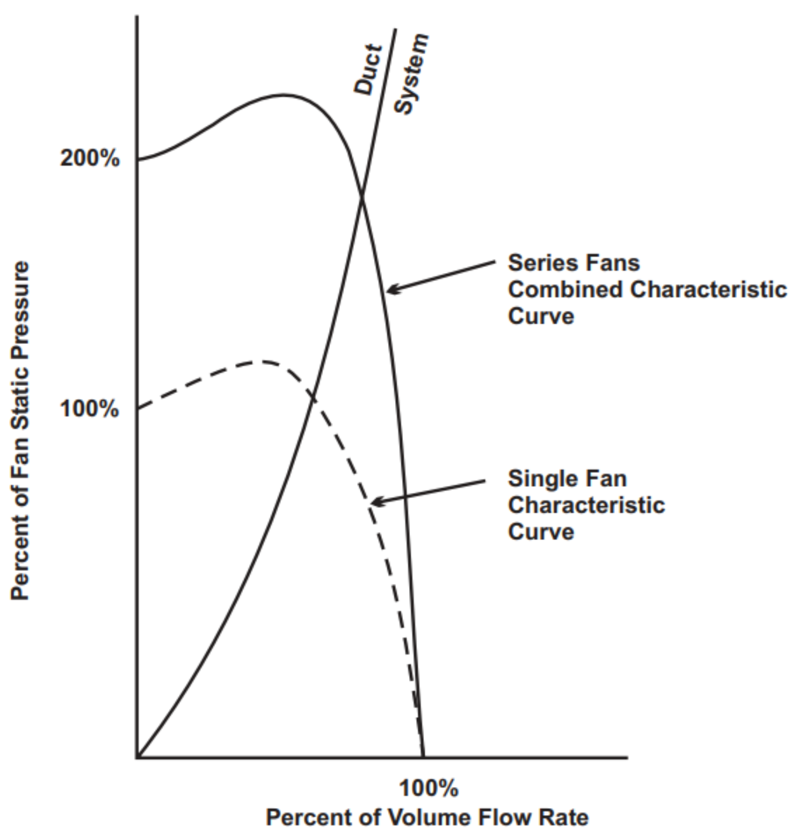


Figure 4.89: Typical Characteristic Curve of Two Fans Operating in Series

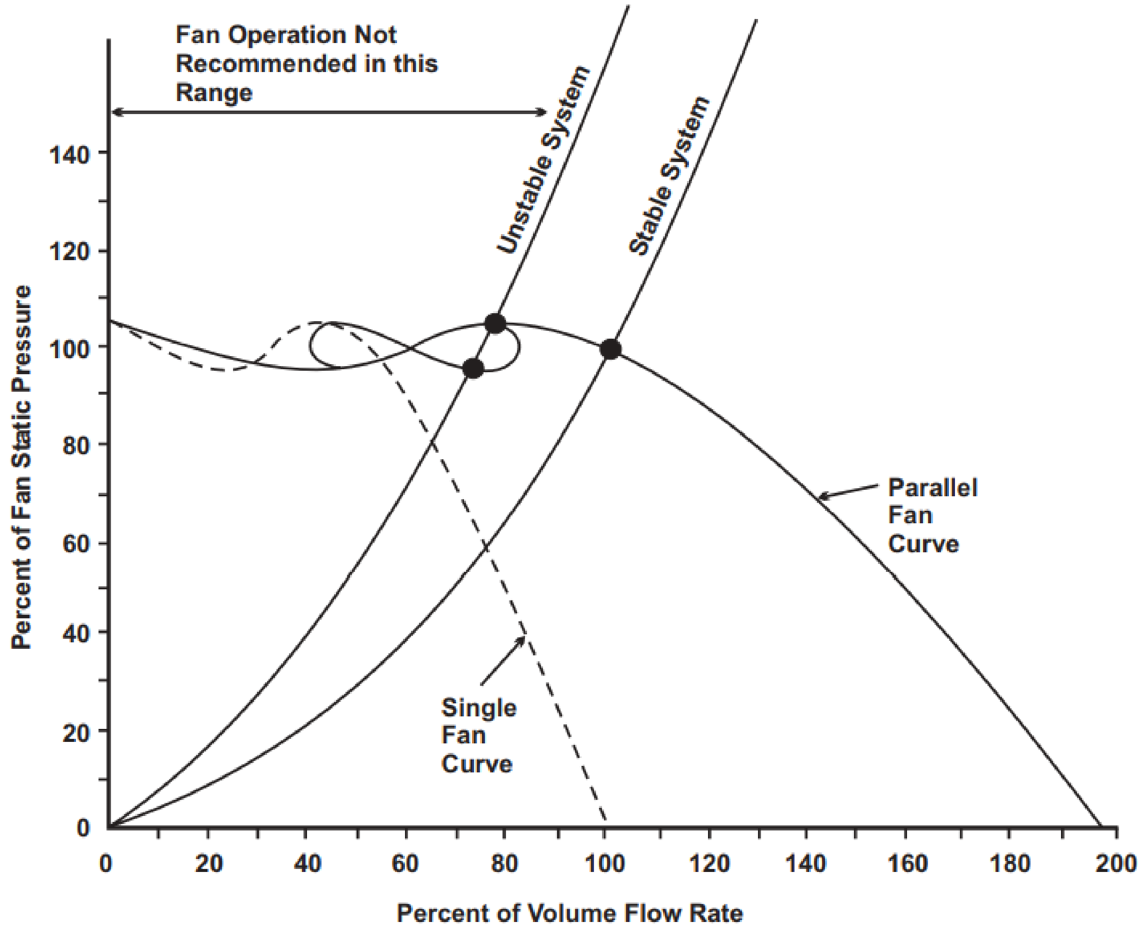


Figure 4.90: Parallel Fan Operation

filter change-out, or repair. Fans should be selected for stable flow throughout the service conditions (clean to dirty filter pressure drop) and combinations of fans.

Mounting

Mounting of the fan and motor on a common base designed for isolation of vibration is recommended. The fan and motor are mounted on a concrete base that acts as an inertial pad to limit the amplitude of vibration and to dissipate vibrational energy. The pad is mounted on spring isolators, which will provide a high degree (99 percent or more) of vibrational damping.

For some systems, positive amplitude limiters may be required to restrain the base from excessive movement under extreme conditions (such as the accelerations imposed by a DBE). Some designers require hard-mounting of fans where seismic requirements and continued operation during and after an earthquake should be considered. Infiltration may be reduced by designing a tighter building structure. Careful balancing of the fan shaft and impeller to minimize vibrations that cannot be isolated via installation design is particularly important in this latter design.

Building Pressure Effects

Sizing of supply and exhaust fans should recognize the interaction of these fans with each other in order for nuclear air-cleaning systems to maintain proper space pressure relative to surrounding areas.

In push-pull systems (systems containing both supply and exhaust fans that operate at the same time), the space pressure depends on the relative capacity of the fans. If supply flow exceeds exhaust, the space is positive. If exhaust exceeds supply, the space pressure will be negative. When space pressure is required to be negative, the exhaust fan capacity should compensate for infiltration, pressure surges, high wind effects (pressure variations in the building and ductwork due to variable wind conditions exterior to the building), as well as temperature variations between supply and exhaust air, to eliminate any possibility of over pressurizing the building via the supply fans. The pressure effects of other building ventilation systems serving adjacent spaces should also be considered.

Improper fan operation can be avoided by carefully evaluating system pressure drops and interactions under all predictable operating conditions, and by specifying the type and size of fan that matches the demands of the duct system as installed. Control should be exercised over the installation of ducts and fans to prevent field compromises that can reduce the ability of the system to perform as intended.

4.5.4.4 Fan Construction

AMCA has developed standards for fan construction. In general, these standards are applicable to the construction of fans for nuclear air cleaning systems. In addition, fans for nuclear air cleaning systems should be constructed in accordance with ASME AG-1, Section BA, which defines additional specific features that are required for nuclear applications.

4.5.4.5 Qualification and Testing

Fans for nuclear air cleaning systems should be qualified, rated, and tested for the following factors:

- Performance.
- Structural capability.
- Vibration.
- Sound.
- Leakage.
- Environmental conditions.

ASME AG-1 Code, Section BA, provides inspection and testing requirements for fans and motors. AMCA 210 defines the methods for testing fans for rating purposes. ASME AG-1 Section TA provides field testing requirements, and ASME/ANSI N511 provides guidance for in-service testing. Environmental qualification and testing of electrical components should be in accordance with IEEE-323, *Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations*. Standard motor tests that include "First Unit of a Design" and "Routine Motor Tests" (all motors) should be performed in accordance with IEEE 112 and ASME AG-1, Section BA. Documentation of test results should be prepared in accordance with the above references.

4.5.4.6 Fan Reliability and Maintenance

Operational reliability is an important consideration in selecting fans for nuclear applications. Even when the system is planned for part-time or intermittent operation, continuous operation may be required after the system goes into service. This should be a consideration in the design and procurement process.

Adequate access for maintenance and service is imperative, and fans installed above floor level should have sufficient clear space around and below for personnel to get to them with the aid of ladders and/or scaffolding. Permanently installed ladders and galleries are recommended to ensure ease of access for maintenance and repair. Procedures should be developed for periodic, preventative maintenance based on the fan manufacturer's recommendations and actual field operational experience. These procedures are critical for the reliability of the fan and its operational readiness in the event of a DBA.

4.5.4.7 Special Duty Considerations Temperature, Pressure, and Humidity

Fans are constant-volume machines whose airflow rate can be impacted by variables such as temperature, pressure, and relative humidity because they affect the mass flow rate of air being moved. It is necessary to identify and specify these variables for normal and abnormal conditions so the fan manufacturer can make proper fan and drive selections. In addition, temperature, pressure, and humidity can affect fan components such as the bearings and bearing lubricant. Therefore, the fan manufacturer should know these properties to make proper material selections for fan components.

Material Moving

Fans that are required to move particulate matter require identification and specification of the properties of the airstream. Particulates can be abrasive, require high transport velocities, or be composed of corrosive, explosive chemicals. These materials can affect the fan wheel, casing, shaft, bearings, bearing lubricant, and the fan manufacturer should know these properties to make the proper material selections for the fan components.

Contaminated Air Moving

Fans that are required to move contaminated air (primarily radioactive particles in nuclear facilities) also need to have these properties identified and specified. Radioactive contaminants can affect some of the materials used in fan construction (primarily bearing lubricants) or in ductwork components that are attached to the fan (flexible connections and gaskets). Another primary concern is contaminated leakage into or out of the fan. The fan manufacturer should know the properties of the contaminated air so that proper material selections and leakage provisions can be provided.

4.5.5 Air Intakes and Stacks

4.5.5.1 Locating Intakes and Stacks

The design and location of exhaust stacks and air intakes have an important bearing on system performance. If air intakes are too close to the ground, blowing sand, dust, grass clippings, and other particulate matter may be drawn into the building, plugging the supply-air filters and/or reducing their life. Exhaust fumes from vehicles passing nearby or standing close to the building may also be drawn into the building. Intakes should be sited to protect them from snow, ice, and freezing rain during the winter, and baffles or louvers should be provided to give protection from driving rain and to minimize the effect of wind. Architectural louvers should be designed and tested in accordance with AMCA 500-L for pressure drop and water penetration. Wind pressure can have an appreciable effect on flow rates in a low-head ventilation system and can cause pulsations that may disrupt or reverse differential pressure conditions between the zones of the building.

Average wind direction and weather conditions that are likely to cause stack discharges to areas close to the ground (known as looping and fumigation) should be analyzed when establishing the location of stacks and intakes. This analysis is necessary to ensure that stack effluents cannot be drawn back into the building or into an adjacent building. Intakes should be located upwind of stacks (based on the prevailing wind for the site). Intakes downwind of shipping docks may be prone to drawing vehicle exhaust fumes into the building. Intakes located close to a roof or in a roof penthouse may have the same problems as those located too close to the ground due to aerodynamic building downwash.

Considerable guidance on the location of intakes and exhaust stacks is given in Chapter 16 (“Airflow Around Buildings”) of the 2017 ASHRAE *Handbook of Fundamentals.* The flow around adjacent structures is complex and is affected not only by a building’s dimensions, but also by the topography surrounding a building. Additional guidance can be found in Section 6.8.3 of DOE-HDBK-1224-2018, *Aerodynamic Effects of Buildings*. Proper consideration should be given to wind (speed/direction) and stack flow patterns for a single rectangular building. Air intakes located within the recirculation zone or contaminated region will re-entrain the effluent. Computational fluid dynamics models could be developed to determine flow patterns around the building.

Intakes located on the sides of buildings may also be affected by the pressure (positive or negative) at those points. Ventilation systems should be designed and sized to account for this pressure, especially if a negative pressure is possible for a supply system or a positive pressure may exist for an exhaust system. A static pressure at least equivalent to the surface pressure associated with the design wind velocity for the specific location should be included in system pressure calculations. Pressure controls also should be used to regulate flow fluctuations occurring due to the wind velocity and surface pressure.

In northern climates, intakes should be designed to minimize snow entrainment. Even at low velocity through louvers, snowflakes can clog medium efficiency filters located close to the louvers. In addition, hoarfrost can form on operable louvers and prevent their operation. Hoarfrost can also block louver screens. To prevent such potential problems, it may be advisable to heat the areas adjacent to the louvers. If snow is blown or otherwise induced into the ventilation system and no provision is made for settling or dropping out snow or ice particles, the filters can become clogged.

The following factors should be considered when locating stacks:

- High stack velocity is a poor substitute for proper stack location. A stack velocity to wind velocity ratio of 4:1 is required to discharge effluent out of the recirculation cavity boundary for a stack located flush to a roof.
- If an enclosure is needed around the stack, the stack should extend above the building zone of the enclosure and should not be flush to the enclosure.
- A circular stack shape is recommended. Nozzles may be used at the tip of the stack to increase exit velocity.
- Stack caps that deflect effluent downward are not recommended. High exit velocities will prevent rain from entering. Some drainage provision is recommended instead of rain caps.
- For both stacks and intakes, provision should be made for drainage of water or melted snow that may be induced into the system.
- Stacks should be located where they cannot damage the facility they serve or other important nearby structures.

4.5.5.2 Sizing Intakes and Stacks

Air intakes should be sized to minimize pressure drop and maintain air velocity through the free area below the velocity at which water droplets may be entrained (usually less than 500 fpm). Manufacturers should be requested to provide pressure drop and water penetration test results for louvers tested in accordance with AMCA 500-L.

Sizing of stacks is even more important to prevent re-entrainment of the release due to the aerodynamic effects of the facility and ensure proper dispersion. Additional guidance is contained in Section 6.8.3 of DOE-HDBK-1224-2018, *Hazard and Accident Analysis Handbook*. Dispersion calculations should be performed to determine whether elevated, ground-level or mixed mode effluent release is required to maintain offsite personnel exposures within the plant environmental permit, Technical Safety Requirements (TSR), and applicable Federal, State, and local regulations. The term “elevated release” typically refers to stacks that are situated well above the tallest building. Ground level releases are typically exhaust points located on the building wall or roof. “Mixed mode” refers to stacks that are marginally higher than the tallest building. Additional guidance on mixed mode releases can be found in USNRC Regulatory Guide 1.111, *Methods for Estimating Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases from Light-Water-Cooled Reactors.* When calculating atmospheric pressure change and missiles from a hurricane and tornado, and other missile barrier needs, the need to prevent access by unauthorized personnel should be considered. (See DOE-STD-1020-2016 and DOE-HDBK-1220-2017.)

The exit velocity of the stack should be at least 1.5 times the wind velocity to minimize downwash. Stacks may need to be partitioned or sectioned if multiple systems discharge into the stack and individual system operations do not occur at the same time or frequency. A minimum stack exit velocity of 3,000 fpm is recommended to prevent downwash from winds up to 22 mph, to keep rain out, and to prevent condensation from draining down the stack. If condensation may be corrosive, a stack velocity of 1,000 fpm is recommended with a drain at the bottom to remove condensation and a nozzle at the top of the stack to maintain high exit velocity. However, high stack exit velocity does not remove the need for a stack meeting GEP height requirements. The structural design of stacks for wind gusts up to 115 mph should be considered based on the climatology of the particular site as identified in ASCE 7.

4.5.5.3 Structural Design Aspects

Louvers designed for conventional ventilation and air conditioning applications are usually acceptable for use as air intakes for nuclear air cleaning systems. If louvers are required to remain in place following DBAs (such as earthquake or tornado), they should be designed in accordance with the requirements of ASME AG-1, Section DA.

Historically, stacks were designed in accordance with the requirements of ASME AG-1, Section AA, and ASME STS-1-2000, Steel Stacks. Most stacks today are lined Fiberglass-Reinforced Plastic (FRP) stacks. Guidance can be found in ASCE/SEI 52-10, *Design of Fiberglass-Reinforced Plastic (FRP) stacks.* Loading due to design basis winds, tornadoes, hurricanes, and other abnormal meteorological conditions should be included in the structural analysis, as well as dynamic loads due to seismic excitation whenever applicable. Even if not required to remain functional, stacks should be designed so they do not collapse and cause unacceptable damage to surrounding structures, systems, or components. Stiffeners for stacks should be located on the outside to avoid providing ledges for potential “buildup” of radioactive material, even though the air has been “cleaned.” The structural design of stacks should be qualified by analysis in accordance with AG-1, Section AA. Care should also be exercised in the structural design so that stacks do not “crimp” or bend and cut off the effluent flow if they are subject to a strike by wind-generated missiles.

Openings in nuclear-safety-related structures for either air intakes or exhaust stacks should be protected from the effects of high wind or tornado missiles if such a missile could damage a nuclear-safety-related component and prevent it from functioning. Missile protection typically involves utilizing staggered building wall structures or a lattice of steel bars to prevent a straight-through missile path. Sufficient space should be allocated for these intake structures. Free-area reduction caused by using staggered walls or steel bars in the openings should be considered when sizing the openings, particularly intakes, so that velocity requirements are not exceeded.

For metal exhaust ducts, see the American Conference of Governmental Hygienists, *Industrial Ventilation, A Manual of Recommended Practice* (2013), Chapter 5, “Exhaust System Design Procedure.”

4.5.6 Instrumentation and Control

4.5.6.1 Codes and Standards Requirements

Instrumentation and control systems, components, and equipment should meet the requirements of ASME AG-1, Section IA. In addition, they should be qualified according to the requirements of IEEE 336, 383, and 384.

4.5.6.2 Functional Requirements

The function of the instrumentation and control systems associated with nuclear ventilation and nuclear air cleaning systems is to control the environment of the space served within the limits of the controlled variable and to monitor the performance of the system and its components to ensure safe, efficient, reliable operation. The design of instrumentation and control systems should consider the consequences of single failure as well as environmental conditions.

The primary variables by which nuclear air cleaning systems are controlled are temperature, airflow rate, and pressure. Temperature, pressure, flow, and radioactivity levels are monitored to indicate system performance and alarm abnormal conditions.

Effluent air cleaning systems typically are controlled to maintain a minimum negative pressure or building pressure around a preselected flow rate. Habitability systems are usually controlled to maintain a constant airflow rate that is selected to maintain a positive pressure in the space served. Temperature is also usually controlled for habitability systems.

Instrumentation should be provided to monitor the radioactivity levels of effluent discharged into the atmosphere. Each discharge point that could potentially have concentrations exceeding TSR limits should be monitored. Monitoring of emission airflow rates and concentrations is also required. Values in excess of established high limits should be alarmed in the control room. In addition, airflow rates and radioactivity levels for habitability systems should be monitored and alarmed.

The best indicator of system performance for continually operating systems is the level of radioactivity. Monitoring flow rates and concentrations both before and after air cleaning units could indicate trends in filter degradation. The controls recommended in ASME AG-1, Section IA, should be provided to assist the operators in monitoring system performance.

4.5.6.3 Airflow Control

Airflow control is one of the most important control variables for nuclear air cleaning systems. Nuclear air cleaning system pressure could vary by as much as 25 to 30 percent, depending on system components, clean filter pressure drop, and the change-out pressure drop**.** It is recommended that airflow rates be maintained within ± 10 percent of design to maintain proper fan performance. The airflow rate is usually required to be automatically controlled by: (1) discharge or inlet control dampers, (2) variable inlet vanes, or (3) variable speed control.

To control the airflow rate, the flow first should be accurately measured. Flow should be measured where the air velocity profile is uniform. AMCA 210 and 203, as well as ACGIH *Industrial Ventilation* provide guidance on the proper location of airflow sensing devices.

Several manufacturers produce airflow measuring devices that can provide accurate averaged velocity pressures, as well as the instrumentation to convert velocity pressures to airflow rates.

An alternative method of controlling the airflow rate within ± 10 percent of design is to select a fan that has a steep performance curve such that a 25 percent change in pressure will not result in more than a 10 percent change in flow rate. This is difficult to achieve, however, due to system margins, system effect factors, and the ability to accurately calculate system pressures.

The choice of control dampers or inlet vanes will depend on fan type, required pressure reduction, and airflow uniformity. Control dampers should be sized to provide controllability. Flow stability should be maintained to avoid a controller “hunting” (control instability).

AMCA 210 recommends the use of variable vane inlet dampers when the fan is to be operated for long periods at reduced flow. The effectiveness of this damper stems from the fact that the inlet vanes generate a forced inlet vortex that rotates in the same direction as the fan impeller; similarly, any restriction of the fan inlet reduces the fan performance. Inlet vane dampers are of two types: integral (built-in) and add-on. The resistance and system effect of inlet vane dampers in the wide-open position should be considered in the original fan selection and system functional design. System effects of inlet vane dampers should be available from the fan manufacturer; if not, the system effect curves of AMCA 210 should be applied to account for pressure losses due to the use of these dampers.

Although variable vane inlet dampers generally provide smooth airflow control down to less than 30 percent of operating-point flow, there have been instances of severe vibration on large fans when the vanes were positioned between 30 and 60 percent opening. Because vibration is aggravated by system turbulence, consideration should be given to ways of ensuring smooth airflow patterns in the duct entering the damper and leaving the fan when inlet vane dampers are employed in high-velocity systems. Variable-pitch vane-axial fans may also be used to maintain system flow under varying pressure conditions. Variable pitch fans, however, may not qualify for safety-related seismic applications that require environmentally qualified components.

With the increase in variable air volume air conditioning systems, much has been done to improve variable speed controls for fans. Variable frequency controls, eddy current clutch motors, and mechanical adjustable speed drives are various methods of speed controls for fans. For variable air volume air conditioning systems, the airflow rate is varied to maintain a constant system pressure. For nuclear air cleaning systems, the speed of the fan is varied to maintain a constant airflow under varying system pressures.

Adjustable frequency drives are becoming more economical due to lower-cost solid state electronic components. The speed of the fan motor is directly proportionate to the frequency of the motor. Since the horsepower of the fan is a function of the cube of the speed, there can be significant secondary benefits of saving energy by using frequency drives, as well as better matching of fan performance to changing system pressure requirements.

4.5.6.4 Pressure Control

Effluent air cleaning systems are typically controlled to vary the system flow rate to maintain building (or space) pressure. This is accomplished by maintaining constant supply airflow and varying exhaust flow by adjusting control dampers and inlet vanes, and through speed control. Accurately sensing building pressure and outside air pressure are important for achieving a stable operating system. The sensing system should incorporate a “dead leg” to dampen the system reaction to wind gusts. Multiple outdoor and, if necessary, indoor sensors should be provided to obtain an average outside air pressure. To maintain a building at a negative pressure with respect to the lowest outside air pressure, the outdoor sensors should be located on each exposure. The system should then be designed to control flow based on the highest positive pressure sensed (the one that would result in the most infiltration).

Sensors should be located with due consideration given to local pressure fluctuations, eddy currents, and the turbulence that can be experienced at building corners and roof edges. The ASHRAE *Handbook of Fundamentals* provides guidance on determining turbulent zones due to airflow around buildings. This information should be considered in locating the sensors.

4.5.6.5 Qualification and Testing

All instruments used in safety-related nuclear air cleaning systems are required to be qualified for environmental and seismic conditions in accordance with ASME AG-1, Section IA, IEEE 323, and IEEE 344. All instruments and devices should be calibrated and tested in accordance with the manufacturer's test procedures. In addition, all power wiring internal to control panels, except control or shielded cable, should be subjected to a high-potential test to demonstrate freedom from ground and correct wiring connections.

It is recommended that extensive onsite pre-operational testing be performed on all instrumentation and control systems associated with nuclear air cleaning systems prior to placing the systems in service. Preoperational testing should be performed to confirm correct installation and design and to ensure correct operability of the control system and operated equipment.

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5.0 SPECIAL TOPICS

5.1 Fire Protection of Air Cleaning Systems[23]

5.1.1 DOE Fires Affecting Air Cleaning Systems

Fires in nuclear facilities have been caused by a variety of energy sources, including electrical energy and spontaneous combustion of pyrophoric metals. While fixed fire suppression systems or operator intervention have limited the size and consequences of most of these fires, some did propagate and cause significant damage and material release. There have been numerous occurrences of fire in nuclear facilities since the beginning of the Manhattan Project and many lessons learned from those fires. Some lessons have been learned at great expense. A brief history is discussed in the 2003 *Nuclear Air Cleaning Handbook* (DOE-HDBK-1169-2003) in the hope that the lessons will not be forgotten or ignored by facility designers and operators.

The most significant fires involving the HEPA filters of confinement ventilation systems have occurred at the Rocky Flats Plant. In 1957, pyrophoric ignition of plutonium in a production line, spread within the glovebox system and eventually ignited combustible cellulose filters in the production box and spread from there via laminated plexiglass window materials and other unknown combustible materials in the ventilation system to involve and destroy combustible HEPA filters in the final filter stage. Delays in fighting this fire were due to radiation safety concerns and delays in using water due to criticality concerns allowed it grow. It was extinguished soon after water was used, but a buildup of combustible vapors and dusts in the ventilation ductwork and the final filter stage ignited and resulted in a small explosion. This severely damaged the HEPA filters in the final filter stage and allowed the second-highest known plutonium release at Rocky Flats to occur. A significant portion of the plutonium released from this fire was deposited offsite. As a result of this event, fire-resistant glass fiber HEPA filters were researched, developed, and put into service in the nuclear industry. The release could have been more severe, but much of the plutonium was at the bottom of the stack due to the weight of the material, thus reducing the amount lofted out of the exhaust stack.

Another fire occurred at Rocky Flats in 1969 in a production line glovebox. The exact cause of this fire is unknown, but the area of origin included a storage cabinet that housed small, open metal containers filled with plutonium machine turnings. It is speculated that these plutonium briquettes self-ignited. The cabinets, which were constructed of high-density pressed wood shielding material and plastic, were included in the production line to reduce neutron exposure to workers. Heat detectors originally installed in the glovebox were removed to the underside of the glovebox floor to accommodate the cabinet. A fire detector alarm alerted the fire department. When the firefighters arrived, the building was smoke-filled, indicating the fire had escaped the confinement system (likely initially through the glovebox gloves). While localized

[23] This guidance is drawn (in somewhat condensed form) from Chapter 10 of NACH (2003). It should be viewed as supplementary to guidance and information offered in DOE-STD-1066-2016. Where the guidance here and that of DOE-STD-1066-2016 are not consistent, DOE-STD-1066-2016 should be followed.

contamination was detected outside the building, no measurable contamination escaped the site.

5.1.2 Fire Phenomena

Fire is a complex phenomenon that involves the initiation of an event and subsequent actions that can mitigate or exacerbate the event's effects. The matrix in **Table 5.1** covers: (1) the initiation and generation of harmful products from a fire; (2) the means by which these harmful effects are transported throughout the confinement ventilation system; and (3) the impacts of these harmful effects on the main components of the confinement ventilation system.

Table 5.1 – Fire Phenomena

	Heat	***Smoke***	***Related Effects***
Generation	Fire growth	Initial aerosol makeup	Water vapor, chemical releases, deflagrations
Transport	Temperature in ducts (less heat transfer and dilution)	Change in aerosol with time and temperature	Change with movement through ducts
Effects on filters	Media failure	Filter media plugging	Filter media plugging and failure due to delta P

Fires occurring outside a confinement ventilation system, e.g., within a room, generate heat that exposes the outside of ducting as well as produce combustion products that are drawn into the confinement ventilation system while operating as intended. These combustion products will impact the components of the confinement ventilation system. Hot gases from such a fire will be entrained within the system and will be conveyed via the duct system to the filter banks. While a certain amount of heat dissipation (heat transfer to the duct) and dilution will occur, over time the gases may cause steady deterioration of the filter medium and may ignite combustible framing. HEPA filters with fire retardant wooden frames will delay ignition, but they are still considered combustible.

5.1.2.1 Smoke Generation

Smoke contains particulates of combustion that can pose a significant plugging threat to HEPA filters. Smoke is a suspension of solid and/or liquid particles and gases resulting from combustion and pyrolysis. Soot is an intrinsic part of smoke. However, the term "soot" can be further refined to mean finely divided particles, mainly carbon, produced and/or deposited during incomplete combustion of organic materials. Moreover, the amount of smoke generated from any material is strongly influenced by the same conditions that effect combustion efficiency.

In general, smoke is a heterogeneous combination of solid and liquid particles of varying size and composition. Their instantaneous character depends on the material of origin, combustion conditions, environment, and flow dynamics. The sizes of particulates vary from 0.002 to 0.5

µm, depending on the experience described above. Conditions related to incomplete combustion generally result in an aerosol distribution of larger mean particulate size. However, if the smoke concentration is high, particle agglomeration (smoke aging) proceeds rapidly, as does fallout and surface deposition.

Agglomerated smoke aerosols can attain diameters as large as 10 µm in plumes from fires; however, visibility is most influenced by particulates with diameters of $\geq$1.0 µm. Collections of data on smoke production rates (g of soot/g of material burned) are available and can be used to estimate visible obscuration and smoke detector response time.

5.1.2.2 Water Generation

The quantity of water generated in the fire is as important as the soot and other particulates. Water vapor can condense on the particulates in smoke, both increasing their average diameters and leading to increased agglomeration resulting in generally larger particulates. Larger particulates lead to more rapid HEPA filter plugging.

5.1.2.3 Heat Loss in Ducts

Hot gas from fires may enter the exhaust duct system and lead to excessive temperatures at the HEPA filters if not mitigated. The two primary tools for analyzing the cooling of hot exhaust gas are: (1) dilution analysis with additional exhaust streams, and (2) duct cooling by convective and radiative heat transport.

As the combustion products from a fire travel through the length of a duct, losses occur. Thermal energy is added or lost through the walls of the duct according to the temperature differential between the products of combustion gases in the duct and the atmosphere external to the duct. Solid and liquid particulates are deposited along the duct interior surfaces according to a number of factors.

Because confinement systems are part of the enclosures that support operations with nuclear materials, computer codes have been developed to predict the results of accidents on the internal conditions within the system. For fire events, the room fire models discussed above can serve as the source term for codes that treat the response of components within the confinement ventilation system. Modeling tools are available (such as CFAST[24]) to help analyze heat transport in the ducts. In some cases, these models will not account for loss of heat from the heat transfer for conservatism.

5.1.2.4 Smoke and Water Loss in Ducts

A significant quantity of smoke and water may settle out in the ventilation ducts. In one configuration where the duct was located outside the fire area, it was observed that about 60 percent of the aerosol mass (including water) was lost between the duct entrance and the HEPA inlet (about 19 feet for a 2-foot × 2-foot cross-section duct).

Transport of related combustion products such as smoke particulates can be modeled using available techniques. Analysis methods for the entrainment and transport of these products in

[24] Consolidated Fire and Smoke Transport

confined situations such as ducts are generally well understood. The form and dispersion characteristics of the combustion products in question also should be studied. Once this is done, the effects on the HEPA filters can be shown over time.

5.1.2.5 Effects on Filters of Heat, Smoke, and Related Products

The impact of fires on the integrity of the HEPA filters can be determined through a sequence of analyses to establish: (1) the dynamics of the design basis fire; (2) the generation of smoke, water, and heat (temperature) that enters the confinement ventilation system; (3) the mitigation of smoke, water, and heat through the ducting to the HEPA filters; and (4) the response of the HEPA filters to the smoke, water, and heat that reach them. The interaction of smoke, water, and heat play a major role in the plugging of HEPA filters, as well as the consequent rise in filter pressure drop and possible reduction in exhaust flow. This sequence of analysis will determine the potential of the design basis fire for causing structural damage to the HEPA filters and thereby increasing the filter penetration. Finally, the effect of the smoke and water loading and the air temperature on the HEPA filters needs to be determined.

5.1.2.6 HEPA Filter Response to Temperature

Section 5.1.4.3 of DOE-STD-1269-2022 requires that fire-resistant HEPA filters meet the requirements of Underwriters Laboratory (UL)-586, *High-Efficiency, Particulate, Air Filter Units*, while medium efficiency filters meet the requirements of UL-900, *Performance of Air Filter Units*. These UL test methods qualify the construction materials for the filter, frame, and gaskets. To be listed by UL under UL-58613 as a HEPA filter unit, HEPA filters are required to pass the following three criteria:

- Withstand 750 ± 50 degrees Fahrenheit heated airflow for 5 minutes at not less than 40 percent of rated capacity.
- Have a greater than 97 percent test aerosol efficiency after exposure to the hot air test and cooling.
- Withstand a spot-flame test in which a Bunsen burner flame at 1,750 ± 50 degrees Fahrenheit is placed on the filter with no after-burning when the flame is removed.

For the spot flame test, a horizontal Bunsen burner is touched to the filter at three locations for 5 minutes at each site. Afterwards, the burner flame is moved to touch the filter frame, filter pack, and sealing materials. To pass the test, flaming on the downstream side of the filter is required to cease within 2 minutes after removal of the burner flame. Although this test indicates the fire performance of the filter, it is a small-scale test with a limited, controlled heat source that does not replicate the temperatures experienced during actual exposure of the entire filter to a more severe, full-scale fire. Many fires can reach higher temperatures and more severe conditions than this test fire.

Extended exposure to temperatures above 800 degrees Fahrenheit will cause destruction of the casing of wood-cased filters and warping of the casing of steel-cased filters, allowing unfiltered air to bypass the filter. The medium of HEPA filters is thin (0.015 inch) and can be destroyed by incandescent sparks, flaming trash, or burning dust on its surface.

Although HEPA filters can withstand a temperature of 750 degrees Fahrenheit for an extremely limited time, they should not be subjected to continuous exposure to temperatures higher than 250 degrees Fahrenheit. Longer filter life and more reliable service, as well as a greater operational safety factor, can be obtained when normal operating temperatures are below 200 degrees Fahrenheit and higher temperature extremes are avoided.

5.1.2.7 HEPA Filter Response to Smoke and Water Loading

Water from combustion plays a major role in potential HEPA filter clogging with smoke aerosols. The temperature at the HEPA filter is important for determining the extent of water condensation from the fire exhaust. The HEPA filter-plugging studies suggest using the following approach to analyze the potential of fires to plug HEPA filters.

With the design basis fire and its combustion products previously established, transport of the hot gases, smoke particulates, and water vapor through the duct system should be established. The characteristics of the combustion products penetrating the medium efficiency filter or demister should be determined next. This process will yield a mass of smoke aerosols for comparison to a reference mass holding capacity for HEPA filters. The amount of water condensing on the smoke deposits is determined from the temperature at the HEPA filters and from the combustion water loading.

The nature of the aerosols has a major effect on plugging of all filters, including DBS filters, medium efficiency filters, and HEPA filters. Previous studies have shown that, in addition to the mass of the smoke aerosols, the particle size and the state of the aerosol (liquid or solid) significantly affect HEPA filter clogging. In related tests using rolling medium efficiency filters (the media roll advances through the test duct as it plugs), Bergman et al., showed that, once a fire and the ventilation system have reached the point where the smoke generated can plug a HEPA filter, plugging can occur within one minute.[25]

Depending on circumstances and the specific design, the effects of aerosols on various type of filters will vary. Although very large DBS may not plug up as fast as a small HEPA assembly, all filters including DBS filters will eventually plug under enough soot exposure.

5.1.2.8 Filter Exposure to Water

Water is an effective method for reducing temperature, but HEPA filters are not designed to operate when wet and will suffer structural damage. The HEPA filter medium is treated with water-repellent chemicals. Tests have shown a reduction in water repellency effectiveness with each wetting of the medium. The tensile strength of the filter medium can be reduced to failure levels with as little as one wetting. HEPA filters exposed to water should be replaced immediately.

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[25] See Bergman, W., W. D. Kuhl, W. L. Russel, R. D. Taylor, H. D. Hebard, A. H. Bierman, N. J. Alvares, D. G. Beason, and B. Y. Lum, 1980, *Electrofibrous Prefilters for Use in Nuclear Ventilation Systems*, Lawrence Livermore National Laboratory, Livermore, CA.

5.1.2.9 Effects on Physical Integrity of the Confinement Ventilation System Components

Fires external to the confinement ventilation system may not only damage the HEPA filters inside the confinement ventilation system, they also may damage the integrity of the confinement ventilation system ductwork and enclosures. If the confinement ventilation system ductwork or enclosures are breached, some or all of the functionality of the confinement ventilation system will be impaired. This should be considered in the design of the physical components and the fire suppression systems provided in the facility.

5.1.2.10 Effects of Wildland Fires

Wildland fire experience such as at the Cerro Grande fire in Los Alamos in 2001 demonstrated the potential for smoke to adversely affect confinement ventilation systems. Facilities in areas where this type of event may occur are required to analyze the hazard in their authorization basis documents. During the 2001 Cerro Grande fire, some confinement ventilation systems in facilities at the Los Alamos National Laboratory were shut down to prevent the rupture of HEPA filters due to clogging from smoke. Other external situations (such as volcanic eruptions or the dust from denuded landscapes) can also create abnormally dusty conditions that cause clogging of medium efficiency filters and HEPA filters and present serious threats to confinement ventilation systems. System designers and operators should implement features that minimize the probability of having to shut down confinement ventilation systems in other than extreme emergency situations. During emergency situations, if the Incident Commander determines that a confinement ventilation system has been breached and radioactive material is being released, a decision should be made whether to shut the confinement ventilation system down completely or operate it in a manner that would minimize the impact. Additional prefilter change outs may also need to be considered near facilities subjected to wildfire exposures during and immediately after emergency periods of such events.

These hazards may reveal the need for additional safeguards, including but not limited to, administrative controls of the removal of natural vegetation and other combustibles near filter inlets, installing smoke removal systems such as an ESP medium efficiency filter or installing additional filtration to preclude ingress of particulate into the building. NFPA Standard 1144, *Protection of Life and Property from Wildfire*, provides guidance on minimum defensible spaces around all buildings. High-hazard facilities would be expected to have defensible spaces exceeding these minimum values.

5.1.2.11 Fires Occurring within Confinement Ventilation Systems

Fire may originate from sources within the confinement ventilation system (e.g., glovebox-sized operations and small hot-cells). The effects of fires occurring within confinement ventilation systems, although similar to those resulting from fires external to the confinement ventilation system, may be different and thus require different controls.

5.1.2.12 Generation of Heat, Smoke, and Related Products

Fire events occurring inside a confinement ventilation system may appear in a number of physical forms. Fire may occur in ordinary combustible material. The amount of combustible material within a confinement ventilation system generally would not be as much as in a larger room, so the fire growth characteristics may be somewhat altered.

Fire may occur in the radioactive materials in a confinement ventilation system, or a fire involving ordinary combustibles may subsequently involve radioactive materials. A fire involving a flammable liquid or gas used inside a confinement ventilation system also may occur. These events may take the form of a flame front moving rapidly through a flammable vapor, a flame front moving rapidly enough to deflagrate and produce some overpressure, or even a detonation if the conditions for such phenomena exist.

Filter fires can occur due to either decomposition of combustible dust deposits within the filter, organic decomposition of chemical residue carried by the airstream from upstream processes, or spark/ember introduction from an upstream source. While introducing a water spray within or prior to the duct inlet can prevent the latter condition, fires originating at the filter itself cannot be satisfactorily mitigated by automatic suppression methods. Consequently, reliance is placed on the manual deluge system and fire department response.

Industrial and institutional loss experience has shown that over a period of time even “office dust” accumulations can form highly combustible residues on filters that are sufficient to cause damage if ignited. It also has been established that the concentration of these fuels need not be high to cause severe damage due to the fragility of the media. Fire-retardant chemical preparations for the filter media may initially make ignition difficult, particularly on clean media. However, this retardant material tends to become less effective over time and does nothing to retard or reduce the combustibility of dust or residue deposits from the airstream itself.

Administrative controls and alarm interlocks are designed to alert operators about impending change-out intervals that have been established to maintain dust or residue inventories below radiological actions points. It is not feasible, however, to eliminate the potential for direct filter fires or to practically reduce residue levels below those that may damage the filter itself.

5.1.2.13 Transport of Heat, Smoke, and Related Products

The transport of hot gases, smoke, water vapor, and chemicals from an internal fire through a confinement ventilation system can be modeled in much the same way as is done for an external fire. A fire occurring within the confinement ventilation system may affect the transport mechanism by altering the airflow through the system more than an external fire.

The transport mechanism also may be affected if the actual structural confinement barrier of the confinement ventilation system is involved in the fire and is contributing to its spread. The accumulation of dust and debris inside the air cleaning system ductwork over long periods of operation provides a mechanism for transporting flames from an ignition source to the filters, and also can produce soot that can clog filters in a fire.

5.1.2.14 Effects on Filters of Heat, Smoke, and Related Products

The effects of the products of combustion reaching the HEPA filters are the same for internal and external fires. The same physical parameters affect the manner in which the filters are threatened.

5.1.3 Fire Hazard Controls and Design Features

5.1.3.1 Objectives and Requirements

There are three major objectives for fire protection of confinement ventilation system:

- To prevent fires from affecting the operation of the ventilation system;
- To protect the filtration function; and
- To prevent the release of material that has accumulated on filters.

General Requirements

Special hazards may cause exposure of the filters to the following: highly combustible dust loading; pyrophoric materials; chemically reactive, explosive, or corrosive vapors; or high-moisture conditions that may cause rapid degradation of HEPA filters. These should be evaluated on a case-by-case basis by a fire protection engineer who understands the process sufficiently to determine the protection warranted.

A comprehensive fire protection scheme for filter housings should include the following principles:

- The ventilation system filter housing construction materials should be noncombustible.
- Process hazards inside and outside the ventilation filter housings should be controlled.
- General area sprinklers should be provided within all process areas, in accordance with the facility Fire Hazards Analysis.
- The final filter housing should be separated from the general building area by fire-rated construction.
- Automatic water spray should be installed upstream (before) the demister filter and before the first-stage filters.
- Manual water spray should be installed and directed at the first-stage HEPA filter.
- Automatic fire detection should be provided in the inlet ductwork, prior to the HEPA filtration plenum, and within the plenum where there is the possibility of combustible materials within the plenum.
- Automatic flammable gas detection should be provided in filter housings where flammable or combustible processes are performed.

The FHA for a confinement ventilation system may indicate the need for further fire protection measures.

5.1.3.2 Fuel Control

The flammability/combustibility of materials should be considered in designing the confinement ventilation system. This is a first line of defense against fire, without which any ignition will lead to a dangerous situation. NFPA standards and DOE fire protection criteria provide requirements and guidance on how to accomplish fuel control. The FHA should address the issue of materials flammability/combustibility as it pertains to the facility under analysis.

If the process involves the presence of flammable or combustible vapors or liquids, the allowable concentration of flammable vapors inside the filter enclosure should be limited and controlled. The maximum permissible concentration of flammable vapors is normally taken to be 25 percent of the lower flammable limit.

5.1.3.3 Control of Energy Sources

Ignition sources inside the filter enclosures should be limited to those necessary for operating the system. Electrical systems should be installed in accordance with NFPA 70, the National Electrical Code. The presence of flammable gases or vapors in the operation of the confinement ventilation system will require specialized electrical equipment to prevent their ignition, e.g., NFPA 70, Article 500.

5.1.3.4 Passive Design Features

The design of the duct runs can greatly influence the effect of a fire in the facility or within the ductwork on the ability of the confinement ventilation system to perform its required safety function. This section will address the physical configuration aspects of the ducts and filter housings. Ductwork and related equipment are required to comply with the criteria of NFPA 90A, *Installation of Air Conditioning and Ventilation Systems* and NFPA 91, Standard for *Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*. These standards provide explicit requirements for integrating the ventilation system with the building construction, as well as operational guidance for systems inspection, cleaning, and maintenance. Other sections address the active fire protection or cooling systems that may be required to maintain confinement ventilation system functionality.

Another significant consideration in the design and layout of an air cleaning system is provision of separate systems for each building fire area. Buildings are subdivided into discrete fire areas to limit fire damage to only one area. Fire areas are established to limit the maximum possible fire loss and in accordance with the building codes. If fire area boundaries are penetrated to allow passage of the air cleaning ducts, the possibility of fire spreading to multiple fire areas is introduced, potentially resulting in much more extensive fire damage.

5.1.3.5 Duct Response to Fire

There may be situations where fire dampers cannot be installed at firewall duct penetrations because of the critical safety requirement to maintain confinement ventilation. In some cases, ducting may traverse other fire areas before reaching the filter banks. The quality of the duct construction and installation are the most important factors in maintaining the integrity of the ducting. A number of factors need to be considered:

- Where the duct penetrates a firewall, distortion during a fire may permit flames to pass through the wall around the perimeter of the duct. Investigators have performed full-scale fire testing that provided insight into the performance of reinforced ducting under limited fire exposures. One investigation concluded that a reinforced duct could withstand a design basis fire without collapse or deformation.

- Conductive heat transfer through the duct may ignite combustible materials in adjacent fire areas. This can be mitigated by insulating or enclosing the duct as determined by the FHA (generally 10 feet).
- Duct collapse can occur due to weakening of the duct or the hangers when heated. Additional hangers and/or reinforcement of the duct at the penetration point will mitigate this potential problem.
- Where there are duct openings in a non-fire space, the FHA should consider the potential for fire spread and the need for additional safeguards.

5.1.3.6 Air Supply and Extraction

The method of air supply and extraction profoundly influences the efficiency with which a fire burns. Most gloveboxes are designed so that the air supply enters at the bottom on one side of the box and exits at the top on the other side. This design ensures that a vigorous fire will persist so long as fuel and air are available. If, the ventilation pattern is reversed and air enters at the top of the box and exits at the bottom, however, combustion products will mix with the supply air to weaken and ultimately extinguish the fire. This tactic is effective for all but very large enclosures.

5.1.3.7 Entrance Filters

Because the duct-intake filter is the major dust collector, it is also the primary component in which a fire could occur. Protection of the HEPA filter downstream from sparks and burning fragments from the duct-intake filter may be needed if the distance between them is not great. If it is less than 20 to 30 feet, a fine (20 to 30 mesh) screen may be installed downstream of the duct-entrance filter (such screens should be located where they are convenient for periodic cleaning). Because lint tends to bridge the openings, screens, and coarse filters (e.g., furnace filters), installation of fine-mesh screens on the face of the duct-entrance filter is not recommended; however, this does not preclude installation of a mesh screen for physical protection of the filter. For glovebox and hot cell applications, the duct-intake filter should be designed for ease of removal and replacement from the contained space. The filter should also be afforded maximum protection against the effects of or ignition by a fire in the contained space.

5.1.3.8 Medium Efficiency Filters

Medium efficiency filters are usually provided in the central filter housing in addition to or in-lieu of duct-intake filters. Again, fire is more likely to occur in the medium efficiency filter rather than in the HEPA filter downstream. Medium efficiency filters should never be mounted directly on the face of the HEPA filter or on the opposite side of a common mounting frame with the HEPA filter (i.e., back-to-back). A spacing of at least 36 inches between the downstream face of the medium efficiency filter and the upstream face of the HEPA filter is recommended—not only for maintainability, but also to provide space where burning fragments and sparks can burn out or settle to the floor of the filter housing.

5.1.3.9 Filter Housings

HEPA filter housings/plenums should be protected from facility fires by fire-rated construction (generally 2-hour). High temperatures in exhaust filter housings can be minimized by long runs of duct preceding the housings/plenums, by

- Intake of dilution air from air streams from other contained or occupied spaces of the building,
- Cooling of the exterior of the duct with water spray, and
- Cooling via water spray installed inside the duct (has been employed in some applications).

The overall intent is to locate the HEPA filters where they are least likely to be exposed to elevated temperatures, hot sparks, and burning embers from a potential fire in the process line.

5.1.3.10 Fire Screens

A fire screen is a noncombustible sheet of meshed metal similar to a roughing filter that is intended to reduce the potential for transporting glowing embers/burning brands through the airstream from the fire source to the filter banks. The screen should be installed upstream from the medium efficiency filter(s) and ahead of the filter housings/plenums. Specific design criteria for fire screens can be found in DOE-STD-1066-99.

5.1.3.11 Materials

Ideally, all construction materials used in confinement ventilation system enclosures should be noncombustible. Use of noncombustible materials for the enclosure will help limit the total amount of fuel available to burn if a fire occurs, and also ensure integrity during a fire event. If suitable noncombustible materials cannot be used because of process, shielding, corrosion-resistance, or other special purpose requirements, attempts should be made to minimize the quantity and surface area of the installed combustible materials should be minimized. If a combustible duct material is utilized, installation of automatic sprinklers within the duct may be required according to DOE, NFPA, or FM Global requirements. Additionally, an approved or listed duct material may be required, e.g., fire retardant FRPs.

The preferred construction materials for ductwork are steel, stainless steel, or galvanized steel. If FRP ductwork is required because of corrosion issues, special ductwork that meets the flame-spread criteria in NFPA 90A is required. Acoustic linings or duct silencing materials are combustible and are not permitted inside air cleaning system ductwork.

5.1.3.12 Wood Filter Frames

If wood is used for HEPA filter frames, a fire-retardant treatment is used that results in (a) a flame spread of 25 or less and (b) a smoke-developed rating of 50 or less when tested to ASTM Standard E-84. This test measures the speed at which flames will travel across the surface of the material being tested. As a comparison, the flame spread of red oak boards is 100, while the flame spread of concrete or unpainted steel is zero. Thus, even with the fire-retardant treatment, wooden filter frames will combust in a sufficiently severe exposure fire.

5.1.3.13 Fire Barriers

HEPA filter housings/plenums located within nuclear or hazardous process buildings are required to be separated from the remainder of the building by a minimum of 2-hour-rated fire barriers. This requirement is intended to ensure HEPA filters are protected from fires occurring in the process building. One common type of 2-hour-rated barrier is constructed of 8-inch-thick concrete block walls and a poured concrete ceiling. Another method is to provide this level of required separation is to locate the filter housing external to the process building. If the filter housing is located in a separate building, no specialized fire barriers are required, provided the housing is located at least 20 feet from the process buildings and the exterior walls of both buildings have no unprotected openings, and are of non-combustible construction. If the filter housing is located less than 20 feet but more than 5 feet from the process building, the filter housing is required to be constructed as a 1-hour-rated fire barrier. Filter housings are required to be installed in 2-hour-rated firewalls if they are less than 5 feet from the process buildings.

Small filter housings, which have a leading-edge surface area of 16 square feet or less, are not required to be separated from the rest of the building, provided the building has area-wide automatic sprinklers.

Penetrations through the air cleaning system enclosure fire barriers are only permitted for services necessary to the operation of the filtering system. Where penetrations cannot be avoided, the openings created through the fire barrier are required to be properly sealed with a listed or approved, penetration seal method. Penetration seals are tested and approved under the requirements of ASTM E-814, *Fire Tests of Through Penetration Fire Stops*. The penetration seals should also be compatible with and capable of continued exposure to the types of materials and atmospheres present inside the filter enclosure. Doors in 2-hour-rated enclosures are required to be Class B (90-minute) fire door assemblies. Doors in 1-hour-rated enclosures are required to be Class C (45-minute) fire door assemblies. The requirements for construction and installation of fire doors are found in NFPA 80, *Fire Doors and Other Opening Protectives*. HVAC ducts that penetrate 2-hour-rated enclosures should be protected with UL-listed or FM Approved fire dampers. HVAC ducts that penetrate 1-hour-rated enclosures are not required to have fire dampers.

In some cases, it is necessary for ductwork that is part of the nuclear air cleaning system to penetrate fire-rated barriers. Fire dampers cannot be installed in these ducts because their operation during a fire would cause the dampers to close causing the isolation of ventilation flow. Because the air cleaning system is required to be functional at all times, an alternative method of fire protection should be provided. It is recommended that a qualified fire protection engineer be consulted to evaluate such configurations on a case-by-case basis. In some cases, it may be possible to obtain an exemption on the use of fire dampers where building alterations would involve working in highly contaminated areas. During the evaluation, the qualified fire protection engineer will determine a technically justified approach providing the level of protection required without causing unwarranted impacts to the overall system's operational capabilities.

5.1.3.14 Active Design Features and Fire Hazard Controls

One of the goals of the nuclear industry has been to provide gloveboxes, caves, canyons, hot cells, fume hoods, and other radiological confinement areas with practical ventilation exhaust systems that can remain in service during a fire that can capture all of the airborne radioactive contamination from the fire. It has been established by both consensus standards and industry/government regulations that ventilation components in nuclear air cleaning systems should continue to perform their safety functions effectively under all conditions by confining radioactive or other potentially dangerous materials. To realize this for fire protection purposes, it is necessary to protect the filter housing in the exhaust system from heat, smoke, and burning material that would be generated during a fire scenario. In the event of fire, the release of contaminated smoke through a ruptured or damaged filter housing may have more serious consequences than any potential casualty losses from the fire itself.

5.1.3.15 Fire Dampers

Fire dampers should not be provided in ductwork penetrating fire-rated construction when the ductwork is part of the nuclear ventilation system and is required to continuously operate. In lieu of fire dampers, a performance-based approach is performed by a qualified fire protection engineer. This evaluation may require (for example) one of the following:

- Duct wrapping utilizing a listed or approved duct wrap,
- A sprayed-on material,
- Enclosure of the duct in fire-rated construction,
- Structural enhancements to the duct at the duct penetration.

5.1.3.16 Fire Detection and Suppression Systems

Detection Systems

Detection equipment for early warning of fire conditions should be provided in all HEPA filter housings/plenums. Rate anticipation heat detectors are most commonly used because of their good stability, low maintenance requirements, and relatively quick response to heat. Linear heat detection is also acceptable and may be preferable due to ease of installation, resistance to varied chemicals, and especially ease of testing.

Sampling types of smoke detection systems has been suggested as a means of providing early warning, however, precautions should be taken to ensure they do not provide a leak path that bypasses the filters. Such systems are utilized strictly in accordance with their listing/approval.

Alternative fire detection methods are possible depending on the specific design of the filter enclosure. If flammable liquids or gases are used and the possibility of explosion exists, rapid detection using flame detection devices may be needed.

NFPA Standard 72 provides the requirements for the installation of fire detection devices and systems.

Automatic Fire Suppression Systems

Prior to the Brown's Ferry nuclear power plant fire in 1975, the use of water on electrical fires was not considered a safe practice by the nuclear power industry. Following the Brown's Ferry fire (see NRC NUREG-0050, *Recommendations Related to the Brown's Ferry Fire*), Factory Mutual (now FM Global) and other organizations performed studies to test the use of water in electrical spaces (see Electric Power Research Institute (EPRI) NP-188131 and EPRI NP-2660). In addition, Sandia National Laboratories (SNL) performed tests on cable tray protection schemes (see NRC NUREG/CR-2377,33 NUREG/CR-2607,34 and NUREG/CR-3656). These studies by Factory Mutual and other organizations proved that fighting fires in grouped cables could be accomplished efficiently using water (these tests were done on unenergized electrical cables, however, the conclusions on the use of water as an efficient extinguishing agent were confirmed).

Following the Brown's Ferry fire and the tests performed by Factory Mutual, SNL, and others, the inhibition against using water to extinguish fires in all spaces with electrical equipment began to subside, and fire protection engineers made more deliberate assessments of the type of electrical occupancy when considering use of water as a fire suppressant. Automatic fire suppression systems throughout a facility will control a fire in its early stages of growth, thus mitigating fire effects that could impact the functionality of the confinement ventilation system. Wet pipe sprinkler systems are the most common type of automatic fire suppression system and have a proven record of fire extinguishment. Other types of systems exist and are described further in this section. Activation of a suppression system will control and/or extinguish an incipient fire and automatically alert first responders or the fire department.

Consideration should be given during the design phase on the testing and maintenance of fire suppression and fire detection systems throughout the life of the system/facility. Consideration also should be given to avoiding interference with or inhibition of the safety function of other safety features (i.e., water addition/criticality controls, HEPA filters).

5.1.3.17 Wet Pipe Sprinkler Systems

Wet pipe sprinkler systems are used to control the fire potential in the facilities where there is a confinement ventilation system. Such systems will control and/or extinguish the fire and thus limit the threat to the facility, the HEPA filters. These systems will also limit physical fire damage to the ductwork of the confinement ventilation system.

The need for wet pipe sprinkler protection is established by the FHA. The design and installation requirements for these systems are contained in NFPA Standard 13, *Standard for the Installation of Automatic Sprinkler Systems*.

5.1.3.18 Deluge and Water Spray Systems

A deluge sprinkler system is one in which the sprinklers are normally open and water flow is controlled by a valve in the piping leading to the open sprinklers. When this valve is opened, water is discharged from all the open sprinklers at the same time.

Two types of deluge systems are required for protection of HEPA filter housings. The first type is automatic with the water-spray sprinklers being located upstream of the demister filters. This type of system is generically referred to as a water curtain, as it consists of closely spaced, open deluge nozzles connected to sprinkler piping located in front of and above the demisters. When the system is activated, all of the nozzles spray water simultaneously downward, forming a wall of water. This system is intended to cool incoming air, hot sparks, and flames before the medium efficiency filters are threatened. The water curtain is located upstream of the demisters so the water spray carryover can be diverted (i.e., knocked down) to prevent moisture from reaching the downstream HEPA filters.

Operation of an automatic deluge spray system is initiated by a fire detection system (generally heat detectors) located in the ducting, just prior to the filter plenum. The detection system opens a deluge valve, allowing water flow to the nozzles. The spray nozzles are open sprinklers listed/approved for their intended use. The automatic system is also equipped with a locked bypass valve that can be manually opened if the detection system or the deluge valve fail to operate. Closed-head pilot sprinklers are sometimes used in place of an electrically-operated heat detection system to open the deluge valve. In this case, the pilot sprinklers serve only as temperature sensors and do not spray water. The use of pilot sprinklers has an advantage for safety class systems since they do not require energy to activate.

Fires produce smoke and soot that will cause rapid clogging of filters. Because the automatic spray deluge system functions much like the scrubbers that are used to clean stack exhaust, there is an expectation that the automatic system may also reduce smoke clogging. However, the nozzles are not optimized for smoke reduction due to their larger droplet size. In limited research with spray nozzles, it was found that smoke clogging decreased in some cases but increased in others.[26] Therefore, premature manual activation of the spray deluge system to reduce smoke is not recommended without further research to quantify results for specific arrangements and combustible contents. Operational procedures such as shutting down or throttling back the blowers to prevent rupture of clogged filters during a fire should be addressed in the authorization basis documents. The generic operational procedures provided here resulted from studies at a DOE site and are applicable to the procedures at most sites. Use of these procedures should be preceded by a thorough design review to ensure their specific applicability.

Demisters should be installed between the automatic spray nozzles and the HEPA filters. Demisters are specially configured metal panels that redirect the water droplet trajectory toward the floor of the enclosure. Performance criteria for demisters are contained elsewhere in this handbook. The demisters should be positioned at least 3 feet upstream of the HEPA filters, and approximately 6 inches downstream of the automatic deluge nozzles.

The second type of deluge system is a manually activated deluge spray system. This system is operated only if the filters begin to combust because it discharges water directly onto the first stage filter system. Combustion cannot only breach the filters but may also release particulate that has accumulated on the filters over time. Facilities without this manual system should rely on firefighters to attack HEPA filter fires with hose streams. The manual deluge system is intended to avoid unnecessary exposure of firefighters who would otherwise need to enter the hazardous environment within the housing/plenum. The manual system also has a much more

[26] PNNL-18894 (WTP-RPT-197, Rev 0), Pretreatment Engineering Platform Phase-1 Final Test Report, Dec. 2009, Pacific Northwest National Laboratory, Richland, WA; PNNL-22415 (WTP-RPT-221, Rev 0), Large Scale Spray Releases: Additional Aerosol Test Results, August 2013, Pacific Northwest National Laboratory, Richland, WA.

efficient flow pattern and utilizes less flow than a fully charged fire hose. The manual control valve for the manual deluge spray system is normally locked in the closed position and only accessible to firefighters. Fire department training programs should address operating procedures for these valves.

The potential for nozzle plugging or corrosion in housing deluge systems should be considered during design. Potential remedies include, but are not limited to, strainers, blow-off caps, and corrosion control measures such as use of special corrosion-resistant materials or coatings. Some sites have utilized stainless steel nozzles to avoid the potential for corrosion. These sites felt that the increased cost upfront was well worth the investment.

The automatic extinguishing systems should be designed to comply with the requirements of NFPA 13 and NFPA 15*, Standard for Water Spray Fixed Systems for Fire Protection*. These standards provide the requirements for designing and installation of the system its components, as well as associated installation requirements. Research conducted by Dow Chemical Company following the 1969 filter housing fire at Rocky Flats determined that the minimum water supply for the system should be hydraulically calculated to provide at least 0.25 gpm/ft^2 over the entire face area of the filters, or one gpm per 500 cfm of airflow, whichever is greater.

The automatic deluge system uses standard deluge-type sprinklers installed on the piping at a minimum spacing of 4-feet. The system should be activated by the rate-compensated heat detection system, linear heat detection or by pilot-operated sprinklers. A manually operated release is also provided on the deluge valve in the event a malfunction in the releasing system occurs. The use of corrosion-resistant deluge sprinklers and piping should be considered for all installations.

5.1.3.19 Water Mist Systems

Water mist technologies have been developed that use fine water sprays to efficiently control, suppress, or extinguish fire using limited volumes of water. Their use in a specific confinement ventilation system should be carefully analyzed in the FHA. See NFPA 750, *Standard on Water Mist Fire Protection Systems*. The challenge with this type of system are the effects of the facility ventilation on the ability of the mist to extinguish the fire via heat absorption and/or smothering.

5.1.3.20 Sprinklers within Ductwork

Provision of wet-pipe or deluge sprinkler systems within ducts or filter housings is the exception rather than the rule, however, deluge sprinkler systems are routinely provided on carbon-filled adsorption systems in nuclear power reactors. On deluge systems for adsorption filters, fog nozzles with as fine a droplet-size distribution as possible are recommended for maximum cooling and smoke particulate capture. To limit the volume of water discharged, consideration should be given to an automatic recycling (re-setting) deluge system.

5.1.3.21 Demisters and HEPA Filters

Water protection for HEPA filters has been controversial due to concerns about water plugging of the filters. The research that led to this concern was based on conditions that are not reflected in an actual filter installation. Specifically, the research involved soaking filters in pans of water. However, in a properly designed confinement ventilation system, demisters significantly reduce the amount of water from the automatic deluge system reaching the filters. Manual deluge systems are only operated after the filters begin to combust. Consequently, water damage is no longer an issue. This topic is further discussed in DOE-STD-1066-99.

5.1.3.22 Fire Department Standpipe Systems

Because the possibility of a fire affecting the filters cannot be entirely eliminated; some provision for manual firefighting via a standpipe system (meeting the requirements of NFPA 14, *Standard for the Installation of Standpipe and Hose Systems*, is necessary. The fire department will almost always use its own hose packs.

The use of a hose stream can only be considered when all other automatic and manual safeguards have been determined to have failed. At this point, the filters cannot be saved, however, hose streams may prevent fire spread to subsequent stages of filters and avoid failure of the final filter stage that could release contamination. In addition, a hose stream can serve to prevent further damage to the filter mounting frames and housing, the duct, or the building. Similar observations can be made for the common types of sprinkler systems, both automatic and manually actuated, if they are installed inside the filter housing.

5.1.3.23 Water Runoff Collection

Facilities protected by sprinklers or deluge systems should have a provision to collect and dispose of water used for fire extinguishing. In addition, design of the water drainage system has to be consistent with the characteristic of water as a neutron moderator. In some cases, water collection for filter plenums may consist of a criticality-safe water collection tank. Also, the plenum drains may have a 2-inch lip that will permit up to two inches of water to collect in the plenum prior to being discharged to the collection tank. This permits short duration flows to be captured within the plenum and allowed to evaporate.

5.1.3.24 Gaseous Agent Systems

Some spaces external to the ductwork are protected with gaseous fire suppression systems. There are NFPA standards for the design of these systems that include Halon alternatives and carbon dioxide systems. Competent technical persons should be consulted to design these systems.[27] The same challenges exist for these systems in nuclear facilities where the ventilation from the space has a significant impact on maintaining the concentration of the gas within the space. Typical industrial occupancies the ventilation system is isolated prior to the activation of the system. For nuclear facilities, isolation of the ventilation system is nearly always not advisable (or permitted).

5.1.3.25 Flammable Gas Detection

If flammable gases are used, the FHA may require flammable gas detection equipment in the ductwork or filter housings. The installed gas detectors should be connected to an alarm system located at a continuously attended position to ensure immediate corrective actions are taken

[27] Because CO2 is an asphyxiant, its use is discouraged in the DOE complex.

when elevated flammable vapor concentrations are detected. The effective design of systems to detect flammable gases depends on the gases themselves, the airflow characteristics within the confinement ventilation system, the actions that should be taken in response to unacceptable concentrations of flammable gases, and many others. Systems that do not adequately address such issues will either not work or will provide false alarms on a frequent basis which can be an equally unacceptable situation. Competent technical persons who are knowledgeable of the hazards present and the design of such systems should be consulted to design these systems.

5.1.3.26 Protection of Carbon-Filled Adsorption Systems

To prevent loss of confinement for radioactive iodine and iodine compounds, carbon-bed filtration temperatures should be maintained at a level where impregnants and trapped radioiodine cannot desorb. This requires the bed(s) to be large enough that specific loadings of iodine cannot exceed 2.5 mg/g of carbon, and that airflow through the bed can be maintained at some level in excess of 6 (preferably 10) linear fpm. If bed temperatures can be maintained below the level where desorption of impregnants and trapped radioiodine takes place, carbon ignition is unlikely. If a fire should initiate, however, total flooding or dumping of the carbon into a container of water is currently the only effective means of extinguishing a carbon bed fire. Carbon dioxide and gaseous nitrogen are ineffective against activated carbon fires because the fire feeds on the oxygen adsorbed in the pores of the carbon, and the quantity of liquid nitrogen required to provide effective cooling would be unavailable in most cases.

Combustible Metal Fires

Metal fires, particularly fires in water-reactive metals such as sodium, present unique challenges. Water and extinguishing agents such as the Halon alternatives cannot be used, and inert atmospheres such as nitrogen and carbon dioxide require the total exclusion of oxygen to be effective. Combustible metal fires should be addressed in the operating space before it can reach the ducts or filters. However, most of the fire-extinguishing agents that are effective against such fires produce copious clouds of dust that, when released, rapidly threaten to plug the duct entrance filter. This in turn threatens over pressurization of the glovebox or hot cell, resulting in blowback of contamination to occupied spaces of the building. Carbon microspheres and magnesium oxide (sand) have been shown to be extremely effective against plutonium, sodium, uranium, sodium-potassium, magnesium, aluminum, lithium, and other types of fire that produce intense heat. The material can be dispensed automatically or manually and produces essentially no dust when dispensed. In addition, it has negligible chloride content (and so poses no threat to stainless steel equipment and cells), is very easy to cleanup, is inexpensive, and is readily available.

When metals such as aluminum are being processed that have the potential to produce explosive dust, the potential presence of such dust in both the airstream and inside the filter enclosure should be documented in the FHA. Appropriate hazard controls should be provided as necessary—duct-entrance filters alone will not prevent dust from entering the ducting.

5.1.3.27 Filter Assemblies in Plywood Enclosures

Some smaller HEPA filter assemblies are purchased as a single package. These are often self-contained in assemblies constructed of plywood or other wooden composite material. These assemblies have male duct connections on their inlet and discharge sides and are easily dropped into place by clamping existing ducts onto them. Given the lack of fire resistive properties of these filter assemblies, it is not recommended that they be used in new construction.

5.1.3.28 High-Efficiency Metal Fiber Filter Systems

High-efficiency metal fiber (HEMF) filter systems have been commercially available in the U.S. since the mid-1980s. They are made of sintered stainless-steel fibers that are welded into steel housings and steel frames. ASME AG-1 Sections FM, High-Strength HEPA Filters, and Section FI, Metal Media Filters, contain information and guidance on these types of filters. Future editions of ASME AG-1 will contain additional information on emerging technologies, such as Section F, Ceramic Filters.

In contrast to HEPA filters, HEMF filters are not weakened by moisture impingement. They can also operate for longer time periods and in hotter conditions than HEPA filters because the metal filters contain no flammable components and are inherently resistant to high temperatures. However, the finely divided filter media in a metal filter will not resist a direct flame impingement. The resistance of the metal filter to moisture and heat makes this filter attractive for fire protection purposes. Because the use of HEMF filters is relatively new to the DOE community, only limited experiential data on the behavior of these filters in actual fires is available. They are also very expensive to purchase and operate.

5.1.3.29 Radioiodine Absorber Air Cleaning Systems

Although much discussion in the nuclear community has been generated in the past 40 years regarding fire protection of absorbers, little consensus and few conclusions have been reached about the proper method of extinguishing fires in absorbers with combustible material. Available methods include: (1) using a combination of manual and automatic water spray systems, (2) limiting airflow to the absorbers, and (3) using alternative noncombustible absorber media (e.g., silver zeolite). Absorber air cleaning systems are often used in nuclear reactor emergency ventilation confinement systems where they are frequently referred to as charcoal- or carbon-type filters. Other inorganic absorber materials are available for absorber media, including silver oxide, silver nitrate, aluminum silicate, and silver zeolite. It is generally accepted that, as a minimum, absorbers should be provided with fire detection.

For carbon-type filters, American Nuclear Insurers, an insurance carrier for nuclear power plants, recommends the following fire protection:

- Charcoal filters should have a hydraulically designed, automatic water spray system that uses directional, solid-cone spray nozzles controlled by an approved deluge valve. The system should be capable of being manually actuated from a suitably remote location.

- Spray nozzles for horizontal beds or drawers should be oriented above each bed or drawer and should be designed to distribute water evenly across the top of each bed or drawer at a minimum density of 0.25 gpm/ft^2.
- Spray nozzles for vertical beds should be oriented at the top of the bed and should be designed to distribute water evenly across the top of the bed at the rate of 3.2 gpm/ft^2 of charcoal bed.
- A supervised, fixed-temperature detection system should be provided and connected to an annunciator in the control room. The detectors should be located on the downstream side of the charcoal bed to facilitate timely, automatic operation of the spray systems. The spray system should be equipped with a local alarm and should be connected to an annunciator in the control room. The airflow should terminate (with fan isolation) upon water activation.
- For the pressure vessel-type charcoal filter, where a shut-off bypass arrangement is employed around each tank, an automatic water spray system is not required. A hose connection should be available on the side of the tank to allow the introduction of water.

Once carbon in adsorber beds becomes wet, either by actuation of the water sprays, moisture in the air stream, or by any other means, it is extremely important to remove all of the carbon and wash the trays of any residual carbon, as corrosion of the trays will begin to occur and will be accelerated with time.

5.1.3.30 Deep-Bed Fiberglass Filter Systems

Early designs of deep-bed, fiberglass filters did not address filter media replacement. Fiberglass filters plug over time, resulting in combustible deposits that may contribute to fire risk. It is generally accepted that water applied to this type of filter media will extinguish the fire. Precautions should be taken when water is applied to filter media containing radioactive material to prevent the water from being released to the environment.

5.1.3.31 Deep-Bed Sand Filter Systems

For the most part, DBS filters are fire-resistant, chemically inert, and require no special fire protection systems. HEPAs have been traditionally installed prior to the sand filters for fear of sand fires carrying over and plugging the HEPAs.

Since plugging is a “worst case” scenario for both HEPA and DBS filter arrangements, both require mitigation measures. It has been largely accepted that DBS filters, while expensive to construct, decontaminate, and demolish, offer improved performance in their ability to operate in the presence of high temperature, heat, and fire products.[28]

[28] Some tests have been conducted on DBS smoke and soot loading. See Schurr, G. A., D. B. Zippier, and D. C. Guyton, 1972, “Deep-Bed Filter Tests,” 12th Atomic Energy Commission Air Cleaning Conference, USAEC Report CONF-720828. Access at http://isnatt.org/Conferences/12/session10a.pdf.

5.1.3.32 Self-Cleaning Viscous Liquid Filters

This type of filter uses a viscous liquid for cleaning purposes. These filters should be avoided where radioactive materials are handled because they produce radioactive sludge that requires disposal. They also require special fire protection systems because of the combustible nature of the liquid.

5.1.3.33 Electrostatic Precipitator Prefilter

Another type of medium efficiency filter used at DOE facilities is the ESP medium efficiency filter. This medium efficiency filter imparts an electrical charge to particles in the airflow stream, causing them to adhere to collector plates. The ESP medium efficiency filter has been used to extend the life of HEPA filters when processes involve larger-diameter airflow particles. An ESP medium efficiency filter provides some fire protection, as long as the particles resulting from the combustion products of a fire can be properly collected on the filter throughout the fire. Most commercially available ESP medium efficiency filters cannot catch the smaller airborne particles and smoke particles associated with a burning fire. However, more work needs to be done to understand which particle sizes associated with fire can be effectively filtered by an ESP medium efficiency filter. When ESP medium efficiency filters are used, they should be made of noncombustible materials and, as with any medium efficiency filter, the user should pay careful attention to preventing dust loading on the medium efficiency filter during use. In addition, ESP medium efficiency filters should not be used where explosive concentrations of gases or dusts are present.

5.1.3.34 Ceramic HEPA Filters

A ceramic HEPA filter is designed to be noncombustible, corrosion resistant, and compatible with high temperatures and moisture. These filters have the ability to significantly increase filter life span, increase storage life and reduce life cycle costs. These filters are currently under development at the LLNL, the Idaho National Laboratory, and at other DOE sites.

5.1.4 Fire Protection Concepts for Gloveboxes

Fire protection and prevention in gloveboxes is mainly accomplished via the following methods:

- Using noncombustible construction materials. (For information on gloves and windows, which are more vulnerable to fire damage, refer to DOE Standard 1066-99.1, and AGS GO10-2011, *Standard of Practice for Glovebox Fire Protection.*)
- Adhering to acceptable housekeeping policies and procedures.
- Avoiding the use of flammable materials within the box wherever possible. (When no suitable nonhazardous substance can be substituted, the amount of flammables is limited to the minimum required for immediate use. The containers used for flammable substances are safest available for the planned operation.) A Fire Hazards Analysis should be performed by a qualified fire protection engineer establishing the maximum amount of flammable liquid permitted such that the glovebox atmosphere is kept at less than 25% of the lower explosive limit.

- Maintaining a current in-box material inventory. (The box is not used for storage. Boxes usually are inappropriate for storage, especially for chemicals.)
- Establishing a safer, nonoperative box configuration and periodically checking it to ensure that nonoperating boxes are in a safe condition. (Precautions include isolating boxes by closing fire stops, checking through-flow, checking port covers, disconnecting electrical equipment, and removing corrosives.)
- Designing the box with down-draft ventilation (high air inlet, low outlet) to inhibit combustion while still purging the box.
- Providing a protective (inert) atmosphere. (This measure is listed last because those preceding it apply to all gloveboxes, whereas inerting is used only when there is too much risk involved in operating without a protective atmosphere. Assessing the degree of risk involved in an operation is often a subjective evaluation.)

Other methods may be used if analyzed and supported in the FHA. Useful references include the 1999 edition of DOE-STD-1066 and AGS GO10-2011*, Standard of Practice for Glovebox Fire Protection*.

5.1.4.1 Protective Atmospheres

The inerting atmosphere system is designed for continuous operation, whereas the extinguishing system usually has a one- or two-shot, single-incident application before reservicing is required to return the system to the ready state.

Inerting with smothering agents may require that less than one percent oxygen be present in the glovebox atmosphere. Process and product-purity considerations may require as little as 100 ppm[29] of total atmospheric impurities within the glovebox for successful operation. Since many of the detailed considerations are similar for high-purity and fire protection inerting, and because of the widespread application of high-purity inerting, most of this discussion will involve high-purity systems.

Inert-atmosphere gloveboxes that contain radioactive material may be operated at pressure differentials ranging from 0.3 up to 1.5 in.wg negative pressure relative to the surroundings. The gas flow rate is usually determined by the atmospheric purity required and the purity of the incoming gas. The box atmosphere purity can be compromised by air leakage into the box or into service connections, as well as leakage from process equipment in the box.

Filter installation requirements in inert atmosphere gloveboxes can be more stringent than those for air-ventilated boxes because acceptable box air leakage rates can be justified by Helium Mass Spectrometer Detector Leak Analysis with low helium leakage concentrations and maintaining very low PPM oxygen and moisture levels inside the gloveboxes. Joints and fastenings between items of equipment and materials (gaskets and seals) should have extremely low gas permeability. Full-welded joints are recommended for all permanent

[29] Parts per million

fixtures. Gasketed joints may deteriorate in service, imposing continuing costs for periodic testing and repair.

Low-leak systems require quality construction for all components including boxes, filters, and associated ducts. Any in-leakage associated with the filter mounting or connecting duct will adversely affect the quality of the inert atmosphere that can be maintained in the box, and thus the cost of inert gas purification. Penetrations should be minimized in both number and size. The use of smaller HEPA filters allows smaller ports for maintenance. Filter changes should be planned for times when other maintenance operations (routine or special) are taking place inside the box to reduce interruptions to operations, to reduce the loss of inert gas, and to minimize the time required to recondition box spaces.

For fire protection, the preventive step of inerting is more satisfactory, albeit more expensive, though much less than the cost of extinguishing a fire if it were to occur. For normal combustibles an oxygen level of 10% or less is recommended. However, oxygen should be reduced below one percent before it fails to support the oxidation of some pyrophoric metals. The use of dry air (relative humidity less than 20 percent) reduces the hazard of pyrophoric metal fires but does not eliminate it. Moisture in the presence of heated pyrophoric or reactive metals, such as finely divided plutonium, increases the possibility of explosion by generating hydrogen.

The suitability and cost of an inert gas for the process are significant factors when selecting this type of fire control. The gas flow rate in most inert gas boxes is kept as low as possible to be consistent with required box-atmosphere purity levels; low-capacity filters are frequently used. The inert gas may be purged on a once-through basis or recirculated through a purification unit. A word of caution concerning commercially available (off-the-shelf) recirculating gloveboxes: on one occasion at a DOE installation, there was a problem with oil mists developing in the recirculating pumps and being circulated along with the inert gas. Off-the-shelf items cannot be used in a confinement-type ventilation system without evaluation, nor can they be applied as “black boxes” by those responsible for operational safety.

5.1.5 Operations and Maintenance Practices for Fire Protection of Confinement Ventilation Systems

5.1.5.1 Essential Elements

The success of a confinement ventilation system to continue to provide its intended function during a fire situation depends on the reliable operability of the procedures, systems, and barriers as they were designed. To retain that design capability, it is critical that the inspection, testing and maintenance of these systems be accomplished by qualified personnel on an established schedule. Procedures should be practiced, and systems should be regularly inspected to identify procedural issues that may require revision of the maintenance practices and operational procedures.

5.1.5.2 Fire Prevention

The most critical aspect of fire prevention is fuel/combustible control. The storage of any extraneous combustible materials in filter enclosures or areas where radioactive materials are being handled should be strictly prohibited.

Procedures for the use of flammable liquids and gases should be in place and adhered to. Quantities of flammable liquids and gases should be limited to only those required to perform the task.

Accumulation of dust and debris inside the confinement ventilation system ductwork over long periods of operation increases the consequences of any fires that might occur. Periodic cleaning is required to eliminate the presence of undesired fuel.

Appropriate procedures and controls should be implemented to prevent the rapid oxidation of pyrophoric radioactive materials. Much experience exists on the initiation of fires in nuclear facilities that involve or affect the confinement ventilation system. The lessons of the past should be applied to prevent fire from occurring in or affecting confinement ventilation systems.

5.1.5.3 Procedures

All hazards and necessary controls should be delineated in existing operational procedures. Fire protection procedures should complement a facility's safety documentation required by law or contractual obligations.

5.1.5.4 Inspection, Testing, and Maintenance

Inspection, testing, and maintenance requirements for fire detection and suppression systems are contained in the NFPA standards. Proper implementation demands a program that either complies with the NFPA standards or employs a fully justified alternative approach that provides an equivalent degree of reliability.

Establishing and implementing an effective inspection, testing and maintenance program is critical to ensure all fire protection systems associated with the nuclear confinement system will operate as intended. The NFPA Codes and Standards establish the inspection, testing, and maintenance criteria and schedules. In most cases adherence to these codes and standards is required by statute, regulation, or Order. The established schedules can be reduced or extended based on mathematical analysis acceptable to the Authority Having Jurisdiction.

Limited life materials should be identified and replaced according to an established plan, and in the accordance to its listing and or approval.

It is important that water-based fire suppression systems be designed such that they do not have to discharge water on HEPA filter media. Any exposure to water will significantly weaken the filter media and can result in an undesired loss of filtration due to the filter media physically failing. Systems should be designed such that they can be discharge tested without having to actually spray water on the filter media. The design may include covering the filters with plastic, which may also require the isolation of the ventilation flow.

5.1.5.5 Impairment Planning

A program should exist to handle situations where fire detection and suppression systems are impaired. Plans should be developed and instituted to guide facility operations when these systems are not functioning as they should. Impairment plans also should exist for other critical facility systems. The occurrence of an impairment is not the time to develop such plans.

All impairment plans should be analyzed to identify and control to the greatest possible extent the hazards that may exist under a given condition. Impairment programs also identify required compensatory measures such as fire watches and temporary water feeds.

5.1.5.6 Modifications

Modifications in a nuclear facility should follow the protocols for Unreviewed Safety Question determination in accordance with the work control process. This is a somewhat roundabout means of identifying the impact to the established safety basis and all that goes with that, but it is what the current culture understands and accepts. Configuration control should be maintained when modifications are made so that all changes are tracked across all affected documentation and all impacts are identified and understood.

5.1.5.7 Emergency Planning

The successful mitigation of a fire in a nuclear facility containing a confinement ventilation system requires emergency planning and exercises involving all entities that may be called on to mitigate a fire situation. Post-fire recovery plans should exist to aid in the resumption of work in the facility after a fire.

5.1.5.8 Technical Safety Requirements Tie-in

Maintenance and operational procedures may be formalized in the nuclear facility's TSR. Generally, TSRs that apply to fire protection systems will define the operability of the particular system. Operability of the system is nearly always based on the inspection, test, and maintenance criteria within the NFPA Codes and Standards (for example, NFPA 25, 72, 80, 750 and 2001). Also, within the TSR there are compensatory measures dealing with inoperability of a fire protection system. Compensatory measures might include a fire watch, termination of operations, and stopping of hot work.

5.1.5.9 Quality Assurance

All aspects of operations should be clearly linked to the facility's QA Program.

5.1.5.10 Assessments

Periodic management and independent assessment are necessary to ensure that established requirements are adequate and are properly implemented. Refer to Attachment 2 of DOE 420.1C for the required frequencies of such assessments.

5.1.6 Generic Firefighting Procedures

The following recommendations apply to firefighting procedures and instructions. They provide a strategy that minimizes the likelihood of losing filtered, forced ventilation during a fire. These procedures were derived from extensive work at Rocky Flats and are included here because they are generically applicable to all DOE facilities where active fire protection measures are installed for filter housing protection.

A special need for nuclear facilities with confinement ventilation systems is smoke venting. Although smoke cannot be vented to the exterior of a building, there are methods of moving smoke concentrations from one place to another to enable more rapid application of manual suppression.

5.1.6.1 Control Ventilation Configurations, Volumes, and Flow Rates in the Field

An individual who is responsible for ventilation control (and successors or alternates in case of unavailability) should be established in the facility emergency planning documentation. This individual should work in consultation with the fire department sector officer (or incident commander) stationed at incident command, in the control room, or at the housing/plenum to ensure a fire emergency will be successfully mitigated, with minimal impact to the nuclear ventilation system.

DP changes in the initial filter stages should be continuously monitored, even if the DP gauge readout is exceeded. Most gauges have a maximum capability of 4 to 6 in.wg, but a rapid drop from an off-scale high reading to a lower reading will confirm stage failure, as will a significant rise in DP for the next downstream stage. Attention should be focused on the first stage and the next downstream stage until a first stage failure is indicated. A rise in DP may be due to progressive filter plugging from fire particulates or wetting of the filters from deluge spray. Because the initial filter stages are usually (but not always) viewed as sacrificial, the DP may be allowed to rise to the maximum achievable by the fan. If there is only one stage of filtration, then this is not applicable.

For housings/plenums with four stages, the second- and third-stage DP should be monitored at the first indication of a loss of first-stage filter integrity. The third and fourth stage DP should be monitored if the second stage fails.

Ventilation on the affected housings/plenums should be throttled when DP across the final filter stage reaches 2 to 4 in.wg (4 in.wg is the current filter change-out criterion for normal operation).

Failure of initial stages and erosion of margin in the final filter stage is permitted if continued ventilation is necessary to support effective firefighting in the facility. If the fire department officer in charge or incident commander judges that the ventilation system is no longer providing a substantial advantage in controlling or containing the fire, and the emergency commander (generic term) validates that position, action should be taken to protect the ventilation (for example, ventilation should be discontinued at 2 in.wg DP on the final filter stage). Throttling, if selected, should be performed in a manner that maintains the actual DP reading on scale within the 2- to 4-in.wg readings at all times. In no case should ventilation be continued when the differential pressure threatens failure of the final filter stage.

At the first indication of an explosion, the first-stage DP should be monitored for a rapid or complete loss of DP as an indication of failure. The second-stage DP should be immediately monitored under such conditions and the filters should be visually inspected if possible. If the second-stage DP is less than 0.5 in.wg, or greater than 4 in.wg, or if there is visible damage to the second stage, ventilation on the affected housing/plenum should be discontinued. The decision to isolate ventilation should be clearly preplanned and well thought out. Explosive conditions that could clearly impact multiple stages are judged to present too great a risk to any remaining stage to warrant any attempts to maintain active ventilation.

Ventilation should be restored to an affected housing only by the decision of the Emergency Commander or an approved Recovery Plan. Restoration of ventilation should be considered likely to result in a forced convection release from the facility unless other recovery efforts have confirmed no airborne contamination is present in the facility. The decision to restore ventilation also should be preplanned and well thought out.

5.1.6.2 Activation of the Manual Deluge System

The manual deluge system provides an important emergency capability should the first-stage filters be in danger of being consumed by fire. However, manual deluge system activation will likely result in loss of the first stage of filters either through plugging or media failure. Consideration may be given to intermittently flowing the deluge systems with the fans shut down when doing so for short time periods. Before actuating the manual deluge system, the following recommendations should be followed:

- Direct impingement of flame or embers on the first stage filters should be visually confirmed, if possible.
- The manual deluge system should be activated only when it is clearly required, because activation is likely to damage the filters, could cause plugging, and could isolate ventilation. Early activation of manual deluge as a precautionary measure is considered imprudent. If the viewing ports are accessible, they should be used to facilitate confirmation of filter integrity (i.e., visible flaming or smoldering of filter media). Where viewing ports are inaccessible, the inner access doors to the airlocks should be used as an alternative to viewing ports.
- The manual deluge system should be activated only when the fire department officer in charge decides it is necessary, based on a determination from the available evidence that flame is present in the first stage of filters.
- The person in charge of ventilation control at the facility should be authorized to initiate the manual deluge system as necessary prior to fire department arrival. Possible filter plugging and shutdown of ventilation should be anticipated once manual deluge is activated.
- The initial filter stages should be monitored for evidence of plugging or blowout of the first-stage filter (DP changes) and for evidence of either particulate buildup/wetting (DP changes) or flame (visual) on the second and subsequent stages. If flame is confirmed on any downstream stage, all fans connected to the affected housing should be secured immediately.

5.1.6.3 Deluge System Flow Times

The following recommendations address when the deluge system flow should be terminated.

- The housing deluge system flow should be discontinued upon visual verification by the fire department incident commander or other authorized personnel if:
  - (automatic system) there is no visible smoke in the housing upstream of the spray nozzles and temperatures in the filter housings have dropped to or are dropping to safe levels; or
  - (manual system) the fire involving the first stage is extinguished and the spray duration is judged to have sufficiently cooled the filter media and frame.
- Only the fire department incident commander or other authorized personnel should terminate the flow prior to meeting these criteria. Ventilation should only be restored to the affected housing following a decision by Emergency Commander or in accordance with an approved Recovery Plan.
- If filter plugging is preventing effective ventilation, removal of the plugged media should restore ventilation. However, restoration of ventilation is likely to result in a forced convection release from the facility unless other recovery efforts have confirmed there is no airborne contamination in the facility.

The removal of plugged filter media in a confinement ventilation system during a fire situation is fraught with hazards, of course, and should only be done in extreme circumstances.

5.1.6.4 Manual Activation of the Automatic Deluge System

Early activation of the automatic deluge system could increase the potential for the first filter stage to survive. For this reason, the automatic deluge system may be activated manually rather than waiting for high-temperature actuation where early activation provides an advantage. The decision to activate the system should be made by the fire department incident commander and/or the authorized person in charge of ventilation control at the facility based on initial assessment of the fire condition.

Small fires that are under control and expected to be quickly extinguished would not challenge the HEPA filters sufficiently to warrant activation of the system. In addition, the limited available data indicate that early activation is not beneficial in reducing the potential for smoke-induced plugging for those housings equipped with fog jet nozzles for automatic deluge, and the procedures should not call for early activation of the automatic deluge system for those housings. Extensive preplanning should be conducted to define as much as possible the situations in which the automatic deluge system would be manually actuated.

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5.2 Natural Phenomena Hazards

5.2.1 Introduction

This section of the Handbook provides guidance for meeting requirements found in Section 5.2 of DOE-STD-1269-2022, *Air Cleaning Systems in DOE Nuclear Facilities*.

5.2.2 DOE Order 420.1C and DOE Guide 420.1-1A

Safety class and safety significant air cleaning systems are required to meet the applicable Natural Phenomena Hazards (NPH) requirements of Chapter IV of Attachment 2 to the Order, *Natural Phenomena Hazards Mitigation*. Guidance on applying these Order requirements to ventilation systems is provided in DOE Guide (G) 420.1-1A, Section 5.4.12, *Design of Ventilation Systems*, and Table A-1, *Confinement Ventilation Systems Design and Performance Criteria*.[30]

5.2.3 DOE-STD-1020-2016 and DOE-HDBK-1220-2017

Guidance and best practices for applying the NPH requirements of DOE-STD-1020-2016 can be found in DOE-HDBK-1220-2017, *Natural Phenomena Hazards Analysis and Design Handbook for DOE Facilities* (the "NPH Handbook"). For example, the following guidance on mitigating the hazards of volcanic ashfall with respect to ventilation systems is provided in Section 8.4 of the NPH Handbook:

> Section 8.4.6 of the Standard lists some considerations in ventilation design; paramount is filter loading. Designs to accommodate ashfall should account for the airborne concentration, small particle size, and duration of an ashfall event. As noted above in Section 8.3.1, airborne concentration estimates are likely to be imprecise, and a range of values may need to be considered. The small size and abrasiveness of volcanic ash particles may pose unique hazards that should be evaluated in ventilation system design. Ash deposits can be easily re-suspended, so the effects of an ashfall event are likely to linger in a region for days or weeks. In accordance with Section 8.4.6 of the Standard, any effects of ashfall and volcanic gases on other mechanical and electrical systems will also be evaluated.

Section 11 of the NPH Handbook contains an extensive list of technical references and national consensus standards dealing with identifying, analyzing, and mitigating NPH hazards.

5.2.4 Additional References

1. *Seismic Restraint Manual: Guidelines for Mechanical Systems*, 3rd edition 2008, ANSI/SMACNA 001-2008. This document consists of guidelines showing designers and contractors how to determine the correct seismic restraints for sheet metal ducts, piping and conduit used in ventilation systems.
2. ANSI/ASHRAE Standard 171-2008, *Method of Testing Seismic Restraint Devices for HVAC&R Equipment*.

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[30] Note especially the table's items under the headings "External Events" and "Other Natural Phenomena Events."

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(For a more extensive list of NPH references, see DOE-STD-1020-2016)

5.3 Occupational Safety and Health

5.3.1 Introduction

Workers operating and maintaining large ventilation systems in a nuclear facility are exposed to a variety of health and safety risks. Some of these risks are:

- Confined space entry.
- Excessive noise.
- Excessive heat.
- Hazardous biological and chemical substances.
- Respiratory protection.
- Radiation exposure.

The contractor for every DOE nuclear facility is required to have a documented and DOE-approved worker safety and health program that addresses these risks, among many others.[31] This section of the handbook will identify these requirements, associated guidance, and best practices for their application to nuclear air cleaning systems.

5.3.2 Confined Space Entry

Working on a ventilation system frequently involves entering into a confined space, thus activating comprehensive Occupational Safety and Health Administration (OSHA) safety requirements in 29 CFR §1910.[32] Every DOE contractor will have OSHA-compliant confined space entry policies and procedures.

When applying OSHA rules to servicing ventilation systems, these additional best practices should be considered:

a) Specific procedures should be developed in advance for each major maintenance operation. It is not advisable to create the confined space entry procedure as part of the work permit or plan, because time pressures may result in hasty work.

[31] See 10 CFR Part 851, *Worker Safety and Health Program*. (2016)
[32] Imposed on DOE contractors by 10 CFR Part 851. OSHA provides a summary of its confined space program at: https://www.osha.gov/SLTC/confinedspaces/standards.html.

b) Each confined space entry procedure should be walked down fully and adjusted when practical problems are discovered.
c) Each entry procedure should cover all equipment needed to carry out maintenance operations, including personal protective gear. This equipment should be procured, checked, and stored well in advance of actual confined space operations.
d) After the conclusion of each confined space operation, lessons learned should be used to correct and improve the procedure.
e) If a violation of OSHA confined space rules occurs, the cause of the violation should be investigated and remedial actions taken.

5.3.3 Excessive Noise

The driving machinery of large ventilation systems (chiefly motors and fans) may create high sound levels in confined spaces. Workers can be exposed to hazardous sound levels when conducting in-operation repairs or maintenance checks.

OSHA safety requirements for noise hazards are contained in 29 CFR §1910.95, *Occupational Noise Exposure*. Additional OSHA guidance and standards in this area can be found at: https://www.osha.gov/SLTC/noisehearingconservation/. ASHRAE, *Handbook of Fundamentals*, Chapter 8, "Sound and Vibration" (2017), provides useful guidelines and best practices.

When applying OSHA rules on the protection of workers from sound hazards, these additional best practices should be considered:

a) The facility should compile a list of areas where excessive sound levels associated with ventilation systems are present. Each such area should be surveyed to determine the necessary level of hearing protection for workers entering the area for any reason.
b) Sound protection procedures for each designated area should specify the protective equipment required for workers to enter the area, even if just momentarily. This equipment should be procured, checked, and stored in the vicinity of the area for which hearing protection is required.
c) Workers at all levels should be cautioned via prominent signs that entry into a high-noise area without proper hearing protection is prohibited except for emergencies.
d) If a violation of OSHA noise rules occurs, the cause of the violation should be investigated and remedial actions taken.

5.3.4 Excessive Heat

As in the case of excessive noise, the environment surrounding the machinery of a large ventilation system in operation can be extremely hot. Moreover, when the machinery is shut down for repairs or filter replacements, workers may have to work in a hot, stagnant atmosphere, and may also be required to wear personnel protective clothing that makes heat stress more likely.

Both OSHA and NIOSH (National Institute for Occupational Safety and Health, part of the Centers for Disease Control and Prevention) have been active for many years in promoting protection of workers from excess heat exposure. The most recent development is NIOSH's 2016 document, "Criteria for a Recommended Standard Occupational Exposure to Heat and Hot

Environments."[33] NIOSH maintains a website dealing exclusively with heat stress.[34] Applicable OSHA requirements are stated on an OSHA web page.[35]

Finally, 10 CFR Part 851 requires the following:

> (a) With respect to a covered workplace for which a contractor is responsible, the contractor must: (1) Provide a place of employment that is free from recognized hazards that are causing or have the potential to cause death or serious physical harm to workers …"

When applying OSHA rules on the protection of workers from heat stress, these additional best practices should be considered:

a) The facility should compile a list of areas where excessive heat associated with ventilation systems may be present either during operations or during maintenance tasks. Each such area should be surveyed to determine the necessary level of heat stress protection for workers entering the area for any reason.
b) Heat stress procedures for each designated area should specify the protective equipment required for workers to enter the area, even if just for a brief time. This equipment should be procured, checked, and stored in the vicinity of the area for which heat stress protection is required.
c) Workers at all levels should be cautioned via prominent signs that entry into a high-heat area without proper personal protection is prohibited except for emergency situations.
d) If a violation of OSHA heat stress rules occurs, the cause of the violation should be investigated and remedial actions taken.

5.3.5 Hazardous Biological and Chemical Substances

A 2013 scientific paper authored by Polish researchers reached the following conclusions concerning the biological and chemical hazards of ventilation systems:[36]

> Regular checking on the cleanliness of the ventilation systems, as well as their periodic cleaning and, if necessary, disinfection are for the proper maintenance of each system. During maintenance operations (repairs, cleaning, filter replacement), workers are at risks associated with exposure to hazardous chemicals and harmful biological agents. In ventilation systems there are usually favorable conditions for the development of microorganisms, mainly bacteria and fungi, due to surfaces contaminated with dust particles or increased humidity caused by ventilation ducts, air filters, thermal insulation, noise dampers, air coolers, etc. Workers who perform cleaning and disinfection operations on ventilation systems are exposed to chemical agents through contacts with contaminants released from sealing materials, adhesives, fireproof lining

[33] Available at https://www.cdc.gov/niosh/docs/2016-106/default.html.

[34] https://www.cdc.gov/niosh/topics/heatstress/default.html.

[35] https://www.osha.gov/SLTC/heatstress.

[36] Medycyna Pracy, 2012; 63(6):711-22, "Exposure of ventilation system cleaning workers to harmful biological and chemical agents."

and insulating materials, volatile organic compounds present in air filters, noise dampers and insulating materials, as well as with cleaning agents and disinfectants. Exposure to harmful chemical and biological agents may induce adverse health effects ranging from allergic reactions and irritation through infections to toxic reactions and other non-specific symptoms. Due to lack of studies on the exposure of this group of workers, employers face great difficulties in identifying hazards, which prevent them from performing an occupational risk assessment.

DOE has in place a set of general requirements to address biological and chemical hazards. The primary requirements are imposed by 10 CFR Part 851, which mandates compliance with 29 CFR 1910, subpart H, "Hazardous Materials," and with ACGIH, ''Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices,'' (2016). Section 7 of Appendix A to Part 851, "Biological Safety," sets out a program for dealing with biological hazards. Guidance on controlling chemical hazards may be found in DOE Handbook 1139, *Chemical Management*, 2004.

Because addressing the chemical and biological hazards of ventilation systems is a complex task, it is a best practice to prepare a complete occupational risk assessment that takes into account the applicable OSHA requirements and the ACGIH standard. This assessment will serve as the basis for establishing worker controls to protect all facility workers operating or maintaining ventilation systems. The assessment should be revisited on a regular basis not to exceed five years.

Ventilation systems should be designed to minimize the need for workers to use respiratory protection. The goal is to remove the hazard or mitigate the hazard with engineering controls: provide ventilation so that personal protective equipment is not needed, and administrative controls to define safe operating conditions. Design considerations include generation rates, maximum allowable concentrations, the presence of chemicals that can result in combined impacts, and allowable stack release rates. These design considerations facilitate the calculation of removal efficiencies, allowable leak rates of ductwork and equipment, required dilution ventilation airflow in workspaces, and stack flows and concentrations.

5.3.6 Respiratory Protection

Both 10 CFR Part 851 and OSHA's 29 CFR 1910 (§1910.134, "Respiratory Protection") address this topic extensively. Part 851's citation of American National Standards Institute (ANSI) Z88.2, ''American National Standard for Respiratory Protection,'' (1992) now refers to a revised standard, ANSI/ASSP Z88.2-2015, "Practices for Respiratory Protection."

When applying OSHA rules and ANSI standards on respiratory protection, these additional best practices should be considered:

a) The facility should compile a list of areas associated with ventilation systems where respiratory protection for workers may be needed.

b) Respiratory protection procedures for each designated area should specify the protective equipment required for workers to enter the area, even if just for a brief time. This equipment should be procured, checked, and stored in the vicinity of the area for which respiratory protection is required.

c) Workers at all levels should be cautioned via prominent signs that entry into a respiratory protection area without proper personal protection is prohibited except for emergencies.

d) If a violation of OSHA respiratory protection rules occurs, the cause of the violation should be investigated and remedial actions taken.

5.3.7 Radiation Exposure and the ALARA Principle

DOE's requirements for protecting workers from radiation are set out in 10 CFR Part 835, *Occupational Radiation Protection*. Relevant DOE technical standards include the following:

- DOE-STD-1098-2017, *Radiological Control.*
- DOE STD-1107-97, *Knowledge, Skills, and Abilities for Key Radiation Protection Positions at DOE Facilities.*
- DOE-STD-1121-2008, *Internal Dosimetry.*
- DOE-STD-1128-2013, *Good Practices for Occupational Radiological Protection in Plutonium Facilities.*
- DOE-STD-1136-2017, *Good Practices for Occupational Radiological Protection in Uranium Facilities.*

Guidance documents pertaining to radiation hazards include the following:

- DOE G 441.1-2, *Occupational ALARA Program Guide.*
- DOE-HDBK-1129-2015, *Tritium Handling and Safe Storage.*

Radiation safety training is addressed in the following documents:

- DOE-HDBK-1122-2009, *Radiological Control Technician Training.*
- DOE-HDBK-1130-2008, *Radiological Worker Training Materials* (Reaffirmed 2013).
- DOE-HDBK-1131-2007, *General Employee Radiological Training* (Reaffirmed 2013).
- DOE HDBK-1145-2013, *Radiological Safety Training for Plutonium Facilities.*

In nuclear facilities, the primary source of ventilation-related occupational radiation exposure is to service and replace HEPA filters that have filtered radioactive materials. HEPA filter replacement projects are required to apply all of DOE's radiation safety and ALARA requirements and guidance as set out above. The following best practices should be considered for application during HEPA filter change out process:

(a) Because used HEPA filters have accumulated significant amounts of dust and particulate matter, the weight of the filters should be considered when planning replacement.
(b) The sharp edges and corners of HEPA filters have the potential to cause personal injury. Planning should account for this hazard.
(c) The fragility of HEPA media should be considered to ensure that the filters remain intact during changeout and no particulate matter is released.

(d) Changeout planning should cover space considerations: working space, areas for placement of tools and new/used filters, and egress paths for discarded filters.
(e) Changeout planning should include specific methods for transporting new and used filters to and from the filter housing.
(f) Briefings of all staff involved in the changeout process should be conducted prior to commencement of the operation.

5.4 Deep-Bed Sand Filters

5.4.1 Introduction

This section of the Handbook provides guidance and best practices for meeting requirements found in Section 5.4 of DOE-STD-1269-2022, *Air Cleaning Systems in DOE Nuclear Facilities*. The content of this section has been drawn principally from the 2003 edition of the *Nuclear Air Cleaning Handbook*, DOE-HDBK-1169 (archived).[37]

5.4.2 Overview of Deep-Bed Sand Filters

DBS filters have been used in the ventilation and process exhaust systems of radiochemical processing facilities since 1948. The major attractions of DBS filters include large dust-holding capacity, low maintenance requirements, inertness to chemical attack, high heat capacity, fire resistance, and the ability to withstand shock loadings and large changes in airstream pressure without becoming inoperative. The disadvantages of DBS filters include high capital cost, large area, high pressure drop, high power costs, uncertainties in selection, availability, grading, and handling of suitable sands, and disposal of the spent unit. In accordance with ASME AG-1, Non-Mandatory Appendix FL-B, a large-scale DBS filter mock-up supports seismic calculations. Testing of the mock-up will provide validation of the response of the DBS filter structure and media to a design basis earthquake.

DBS filters are deep (several feet thick) beds of rock, gravel, and sand, constructed in layers graded with about two-to-one variation in granule size from layer to layer. Airflow direction is upward, and granules decrease in size in the direction of airflow. A top layer of moderately coarse sand is generally added to prevent fluidization of finer sand. The rock, gravel, and sand layers are positioned and sized for structural strength, cleaning ability, dirt-holding capacity, and long life. **Figure 5.1** shows the cross-section of a typical DBS filter.

Ideally, the layers of larger granules, through which the gas stream passes first, remove most of the larger particles and particulate mass, and the layers of finer sands provide high-efficiency removal. Below the fixed bed of sand and gravel is a course of hollow tile or steel grating that forms the air distribution passages.

The filter is enclosed in a concrete-lined pit. The superficial velocity is around 5-7 fpm, and the pressure drop across multiple layers, sized from 3 1/2 inches to 50 mesh, is from 7 to 11 in.wg.

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[37] Some historical material has been omitted. All historical material is preserved in the archived version of NACH 2003.

Collection efficiencies up to 99.98 percent [determined by in place test with polydispersed 0.7-number mean diameter (NMD) test aerosol have been reported.

A removal efficiency approaching that of a single HEPA filter has been claimed for DBS filters if the proper sands are used and the contact path is long enough. Efficiency tests of DBS filters can only be made using polydispersed test aerosols with an NMD of about 0.7 µm. True efficiency tests of HEPA filters, on the other hand, are made with a monodispersed test aerosol with an NMD of 0.3 µm. In addition, tests of very large units, such as DBS filters, are often made under conditions that sometimes yield results difficult to interpret. For these reasons, although the efficiency of DBS filters approaches that of HEPA filters, it should not be assumed that the efficiency of DBS filters for submicron particles is equivalent to that of HEPA filters.

Following initial installation of a DBS filter at DOE's Hanford Site, nine others were installed at Hanford, SRS, the Midwest Fuel Recovery Plant at Morris, Illinois, and the Zero Power Physics Reactor at Idaho Falls. As of the date of publication, SRS has five functional DBS filters: two servicing F Canyon and H Canyon, one servicing the Defense Waste Processing Facility, one servicing a facility (235-F) that supported Pu238 RTG (Radioisotope Thermoelectric Generator) production, and one servicing Savannah River National Laboratory. Details of existing and former DBS filters are given in **Table 5.2**. Properties of sands and aggregates used as the filtration media of these filters are given in **Table 5.3**.

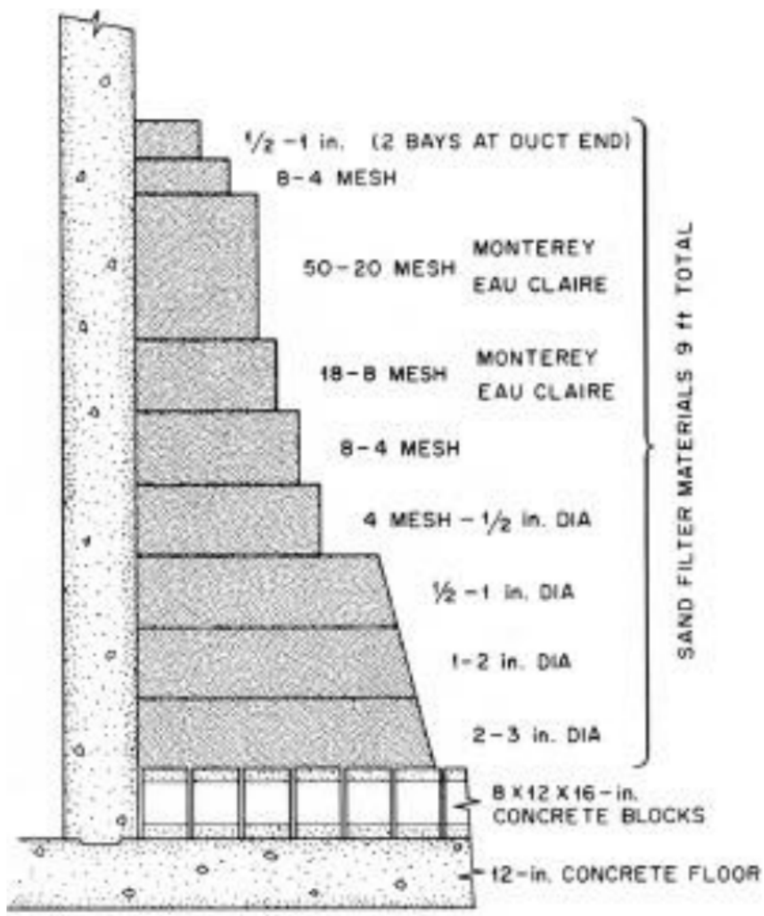

Figure 5.1: Section through Typical Sand Filter

Table 5.2 – Dimensions and Operating Data for U.S. Deep-Bed Sand Filters

DBS Filter No. a	Plan Dimensions b (ft)	Design Flow (cfm)	Design Superficial Velocity (fpm)	Design Pressure Drop (in.wg)	Year of Initial Operation
1	108×46	25,000	5.0	5.0	1948
2	108×46	25,000	5.0	7.0	1948
3	96×96	40,000	4.3	10.0	1950
4	85×85	40,000	5.5	12.0	1951
5	240×100	20,000-30,000	4.8	10.0	1954
6	240×100	20,000-30,000	4.8	9.2	1955
7	360×100	210,000	5.8	10.0	1975
8	360×100	210,000	5.8	10.0	1976
9	140×103	74,000	5.1	Not available	1974
10	72×78	32,000	5.7	Not available	1974
11	50 to 62.5	Not available	d	Not available	1968
12	120 x 192	115,000	5.0	8.0	1995
13	99x83	30,500	3.9	Not available	1987

a Filter identification:

1. T Plant, Building 291-T, Hanford West Area, Richland, WA.
2. B Plant, Building 291-B, Hanford East Area, Richland, WA.
3. U Plant, Building 291-U, Hanford, Richland, WA.
4. Redox Facility, Building 291-S, Hanford, Richland, WA.
5. F Area, Building 294-F, Savannah River Site, Aiken, SC.
6. H Area, Building 294-H, Savannah River Site, Aiken, SC.
7. F Area, Building 294-1F (new), Savannah River Site, Aiken, SC.
8. H Area, Building 294-1H (new), Savannah River Site, Aiken, SC.
9. SRL, Building 794-A, Savannah River Laboratory, Aiken, SC.
10. Midwest Fuel Recovery Plant (MFRP), [c] Morris, IL.
11. Zero Power Plutonium Reactor Facility, Argonne National Laboratory, Idaho Falls, ID.
12. S Area, Defense Waste Processing Facility, Savannah River Site, Aiken, SC
13. F Area, Building 294-2F, Savannah River Site, Aiken, SC.

b Inlet side shown first, outlet side italicized.

c MFRP is not engaged in reprocessing, only storage; sand filter is active.

d This is an emergency relief system.

Table 5.3 – Properties of Sands and Aggregates Used in U.S. Deep-Bed Sand Filters

Property	Filter No. [a]									
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9, 12***	***10***
Depth of bed, feet	9	8.5	8	8	8	8	7.5	7.5	7.5	8
Number of layers	9	8	7	7	7	7	6	6	6	
Depth of layers (inches)										
Granule size range, mesh (unless inches noted)										
Layer A 2-3 inches	12									
2 1/2-1 1/4		12								
3-1 1/4 in					12	12	12	12	12	
3-1 in			12	12						18
Layer B 1-2 in	12									
1 3/4-5/8		12	12	12						12
1 1/2-5/8 in					12	12	12	12	12	
Layer C 1-1/2 in	12									
3/4 in ~ 6		12	12	12						
5/8-1/4 in					12	12	12	12	12	
Layer D 1/2 in -4	12									
3/8 in -3										12
Layer E 4-8	12	6	6	6	6	6	6	6		6
1/4 in -8									6	
Layer F 8-20	12	12	12		12	12	12	12	12	6
8-18				12						
Layer G 20-40										
30-50					36 b	36	36	36	36	
20-50			36	36 b						36

a See Table 5.2 for locations corresponding to number.
b Removed 12 inches from G layer, July 1972, to reduce pressure drop.

5.4.3 Deep-Bed Sand Filter Design

A rough approximation of the collection efficiency of sand, on an activity basis, is given by the following equation:

$$F = -\exp(-KL^{1/2}V^{-1/3}D^{-4/3})$$

where:

F = fractional collection efficiency on a radioactivity or mass basis (dimensionless)

L = depth of fine sand, feet

V = superficial gas velocity, fpm

D = average sand grain diameter, inches

K = proportionality factor (dimensionless)

Note: The values of L, V, and D vary with sands from different sources of the same mesh size and need to be determined experimentally for any given sand.

Values for the proportionality constant, *K,* for several sands tested at Hanford are:

Type of Sand	K
Hanford	0.053
AGS flint	0.045
Rounded grain sand (Ottawa, Eau Claire, Monterey)	0.035

Collection efficiency on a radioactivity basis gives a higher number than the collection efficiency on a count basis, as reflected by the test aerosol test, because larger, more easily collected particles may carry more radioactivity and bias the analysis to give greater value to larger particles. The relationship between count and activity collection efficiency cannot be determined without accurate information on aerosol size distribution and the relationship of aerosol size to radioactivity.

The approximate void fraction of a sand bed is generally about 0.4. Sand permeability tests have shown that intense vibration can cause extreme compaction, resulting in near doubling of the pressure drop. Factors that should be considered include the effects of compaction, steam injection, relative humidity, and velocity change on efficiency and pressure drop. Besides permeability and filtration requirements, the sand should be abrasion-resistant and fracture-resistant and should resist corrosion from the fumes likely to be present in the exhaust airstream. Additional properties of sandfilter media can be found in ASME AG-1, Section FL.

Filter life is determined by the increase in pressure drop and the decrease in gas flow caused by the collection of solids within the sand bed. Filter life can be significantly reduced if solids collection is concentrated in small fractions of the bed or on the finer sand. Uniform concentration of coarse aggregate layers upstream of the fine sand layer tends to maximize filter life.

Clogging of DBS filters is aggravated by local decreases in porosity at the interfaces between graded layers. The mixing of aggregates (sand, gravel) at the interfaces usually results in a lower void fraction at the interface than if no mixing is permitted. The extent of reduction in void fraction depends on the characteristics of the aggregates and on the technique used to charge them into the filter bed. The lowest layer may require hand placement for the first few inches so that no rocks fall through the openings in the distribution blocks. Significant improvement in filter life can be obtained by careful attention to loading. An isometric of this filter is shown in **Figure 5.2**.

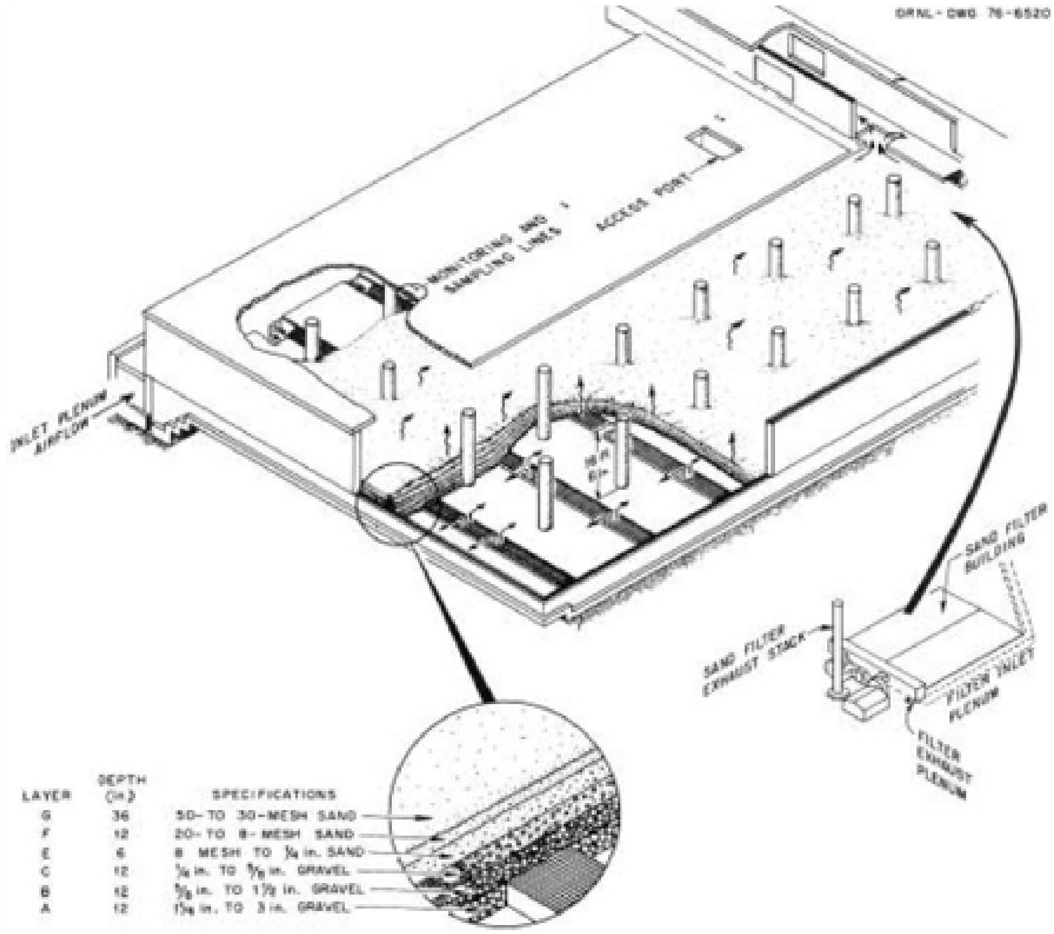

Figure 5.2: Isometric View and Details, Sand Filter at Savannah River National Laboratory

5.4.4 Deep-Bed Sand Filter Plugging

Some filters have experienced plugging at low dust loadings. In one case, the plugging was caused by moisture entering through cracks in the concrete sidewalls of the unit. In another instance, plugging was caused by crystal growth in the filter media fines, probably due to a reaction of nitric acid vapors from the process building with calcite, with dolomite present in the original sand, and with cement dust generated by severe erosion and acid attack on the concrete entry ducts and support structures.

5.4.5 Spent Media Disposal

Deactivation of existing filters is generally accomplished by sealing and abandoning the filter. Spent media are stored in place within the unit. The total unit is replaced by a new filter located close by. Present Government regulations for radioactive solid waste, though unclear, may rule out such in-place disposal in the future. If the material were handled as high-level radioactive waste, each 1,000-cfm capacity of filter would require about two hundred 55-gallon drums for disposal.

5.4.6 Burial in Place

Burial in place (or entombment) for DBS filters is feasible and could be economical if provisions are applied during initial design of the filters to ensure that the walls, floors, and roof integrity are sufficient to satisfy the requirements of 10 CFR Part 61, *Licensing Requirements for Land Disposal of Radioactive Waste*, and the requirements of other regulatory bodies such as the U.S. Environmental Protection Agency.

5.4.7 Decontamination

Because of the irregular surface areas and porous nature of the clay tile, stones, gravel, and sand filter media utilized in DBS filters, decontamination methods currently available would be mostly ineffective. Ancillary materials such as concrete confinement walls and supports and steel grating, if utilized, are potential candidates for decontamination, but make up a relatively small percentage of the total mass of the DBS filter.

5.4.8 References

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