CHAPTER 2

SYSTEM CONSIDERATIONS

2.1 Introduction

A nuclear air cleaning system is an assembly of interrelated, interactive parts that include the air cleaning system components, the contained space served by the air cleaning system (e.g., the glovebox, hot cell, room, or building), and the processes served by that system.

This chapter discusses the design, operational, and codes- and standards-related requirements for nuclear facility air cleaning systems. Topics will include system, subsystem, and component design considerations, as well as general descriptions of various systems used in production and fabrication facilities, fuel processing and reprocessing plants, research facilities, storage facilities, and other applications. This chapter will also consider operating costs and how the design of an air cleaning system directly affects the ventilation system performance and costs. Examples of some lessons learned from the operation and maintenance of nuclear air cleaning systems will be provided.

2.2 Environmental Considerations

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);
- Heat (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 or accident hazard considerations.

In designing an air cleaning system, development of the environmental operating conditions must be the first step. Before appropriate individual system components can be environmentally qualified, the designer must 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 must be identified prior to system design because they must be the basis for the equipment design. If the environmental parameters are carefully considered, a detailed analysis of cost versus long-term operation will 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 2.1** lists some common system environmental parameters that should be considered for system design.

Table 2.1 – Environmental Parameters for System Design

Parameters	*Examples*
Types of gases treated	Air, hydrogen, oxygen, nitrogen, argon, etc.
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, and direct introduction of water sprays for fire protection.
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 (internal), tornado (external)
Design life and operating life	Projected facility and equipment operating life [e.g., high-efficiency particulate air (HEPA) filter service life].

2.2.1 Airborne Particulates and Gases

To properly design an air cleaning system and optimize its performance, the types of contaminants in the gas stream must be identified. All of the contaminants, both particulate and gaseous, including concentration levels and particle sizes, must be evaluated to properly design and size the system. The presence of other particulates, gases, and chemicals must be clearly determined. The presence of volatile organic chemicals (VOCs), entrained water, and acids will affect the performance of various system components and must be addressed, if they are present, in the design of the system and its components.

Intake air cleaning systems or supply systems filter the atmospheric dust 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 offgassing of materials such as paint, solvents, carpets, and furniture. All of these factors must be considered in determining the parameters for proper system design. These contaminants contribute to degradation and sometimes 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.[1] They are also recognized as among the health hazards of nonradioactive air pollution. As shown in **Table 2.2**, over 99 percent, by count, of typical urban air samples have a mean particle size of 0.05 μm.

Table 2.2 – 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

Reports of dust concentrations in air are generally based on the masses of the particulate matter present. As shown in Table 2.2, 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 prefilters. On the other hand, the HEPA filter is highly efficient for all particle sizes down to and including the smallest shown in Table 2.2. The 99.97 percent minimum efficiency claimed 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 ($\mu g/m^3$) in rural areas to more than 20 mg/m^3 in heavily industrialized areas. 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 cubic feet (ft^3). Atmospheric dust concentrations can vary significantly through the year.[2]

Filter selection, particularly prefilter and building supply filter selection, must consider the atmospheric dust concentrations that can be encountered at a particular site at any time of the year.

Figure 2.1, *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 2.2**. A major source of the lint often found on filters is derived from the abrasion of clothing as people move about. In addition, a person at rest gives off more than 2.5 million particles (skin, hair, etc.) and moisture droplets/minute in the size range of 0.3 to 1 µm.[3] Process-generated aerosols fall into two general size ranges. Those produced by machining, grinding, polishing, and other mechanical operations are generally large, (from 1 to several hundred µm), according to the nature of the process, and can be removed effectively by common air filters or other conventional air cleaning techniques. The other size range includes those produced by evaporation/condensation and other chemical operations, which generate droplets and solid

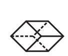
Description	Appearance	Kinds	Percent Present by Weight	
			Range	Average
Spherical		Smokes Pollens Fly Ash	0-20	10
Irregular Cubic		Minerals Cinder	10-90	40
Flakes		Minerals Epidermis	0-10	5
Fibrous		Lint Plant Fibers	3-35	10
Condensation Flocs		Carbon Smokes Fumes	0-40	15

Figure 2.1 – Distribution of Particles

particles that are often submicrometer-sized. These aerosols are more difficult to separate from air or gases, requiring collectors such as HEPA filters. Ultra Low Penetration Air (ULPA) filters provide a higher cleaning efficiency (up to 99.9999 percent for submicrometer particles). [Note: A need for this level of efficiency is rare for nuclear applications. The media used in ULPA filters is weaker than that used in nuclear-grade HEPA filters, a factor that must be considered for any application of ULPA filters to a nuclear air cleaning system or other applications where durability and reliability are concerns.]

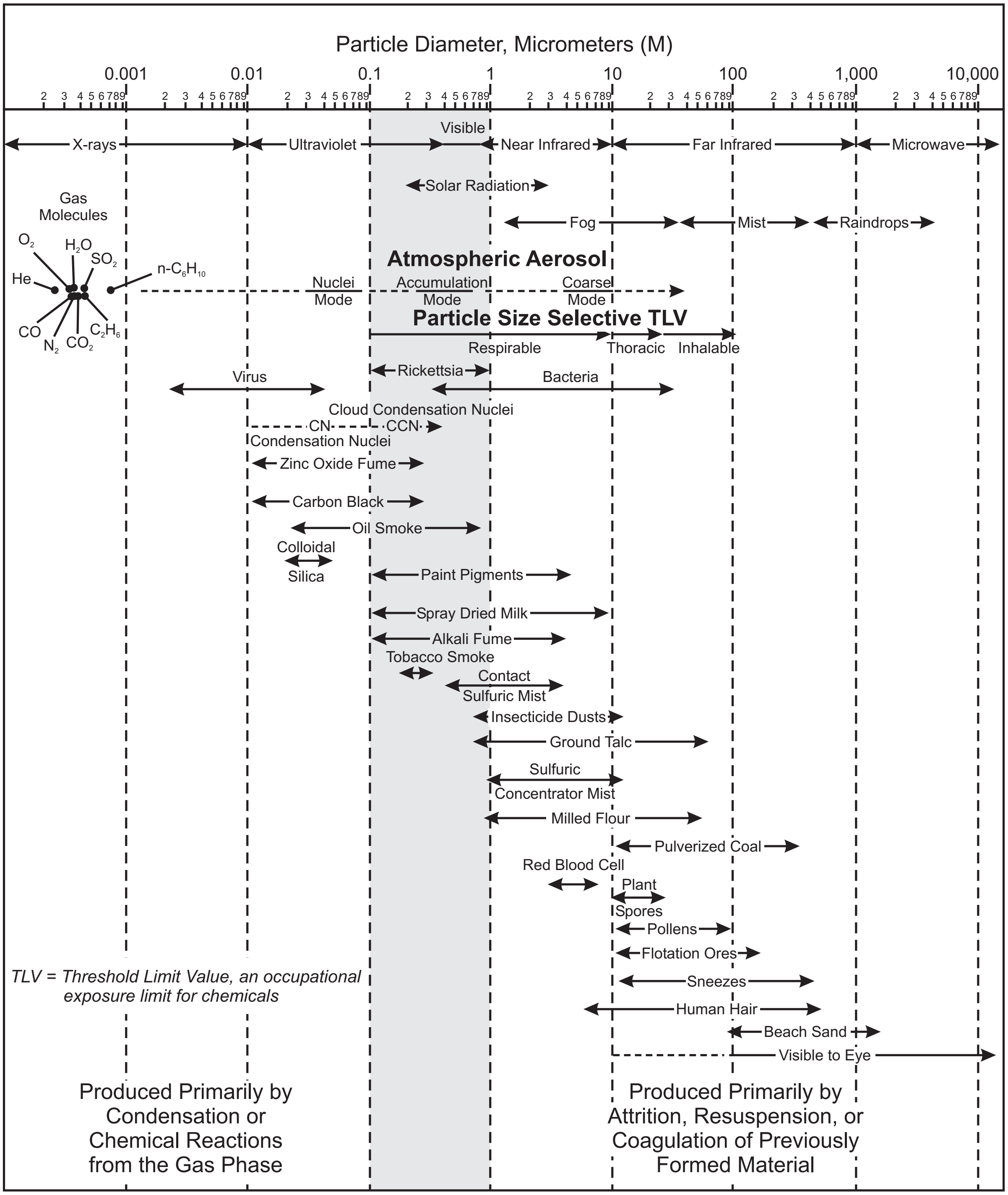


Figure 2.2 – Characteristics of Atmospheric and Process-Generated Particulates, Fumes, and Mists and Effective Range of Air Cleaning Equipment

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 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. The halogen gases, essentially elemental iodine and certain volatile organic iodides, are captured by adsorption either on activated carbon or certain synthetic zeolites.

2.2.2 Pressure

Pressure is one of a number of variables that needs to be evaluated in the course of designing the air cleaning system because it can significantly affect the fan power requirements and the airflow rate. The pressure of the airstream can be impacted significantly by the change from the normal operating pressure to the accident or upset air pressure (e.g., fire may cause pressure increases). See Chapter 5, Section 5.4, entitled "Fans and Motors," for fan requirements.

2.2.3 Moisture

Moisture is an important consideration in air cleaning system design. Moisture in the air may affect the performance of the air cleaning system by binding the particulate filters and/or blocking pores and fissures in the activated charcoal. Where water mist or steam can be expected under either normal or upset conditions, moisture separators and heaters, if appropriate, must be provided upstream of the filters to prevent plugging, deterioration, and reduced performance. Condensation from saturated air and gas streams or carryover from air washers and scrubbers are common sources of moisture. When fire-protection sprinklers are provided in operating areas, ducts, or plenums, moisture can be drawn into the filters if they are activated. In nuclear reactors, large volumes of steam and moisture should be expected in the highly unlikely event of a major loss-of-coolant accident (LOCA) or heat exchanger failure. Moisture on the face of a filter will blind or plug the filter, creating the potential for filter failure. [Note: HEPA filters exposed to carryover from intentional or inadvertent fire sprinkler actuation must be replaced.]

Condensation is particularly troublesome when filters are installed in underground pits, in outdoor housings, or in unheated spaces within buildings. Even when the air entering through the ducts is above the dew point, duct walls, dampers, or filters may be cold enough to cause condensation on their surfaces. Condensation can also take place in standby systems. Inspection of standby filters on a monthly or even weekly basis is recommended to prevent the detrimental effects of condensation.

2.2.4 Temperature

Although some air cleaning system components are prequalified to operate in a given temperature range, the air cleaning system designer must verify all components of the system will function at 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-filled adsorbers.[4] 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 evidence that the filters are qualified for the higher-temperature environments of the specific application.

For high-temperature applications, particulate filtration can be accomplished with the use of metal filters constructed of sintered metal or metal mesh. The construction and performance requirements for metal filters will be found in American Society of Mechanical Engineers (ASME) Code AG-1, *Code on Nuclear Air and Gas Treatment*.[4] 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 iodine-impregnated activated carbon) is 280 degrees Fahrenheit.

When temperatures higher than the operating limits of air cleaning system components must be accommodated, chilled water coils, heat sinks, dilution with cooler air, or some other means of cooling must be provided to reduce temperatures to levels that the components can tolerate. Environmental qualification of an air cleaning system must address thermal expansion and the heat resistance of ducts, dampers, filter housings, component mounting frames and clamping devices, and fans. Electrical and electronic components are specifically susceptible to high and low temperatures and must be designed and qualified for Safety Class and Safety Significant systems in accordance with the ASME AG-1 Code[5] and Institute of Electrical and Electronics Engineers (IEEE) 323, *Standard for Qualifying Class 1E Electrical Equipment for Nuclear Generating Stations*[5] and IEEE 344, *Recommended Practice for Seismic Qualification of Class 1E Equipment in Nuclear Generating Stations*.[6] Operational consideration also must be given to the flammability of dust collected in the ducts and on the filters. All Safety Class and Safety Significant systems must be built to ASME AG-1.

2.2.5 Corrosion

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., perchloric acid salts and ammonium nitrate) that must be specifically considered in the design and operation. The air cleaning system designer must select components and materials of construction suitable for the corrosive environment to ensure high levels of system performance and reliability.

Acid-resistant prefilters 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 corrosive atmosphere, in accordance with the ASME AG-1 Code[4], 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.

Stainless steel is recommended for ductwork and housings when corrosion can be expected. Even this material may be insufficient in some cases, and coated (e.g., vinyl, epoxy) stainless steel or fiber-reinforced plastics may be necessary (corrosion-resistant coatings are covered by American Society for Testing and Materials (ASTM) D5144, *Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants*.[7] 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 perchloric and ammonium nitrate salts, but consideration must also be given to moisture carryover if the scrubbers or air washers are not designed and operated properly. Stainless steel moisture separators are recommended ahead of the filters. Corrosion is always a danger, but is not always obvious. In activated carbon-filled adsorbers, for example, even trace amounts of nitrous oxide or sulfur dioxide will concentrate in the adsorbent over time. 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, contacts corrode, etc. For this reason, all electronic components must be environmentally qualified for the intended application.

Care must 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. In addition, care must be exercised for gasket stability when dealing with radiation. Radiation may also lead to undesirable reactions such as decomposition of Teflon™ into hydrofluoric acid.

2.2.6 Vibration

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. Excessive vibration or pulsation can result in eventual mechanical damage to system components when accelerative forces (e.g., from an earthquake or tornado) coincide with the resonant frequencies of those components. Weld cracks in ducts, housings, and component mounting frames can 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 over longer periods.

Vibration produces noise that can range from the unpleasant to the intolerable. Important factors in the prevention of excessive vibration and noise include planning at the initial building layout stage and space allocation to ensure that 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 be resolved during early design to avoid the compromises so often made during construction that frequently lead to poor duct layout and resulting noise and vibration. Ducts should be sized to avoid excessive velocities, while maintaining the transport velocities necessary to prevent the settling out of particulate matter during operation. Fan vibration can be minimized through the use of vibration isolators and inertial mountings. Some designers require hard mounting of fans where seismic requirements and continued operation during and after an earthquake must be considered. Flexible connections between the fan and ductwork are often employed, but must be designed to resist seismic loads and high static pressures, particularly in parts of the system that are under negative pressure to minimize air-in leakage. Finally, the ductwork system must 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 have been inadvertently introduced during construction.

2.2.7 Electrical

Emergency electrical power is required when specified by facility safety documentation. Emergency power has specific requirements and may not be required for all systems. Standby electrical power is used for many safety air cleaning systems not classified as Safety Class. Standby power is required for safety-significant air cleaning systems.[8, 9, 10] The amount of emergency power required for fans, dampers, valves, controls, and electrical heaters to control the relative humidity of the effluent airstream (as dictated by the facility design requirements) must be accounted for during accident or upset conditions. Close coordination between the system designers of both the air cleaning and electrical systems is required to ensure this is done, as there is a set amount of emergency power available.

2.2.8 Radiological Considerations

Radiation may affect the air cleaning system in at least three different ways:

- The buildup of radioactive material in and around the air cleaning system may limit personal access during operations and maintenance, and must be specifically factored into the design.
- The buildup of radioactive material in and around the air cleaning system may lead to special considerations for construction materials used for the system—particularly those containing Teflon® or Kel-F®. This buildup can also limit component life.
- The amount of radioactive material that may be released limits the acceptable selection and operating ranges for the air cleaning system components (e.g., the HEPA and adsorption units).

The design of workroom ventilation systems should be consistent with the requirements of 10 CFR 835, *Occupational Radiation Protection,* Subpart K, "Design and Control," which establishes the U.S. Department of Energy's (DOE) design objectives for workplace radiological control.[11] Two key components of these requirements are that: (1) for controlling airborne radioactive material, under normal conditions, the design objective will be to avoid releases to the workplace atmosphere, and (2) confinement and ventilation will normally be used to accomplish this objective (i.e., engineered controls should be applied rather than relying on administrative controls). Furthermore, effluent releases from ventilation systems must be in accordance with DOE directives and relevant regulatory requirements (e.g., DOE Order 5400.5, *Radiation Protection of the Public and the Environment*,[12] and 40 CFR Part 61, subpart H, *National Emission Standards for Air Pollution*.[13]

All work conducted within areas serviced by these ventilation systems, or work on the systems themselves, should be performed in accordance with site policies and procedures. The requirements for control of radiation and radioactive material in the workplace are contained in 10 CFR 835.[11] This rule also establishes the requirements for monitoring of workplaces within and surrounding these areas, and that these activities should be conducted in accordance with site policies and procedures.

Some systems have actually experienced radiological degradation from excessive radiation exposure (e.g., the A and B underground filters at the Hanford B-Plant). Radiological degradation, overloading, and faulty installation and change-out of HEPA filters led to contamination of several parking lots and grounds around ORNL's Building 3098.

2.2.9 Confinement Selection Methodology

Workroom ventilation rates are based primarily on cooling requirements, the potential combustion hazard, and the potential inhalation hazard of substances that are present in or could be released to the workroom. Concentrations of radioactive gases and aerosols in the air of occupied and occasionally occupied areas should not exceed the derived air concentrations (DAC) established for occupationally exposed persons under normal or abnormal operating conditions, and releases to the atmosphere must not exceed permissible limits for nonoccupationally exposed persons.[11] 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 must be designed to maintain airborne radioactive material within prescribed limits during normal operations.[12, 13] In addition, the ventilation and air cleaning facilities must perform in accordance with expectations established during the evaluation of potential accident conditions.[8, 10]

The current DACs for radioactive substances in air are specified in 10 CFR 835, Appendix A.[11] 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. [Note: In a similar manner, the same conceptual process can also be applied to nonradiological airborne hazards.] There are no current DOE directives or technical standards that establish such an approach, but guidance is contained in the archived DOE Order 6430.1A, *General Design Criteria*,[14] and further expanded in the *Heating, Ventilating, and Air Conditioning Design Guide for the Department of Energy Nuclear Facilities,*[15] published by the American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., (ASHRAE).

Based on the guidance cited above, one approach would be to group the material in use into the hazard classes shown in **Table 2.3**, and then to zone the facility ventilation systems based on the criteria shown in **Table 2.4**. [Note: The limits given in the tables are guides and should not be considered absolute.] An alternative approach would be to classify the risk based on the anticipated airborne and surface contamination levels, as shown in **Table 2.5**. The user must 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 2.3** illustrates a typical zoning plan for a nuclear facility. Not all of the confinement zones listed in Table 2.4 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 2.3, the general approach is to establish ventilation zones in a three-tiered manner. Multizoned buildings are usually ventilated so that air flows from the less contaminated zone to the more contaminated zone. Areas from which air is not recirculated include areas that produce or emit dust particles, heat, odors, fumes, spray, gases, 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 prohibited. The interiors of exhaust and recirculating ductwork are considered to be of the same hazard classification as the zone they serve. Airflow must 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. [Note: Substantially higher differentials are often specified between Primary and Secondary Confinement Zones (see below) than for other boundaries.]

Table 2.3 – Hazard Classification of Radioisotopes

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

Table 2.4 – 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

[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 2.5 – Zoning of Facilities Based on Contamination Levels

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

[a] For airborne contamination, the DAC is the derived airborne concentration value listed in 10 CFR 835,[11] 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,[11] 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.

The methodology used above is based on the DACs for radioactive substances in air, as specified in 10 CFR 835.[11] For toxics and noxious substances, the DACs must be replaced with Permissible Exposure Limits (PEL), including irritant and nuisance substances, as specified in 29 CFR 1910.[16] However, because the Federal PELs are obsolete in some cases, the Threshold Limit Values (TLVs) published annually by the American Conference of Governmental Industrial Hygienists (ACGIH)[17] should be consulted. In the case of a difference between the PEL and TLVs, it is generally recognized and accepted practice among industrial hygienists to use the more stringent of the two limits. A more convenient (and generally more current) tabulation of occupational exposure limits is published by the ACGIH in the annual issue of *Threshold Limit Values*. 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 440.1A, *Worker Protection Management for DOE Federal and Contractor Employees*,[18] specifies how to select PELs and TLVs.

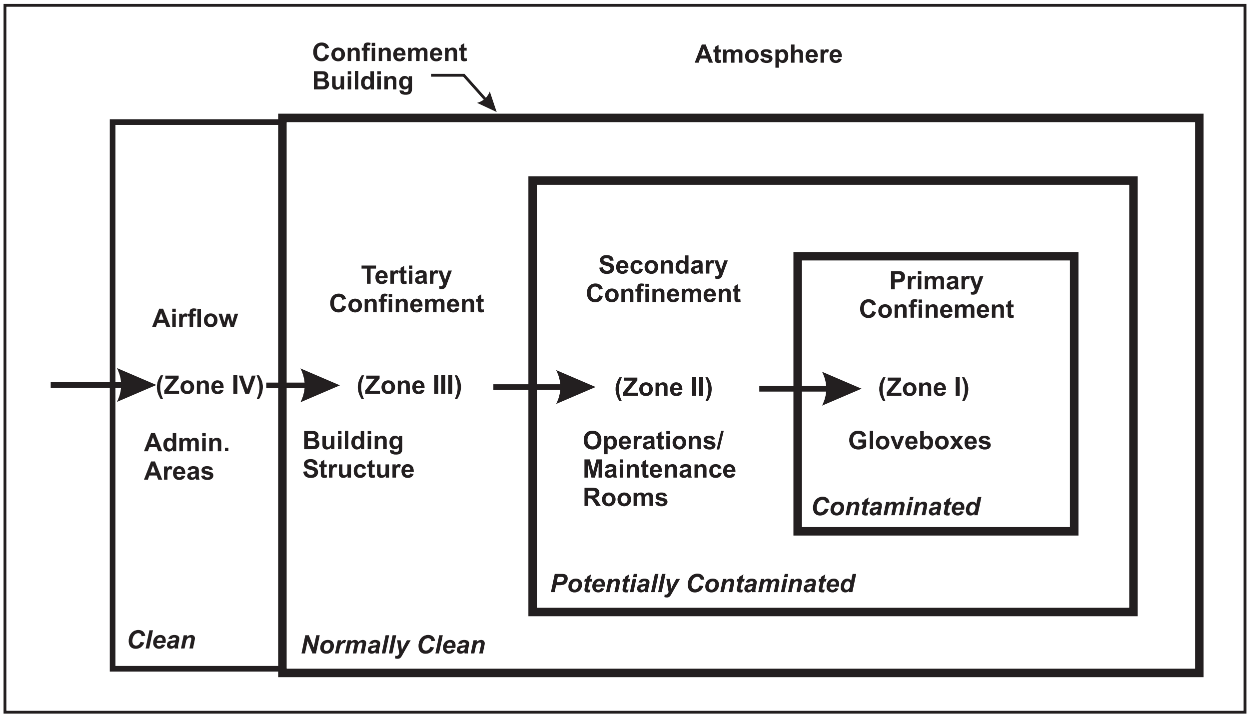


Figure 2.3 – Typical Process Facility Confinement Zones

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 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, or other confinement for handling highly radiotoxic material.[16] Confinement features must 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 must be compensated for by an adequate inflow of air or safe collection of the spilled material. The exhaust system must be sized to ensure an adequate inflow of air in the event of a credible confinement breach. An air exhaust system that is independent of those serving surrounding areas is required. High-efficiency filters, preferably HEPA type, are typically required in air inlets, and two independently testable stages of HEPA filters are required in the exhaust. The exact number of testable stages is determined by safety analysis.[8, 10]

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.[15] Pressure differentials must be available to produce inward airflow into the primary confinement should a breach occur. 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 recommended 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.[15] It is the final barrier against release of hazardous material to the environment. This level of confinement should never become contaminated under normal operating conditions. The secondary and tertiary boundaries may exist in common, as in a single-structure envelope.

Example Airflow Criteria

As an example of the zoning approach discussed in this section, the criteria listed in **Tables 2.6**, **2.7**, **2.8**, **2.9**, and **2.10** are specified at one of DOE's national laboratories for the design and operation of radiochemical and laboratory facilities and for the buildings that contain them.[19] [Note: Numerical values can be reduced or increased depending on the requirements for operating conditions and the DBA for that facility.] **Table 2.11** contains recommendations for the pressure differentials between zones in multizoned buildings.

Table 2.6 – Airflow Criteria for Design and Operation of Hot Cells, Caves, and Canyons (Primary Confinement)

1. A vacuum equal to or greater than 1 (inches water gauge) in.wg relative to surrounding spaces must be maintained at all times to ensure a positive flow of air into the confinement.
2. Confinement exhaust must be at least 10 percent of cell volume/min to minimize possible explosion hazards due to the presence of volatile solvents and to ensure that, in the event of cell pressurization due to an explosion, the confinement will be returned to normal operating pressure (1 in.wg) in a minimum of time.
3. The maximum permissible leak rate must not exceed 1 percent of cell volume/minute for unlined cells and 0.1 percent of cell volume/minute for lined and sealed cells at a Δp of 2 in.wg to ensure minimal escape of radioactive material in the event of cell pressurization; the maximum permissible leak rate for ductwork is 0.1 percent of duct volume/minute at Δp equal to 1.5 times the static pressure of ductwork. Hot cells, caves, and canyons must not be hermetically sealed.
4. Seals and doors must withstand a Δp of at least 10 in.wg to ensure the integrity of closures and penetrations under all operating and design basis upset conditions.
5. The confinement structure must withstand the DBA for that facility without structural damage or loss of function.
6. Operating procedures must be designed to limit quantities of flammable and smoke-producing materials and solvents within limits that can be accommodated by the ventilation system without endangering the functionability of the air cleaning facility.

Table 2.7 – Airflow Criteria for Gloveboxes (Primary Confinement)

1. The vacuum must be at least 0.3 in.wg between the glovebox and the surrounding room. Consult the latest edition of the American Glovebox Society's *Guidelines for Gloveboxes*, AGS-G001,[20] and the ACGIH's *Industrial Ventilation – A Manual of Recommended Practice*[21] for guidance concerning ventilation of gloveboxes.
2. The exhaust rate is not specified, but must be adequate for the heat load and dilution requirements of operations conducted in the glovebox. For example, operations with flammable materials must maintain concentrations below those specified.
3. Airflow must be sufficient to provide an adequate face velocity at the passthrough port to the glovebox [50 linear feet per minute (fpm)] and to maintain an inward velocity of at least 125 linear fpm (with higher velocities mandated by some operators for gaseous effluents) through one open gloveport in every five gloveboxes in the system. This will ensure adequate inflow to prevent the escape of contamination in the event of glove failure.
4. Individual gloveboxes must be isolated or isolatable (under upset conditions) to prevent fire spreading from one box to another.

Table 2.8 – Airflow Criteria for Chemical Fume Hood (Primary Confinement)

1. A vacuum must be at least 0.1 in.wg between the laboratory in which the fume hood is installed and the corridor from which the laboratory is entered.
2. The exhaust rate of the fume hood must be sufficient to maintain sufficient airflow face velocity into the hood to prevent the release of fumes from the hood to the room, even when the operator walks rapidly back and forth in front of and close to the hood face. A face velocity of 80 to 100 linear fpm is recommended for operations with highly hazardous (including radioactive) materials. Higher velocities were once recommended, but are not now due to the generation of vortices by faster airflows which cause air inside the hood to migrate to the outside. Consult the latest edition of the American Industrial Hygiene Association's *American National Standard for Laboratory Ventilation*, Z9.5,[22] for guidance.
3. Each hood in the laboratory should be isolatable by means of dampers to prevent backflow through a hood when it is not in service.
4. Each hood used for handling radioactive materials should have a testable HEPA filter in its exhaust duct, located close to the duct entrance. All hoods should, where practicable, exhaust to a common stack.

Table 2.9 – Airflow Criteria for Secondary Confinement Structures or Buildings

1. The building (structure) must be designed to prevent the dispersal of airborne contamination to the environment in the event of an accident in a hot cell, glovebox, fume hood, or building space.
2. Under emergency conditions, the building must be capable of being maintained at a vacuum of 0.1 to 0.3 in.wg relative to the atmosphere. For increased reliability and simplicity, some buildings are held at this pressure under normal operating conditions. However, if this is not practicable, the ventilation system must be capable of reducing building static pressure to 0.2 in.wg in 20 seconds or less. All building air must be exhausted through at least one stage of HEPA filters. During an emergency, the differential pressure between primary confinement spaces (gloveboxes, hot cells) and other building spaces must also be maintained.
3. Airflow within the building must be from areas of less contamination to areas of higher (or potentially higher) contamination.
4. Recirculation of air within the same zone or room is permitted, but recirculation from primary and secondary confinement zone exhausts to other building volumes is prohibited.

Table 2.10 – Airflow Criteria for Air Handling Systems

1. It is recommended that ventilation (recirculating, supply, or exhaust) and offgas systems must be backed up by redundant air cleaning systems (including filters and fans) to maintain confinement in the event of fan breakdown, filter failure, power outage, or other operational upset. Airflow must always be from the less hazardous to the more hazardous area under both normal and upset conditions.
2. Air exhausted from occupied or occasionally occupied areas must be passed through prefilters and at least one stage of HEPA filters. Contaminated and potentially contaminated air exhausted from a hot cell, cave, canyon, glovebox, or other primary confinement structure or vessel should pass through at least two individually testable stages of HEPA filters in series, as well as prefilters, adsorbers, scrubbers, or other air cleaning components that are required for the particular application. Exact HEPA filter stages are determined by safety analysis.[8, 10] Only one stage of HEPA filters is required for the exhaust of: (1) air that is normally clean, but has the potential of becoming contaminated in the event of an operational upset (e.g., exhaust from a Secondary Confinement operating area) or during service operations when the zone is opened to a zone of higher contamination (e.g., a hot cell service area), and (2) air from a potentially mildly contaminated space (e.g., a Secondary Confinement area).
3. Moisture or corrosives in the exhaust that are capable of damaging or unduly loading the HEPA filters (or other components such as adsorbers) must be removed or neutralized before they can reach components that could be affected.
4. HEPA filters and adsorbers (where required) must be tested in place at a prescribed frequency in accordance with ASME Code AG-1, Section TA[4] and ASME N510.[23] HEPA filter stages should exhibit a stage leak rate better than 0.05 percent, as long as the leak rate is supported by documented safety analysis and provides an adequate safety margin, as determined by an in-place test performed in accordance with ASME Code AG-1.[4]

Table 2.11 – Recommended Confinement System Differential Pressure (in.wg)[15]

Type of Facility	Primary/Secondary	Secondary/Tertiary	Tertiary/Atmosphere
New	-0.7 to -1.0[b,c]	-0.1 to -0.15	-0.1 to -0.15
Existing[a]	-0.3 to -1.0[c,d]	-0.03 to -0.15	-0.01 to -0.15

[a] These guidelines should be used if the existing area/facility differential pressure design basis is unknown or if there are no site-specific standards.
[b] Canyons, cells: -1.0 in.wg (minimum).
[c] Gloveboxes (air) typically operate at -0.3 to -1.0 in.wg with respect to the surrounding room. Gloveboxes (air) typically have alarms set at -0.5 in.wg. Gloveboxes (inert gas): -0.3 to -1.25 in.wg with respect to surrounding room. For the purposes of enabling the operator to work at the glovebox (ergonomic considerations), the operating differential pressure should be closer to -0.3 in.wg
[d] Canyons, cells: approximately -1.0 in.wg.

NOTES:
1. It may be necessary in some cases to split a single zone into two areas, "a" and "b," where one area contains a greater hazard than the other. If area "a" were the more hazardous area, it would be at a negative pressure compared with area "b." Usually, no differential pressure guidelines exist for areas within the same zone. Therefore, maintaining proper airflow directions is typically the primary requirement.
2. Pressure cascades may need to be established within the secondary confinement. A 0.05–in.wg pressure differential between cascade stages is generally adequate.
3. If glovebox relief valves are included, they are typically set at -0.4 in.wg. Relief valves are designed for breach of the glove port.

2.3 Operational Considerations

This section addresses safety and design requirements, safety classification, regulatory requirements, codes and standards requirements, redundancy and separation, and material restrictions.

2.3.1 Operating Mode

According to operational requirements, an air cleaning system may be operated full-time, part-time, or simply held in standby for emergency service. If processes in the building are operated only one or two shifts a day, the designer may have a choice between continuous operation and operation only during those shifts. The designer must evaluate and compare the effects of daily starts and stops on the performance and life of filters and other components to the higher power and maintenance costs that may be incurred by continuous operation. All factors considered, experience has shown that continuous operation of air cleaning facilities, perhaps at reduced flow during weekends and holidays, is generally the most satisfactory mode of operation for buildings in which radioactive operations are conducted. Unless ducts, filter housings, damper frames, and fan housings (i.e., the pressure boundary) are extremely leaktight, outleakage of contaminated dust into occupied spaces of the building may occur during shutdown periods.

Many facilities require standby exhaust or air cleanup systems that are operated only in the event of an emergency or redundant air cleaning facilities that are brought into operation when a parallel online facility is shut down because of failure or for maintenance. When designing standby systems, the engineer must keep in mind the possibility of component, filter, and adsorber deterioration from environmental conditions (e.g., condensation, temperature) even when the system is not in use.

2.3.2 Particulate Filter Change Frequency

The principal costs of operating a high-efficiency air cleaning system are power (e.g., for fans), replacement filters and adsorbers, labor, and waste disposal costs for radioactive contaminated wastes. The principal factor that affects these costs is the frequency of filter changes. Replacement filters and adsorbers and the labor costs to install and test the filter system in-place after installation of replacement filters may make up as much as 70 percent of the total cost of owning a system (including capital costs) over a 20-year period.

Power accounted for only 15 percent of total owning costs in a study made by the Harvard Air Cleaning Laboratory.[24] Measures such as use of high-efficiency building supply-air filters, use of prefilters ahead of HEPA filters, operation of the system below its rated airflow capacity, and operation of HEPA filters until they have reached high airflow resistance before replacement all tend to decrease filter change frequency and thereby reduce costs. Caution should be exercised when establishing filter change frequency. Filters can become loaded with radioactive particles or reach an age when replacement is warranted even though they may not be dust/dirt-loaded to a point that indicates change-out is necessary due to pressure drop. These same filters may also have an acceptance in-place field test result.

For systems governed by commercial nuclear power plant technical specifications, strict requirements for operating filters at maximum pressure drops are specified. Therefore, filters should not be operated at maximum pressure drop; they must always be ready with enough remaining capacity and strength to handle the loading that can be expected from a design basis event.

Lawrence Livermore National Laboratory recently developed the requirement that HEPA filters be replaced 10 years after the date of manufacture. Exceptions to this requirement include:

- Any filter that becomes wet (e.g., as a result of an in-duct water sprinkler's activation or water spraying directly on the filter) must be replaced promptly.

- Any filter that potentially could become wet (e.g., via an in-duct water sprinkler's activation) must be replaced within 5 years of the date of manufacture.[25]

The underlying rationale for this set of requirements is found in Bergman's *Maximum HEPA-Filter Life*.[25] Part of the author's rationale is based on remaining acceptable tensile strength, which cannot be determined by nondestructive field tests.

2.3.3 Building Supply-Air Filters

Atmospheric dust brought into the building with ventilation air constitutes a substantial fraction of the dirt load in the building and the dust load in the exhaust air cleaning system. Removing this dust before it gets inside the building provides the double advantage of protecting the exhaust filters from premature dust loading and reducing janitorial and building maintenance costs. When operations within a building do not generate heavy concentrations of smoke, dust, or lint, it may be possible to substantially reduce the dust loading in the exhaust system by providing medium-efficiency [50 to 65 percent ASHRAE Efficiency/Minimum Efficiency Reporting Value (MERV) 10-11][26] building supply-air filters, thereby shifting much of the burden of what would otherwise be a change of "hot" (radioactive) prefilters in the exhaust system to a more economical change of "cold" supply-air filters. The labor costs involved in replacing "cold" filters is a small fraction of those for replacing "hot" filters. Noticeable reductions in janitorial costs have been observed in several DOE installations after changing to higher-efficiency building supply-air filters.

Louvers and/or moisture separators must be provided at the air inlet to protect the supply filters from the weather. Rain, sleet, snow, and ice can damage or plug building supply-air filters, resulting not only in increased operating costs, but also upset of pressure conditions within the building and possible impairment of the more critical exhaust air cleaning system. Heaters are desirable in the building supply system even in warm climates. Icing has caused severe damage to building supply-air filters at a number of DOE installations, even in the South. Screens should be provided over supply-air inlets located at ground- or roof-level to protect inlet filters and demisters from grass clippings, leaves, dirt, and windblown trash. If possible, inlets should be located well above grade or adjacent roofs so they are not exposed to such materials.

2.3.4 Prefilters

Prefilters are intended to remove large particles upstream of HEPA filters. HEPA filters are intended primarily for removal of submicrometer particles and should not be used as coarse dust collectors. They have relatively low dust-holding capacity, particularly for large particles and lint, and may plug rapidly when exposed to high concentrations of such material or smoke. Lint may tend to bridge the pleats of the filter, further reducing its capacity. The HEPA filter is also the most critical particulate-removal element in the air cleaning system from the standpoint of preserving confinement, and its failure will result in failure of system function.

Prefilters, installed either locally at the entrances to intake ducts, in the central exhaust filter house, or both, extend the life of HEPA filters and provide at least a measure of protection against damage. Local duct-entrance filters also minimize dust accumulation in ducts and reduce an otherwise potential fire hazard. A typical increase in HEPA filter life through the use of prefilters is depicted in **Figure 2.4**. The increase for a specific application depends, of course, on the quality of the prefilter selected and the nature and concentration of dusts and particulate matter in the system.

Generally, prefilters should be provided when the potential dust concentration in the air leading to the air cleaning system exceeds 20 mg/m^3 and should be considered if the dust concentration exceeds 1 grain per 1000 cubic feet (ft^3). The use of prefilters is recommended in engineered safety feature (ESF) systems for nuclear reactors.[27] The decision to install prefilters should be based on providing the best operational balance between HEPA filter change frequency, and procurement and maintenance costs for the prefilters.

Duct-entrance prefilters can be changed without entering or interrupting the central air cleaning facility, can minimize dust buildup in the ducts, and can provide a measure of protection against duct corrosion, accidental high-moisture loadings, and flaming trash or sparks that may be produced by a fire in the working space. On the other hand, a system that has a number of local prefilter installations may cost from two to three times as much as one in which the same prefilter capacity is installed in a central housing.[24]

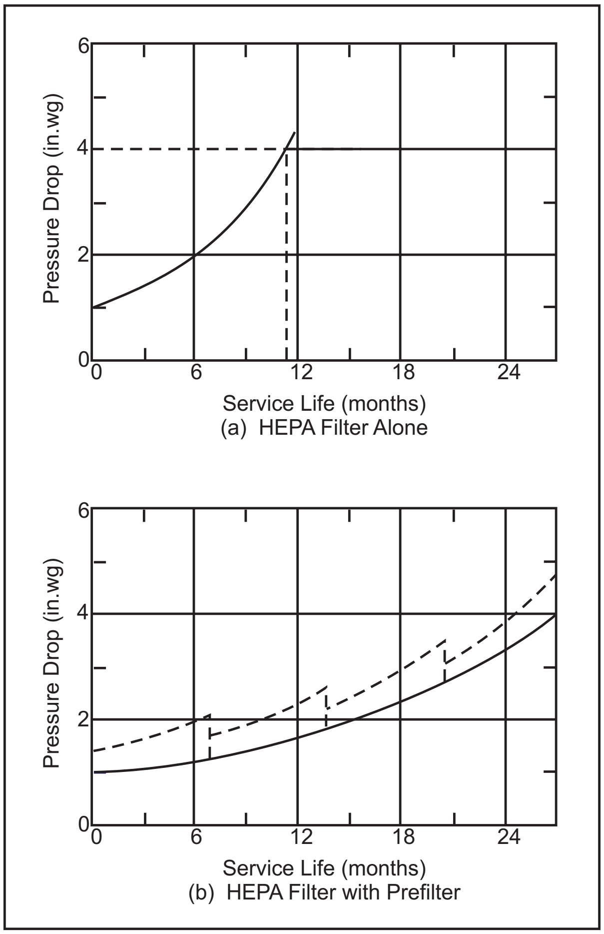


Figure 2.4 – Comparison of HEPA Filter Life With and Without Prefilter

Prefilters in a central air cleaning system should not be attached directly to or installed back-to-back to HEPA filters; they should be installed on a separate mounting frame located at least 4 to 5 feet upstream of the HEPA filters. This installation requires more building space and higher investment costs (particularly when building space is at a premium), but it is justified by increased safety and greater system reliability. Adequate space between prefilters and HEPA filters is needed for access and maintenance and to minimize the propagation of fire by sparks or direct flame impingement. If the possibility of fire is a serious consideration, a removable screen, fine enough to stop sparks (10 to 20 mesh), may be installed on the downstream side of the prefilters.

2.3.5 Operation to High Pressure Drop

Most HEPA filter manufacturers' literature suggests replacement of HEPA filters when the resistance due to dust loading has reached 2 in.wg. HEPA filters are qualified according to the requirements of ASME AG-1, Section FC,[4] to be capable of withstanding a pressure drop, when new, of 10 in.wg without structural damage or reduction of efficiency. [Note: This value is for qualification purposes only, and must not be used for operation.] When other factors such as radioactivity and fan capacity do not have to be considered, replacement at a pressure drop of only 2 in.wg is considered under-utilization of the filter. At many DOE facilities, HEPA filters are operated routinely to pressure drops as high as 4 in.wg. **Figure 2.5** shows the effect of such operation on filter life and maintenance costs.

The advantages of operating to high-pressure drop must be weighed against initial costs (higher-static-pressure fans, larger motors, heavier ductwork), higher power costs, and less efficient fan operation. The installed fan and motor must have sufficient capacity to deliver the design airflow at the maximum differential pressure under which the system will operate, with the filters at maximum dirty-filter pressure drop prior to change. Therefore, consideration must not only be given to the increased installed capacity required to operate to the higher pressure drop, but also to the fact that the fan operates at a penalty much of the time to provide the required airflow over the wide span of pressure drop between installation and replacement of filters.

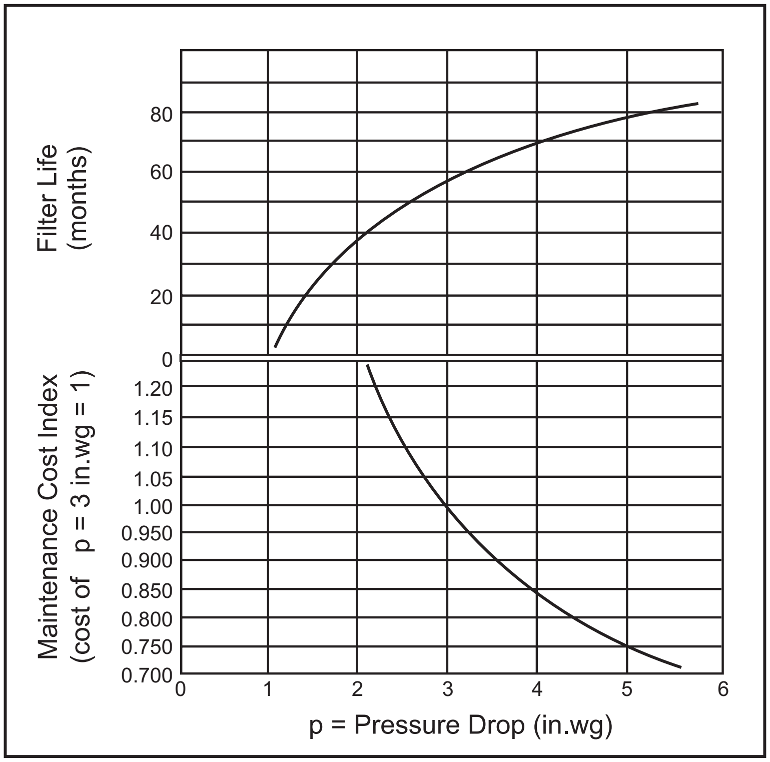


Figure 2.5 – Effect of Operating HEPA Filters to High-Pressure Drop on Filter Life and Maintenance Cost (including replacement filters and labor)

The cost of ductwork, on the other hand, may not be significantly affected by operation to a high pressure drop because there is a minimum sheet-metal thickness for effective welding, regardless of pressure. The cost of fans and motors is a function of the maximum total pressure that must be developed. Fan horsepower can be estimated from the following equations.[28]

$$hp_f = \frac{Q\Delta\rho}{6356E_f} \qquad (2.1)$$

where:

hp_f = fan hp
Q = system airflow, cfm
$\Delta\rho$ = maximum pressure drop across air cleaning system, in. wg. , at time of filter replacement
E_f = fractional efficiency of fan (0.60 usually assumed for estimating).

Motor horsepower can be estimated from the equation:

$$hp_m = \frac{hp_f}{E_m} \qquad (2.2)$$

where:

hp_m = motor horsepower
hp_f = fan horsepower
E_m = fractional motor efficiency (0.90 usually assumed for estimating for 20 hp motors and larger).

Annual power costs can be estimated from the following equation:[28]

$$C = \frac{Q\Delta phr}{8520E'_f E'_m} \qquad (2.3)$$

where:

C = annual power cost, dollars,
h = hours of operation per year,
r = cost of power, cents / k / Whr,
E'_f and E'_m = efficiency of fan and motor, respectively, over the period of operation from filter installation to replacement; these will be less than the design efficiencies.

Although investment and power costs will be lower for systems operated to 2-in.wg pressure drop, the total annual cost of owning a system, including materials and labor costs for filter replacement, may be less for a system in which HEPA filters are replaced at pressure drops on the order of 4 in.wg. Total savings for the facility as a whole may be even greater when the reduced interruption of building operations due to the reduced frequency of filter change is taken into consideration.

Some prefilters can be operated to higher pressure drops than recommended by their manufacturers (but such overuse must be supported by operating experience). This results in less frequent prefilter changes than when prefilters are changed at a pressure drop of only two or three times the clean-filter pressure drop, as recommended by most manufacturers. Care must be taken in selecting prefilters. Because of the many types, efficiencies, configurations, and constructions available, the designer must specifically investigate the safe overpressure allowance for the particular model under consideration. **Figure 2.6** clearly shows the results of overpressuring prefilters. In the case shown, the problem of filter blowout was overcome by working with the manufacturer to reinforce the filter itself. Some benefit could also have been obtained by installing a screen or expanded metal grille on the downstream face of the prefilters against which the filter cores could bear; in any event, screens or grilles would have prevented damage to the HEPA filters when pieces of prefilter struck them.

2.3.6 Sizing and Rating

Underrating. The service of all internal components (except moisture separators) can be extended, and system pressure drop for a given level of dust loading can be reduced by underrating, i.e., by oversizing the system and installing more filter and adsorber capacity to meet system design airflow needs (based on the nominal airflow rating of the components). **Figure 2.7** shows that the increase in filter life obtainable by underrating is roughly proportional to the square root of the degree of underrating. A study by the Harvard Air Cleaning Laboratory suggests that the economic limit of underrating is about 20 percent (i.e., system design airflow capacity).[24]

Overrating. Operation of a system at airflows greater than the installed airflow capacity of the system must be avoided, particularly in systems with radioiodine adsorbers whose performance depends on the residence time of air within the adsorbent bed. When airflow rates exceed the rated airflow capacity of HEPA filters, efficiency is reduced and filter life decreases more rapidly than the equivalent increase in flow rate, as can be seen from the 120 percent curve in Figure 2.7. As noted above, the residence time of contaminant-laden air in adsorber units is inversely related to airflow rate. Overrating of these units decreases their ability to trap gaseous contaminants, thereby degrading their function.

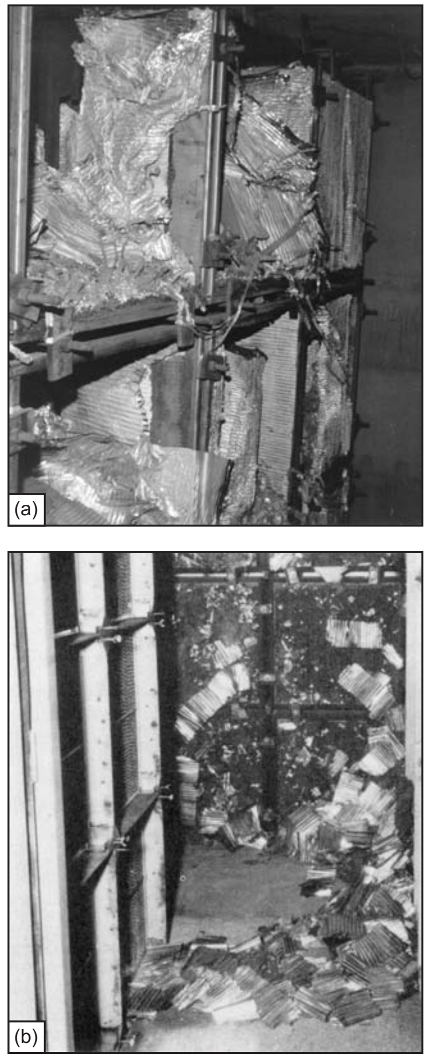


Figure 2.6 – Result of Overpressuring Prefilters

2.3.7 Uniform Airflow Design

In large air cleaning systems, because of the stratification of airflow due to poor transitions between ducts and housings or between housings and fans, or because of poorly designed housings, filters or adsorbers at the center of a bank may receive higher airflow than those on the periphery of the bank. This not only results in non-uniform dirt loading of filters but may also result in excessive penetration of those HEPA filters closer to the air intake if the degree of airflow non-uniformity is great. **Figures 2.8(a) and 2.8(b)** show that penetration of HEPA filters by very small particles is directly velocity-dependent and increases significantly at very high airflow rates. Conversely, penetration of HEPA filters by particles larger than 1 μm may increase at very low flow rates due to the reduction in effectiveness of the impaction mechanism on which trapping of those particles depends. If some filters are operating at very high airflow and some at very low airflow, as could happen in a poorly designed housing and filter bank, it is possible that significant penetration

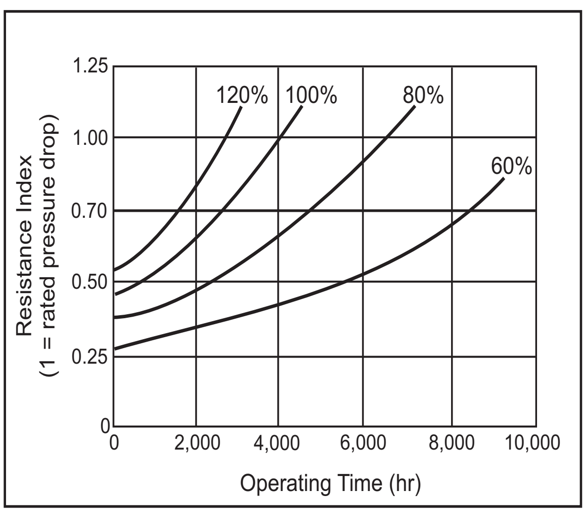


Figure 2.7 – Effect of Underrating on Service Life of Extended-Medium Filters, Based on Percentage of Manufacturer's Rated Filter Airflow Capacity

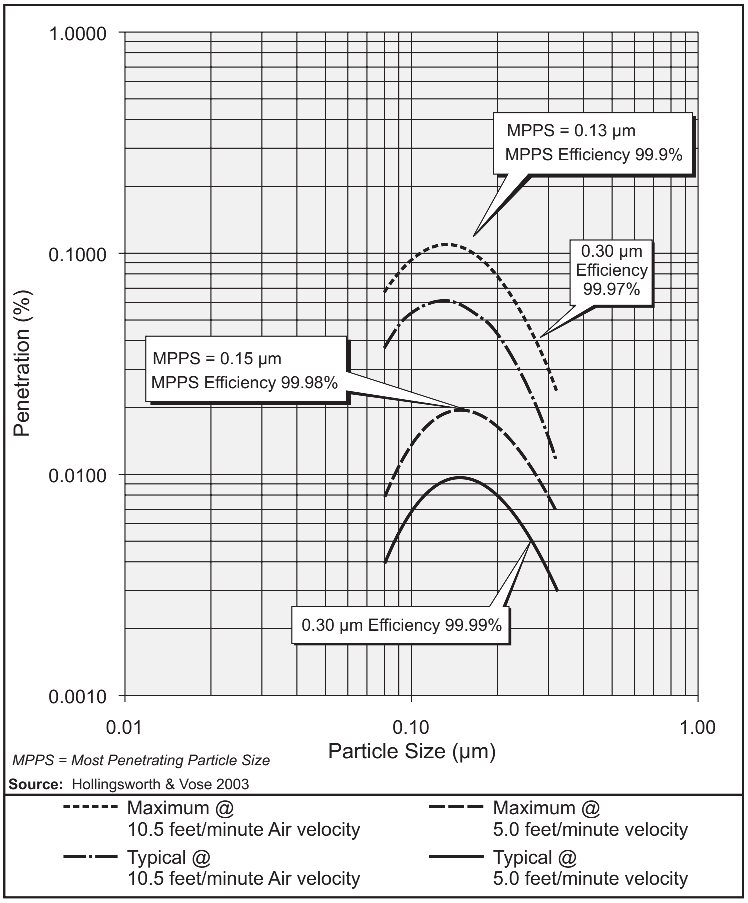


Figure 2.8(a) – HEPA Media Penetration[34]

could occur even though the filters are in good condition. Low flow rates improve the efficiency of radioiodine adsorbers, but high flow rates decrease efficiency. Therefore, significant non-uniformity of airflow through a bank of adsorber cells can reduce the overall efficiency for trapping radioactive gases of interest. A well-designed duct-to-housing transition will produce satisfactory airflow distribution through the banks of filters and adsorbers.[25]

Filter housings can be obtained with built-in devices to assist in generating uniform up- and downstream flow distribution using Stairmand disks and similar devices. These make testing faster and more accurate, and minimize those occasions when personnel must enter the filter housing (a confined space) for any reason.

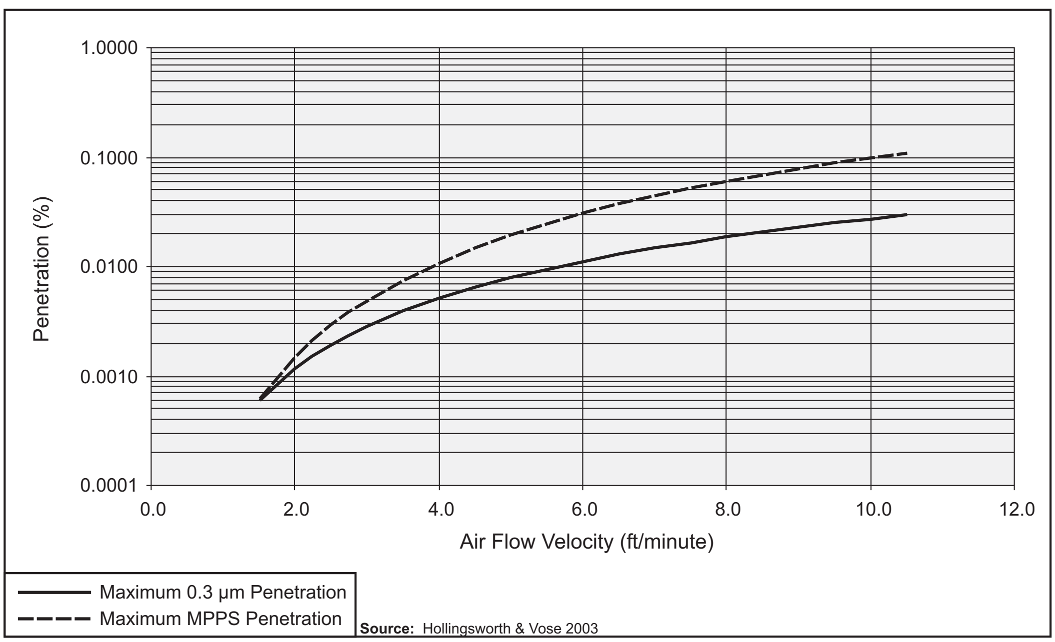


Figure 2.8(b) – Maximum Penetration Versus Airflow Velocity

2.3.8 Maintainability and Testability

Air cleaning systems designed in accordance with ASME AG-1[4] should result in optimum systems for maintainability and testability. There are many previously installed systems that were designed to ASME N509,[29] the predecessor to ASME AG-1.[4] Systems designed to ASME AG-1 requirements should be tested in accordance with ASME AG-1, Section TA. Those systems designed to ASME N509 or still covered by its 2002 maintenance revision, should be tested in accordance with the provisions of ASME N510.[23] Other older systems not designed to either ASME AG-1 or N509 are generally tested by following the guidance in ASME N510.

Maintenance and testing are two operational factors whose cost can be minimized by good initial design and layout of ventilation and air cleaning systems. Inadequate attention to maintenance and testing requirements at the initial phase of the project can result in much higher operating costs. New system specifications should be designed and tested in accordance with ASME AG-1.[4] Some existing systems may have been designed to ASME N509.[33] These and other non-ASME AG-1-designed systems may be tested in accordance with the guidelines provided in ASME N510.[23]

Design of air cleaning systems in accordance with ASME AG-1[4] will result in optimum maintainability and testability. Two elements that largely influence the costs of these functions are the accessibility of components requiring periodic test and service and the frequency of filter and adsorber replacement. In systems that involve handling of radioactively contaminated filters and adsorbers, the frequency of changing these components and the time required to accomplish the change can be especially critical, because the total integrated radiation dose a workman can be permitted to receive in each calendar period is limited. When all personnel have received their maximum permissible dose for the year, the supervisor faces the prospect of having no one available to carry out a needed filter change or a scheduled test. Maintenance and testing of radioactively contaminated and other highly toxic systems are much more costly than the same operations in nonradioactive systems because of the time required for personnel to change into and out of protective clothing; to decontaminate and cleanup the area, tools, and equipment after the operation; to dispose of contaminated filters (a significant cost itself); and to bathe and be monitored by health physicists.

In addition, extra attention must be given to filter or adsorber cell installation (compared with common air filters, for example). If the system does not meet the test requirements of ASME AG-1, Section TA,[4] after the change, then rework must be performed until the problems are found and corrected. There is also a need for health physics monitoring before, during, and after all maintenance operations. The fact that personnel have to work in protective clothing and respirators also adds to the time required. Regardless of these inherently high time and money costs, proper maintenance and testing are primary factors in ensuring the reliability of the air cleaning system, and they cannot be done properly unless the facilities have been properly designed and built.

Frequency of Maintenance and Testing

Measures that reduce the frequency of filter (HEPA and prefilter) and adsorber replacement also reduce system costs and downtime. Several of the factors discussed earlier—the use of good building supply-air filters and prefilters and underrating—serve to extend component life and reduce the frequency and cost of service. Exhaust system HEPA filter and adsorber installations must be tested to the requirements of ASME AG-1, Section TA,[4] after each component change so that any extension of service life also directly reduces testing costs. [Note, however, that regulatory bodies often dictate frequency of testing.]

Accessibility

When laying out ventilation and air cleaning facilities, the designer must consider the location of fans, dampers, instruments, and filter housings, as well as the working space adjacent to them; working space and spacing of banks within man-entry housings; height and array of filter and adsorber banks; and routes to be used for moving new and used filters and adsorbers between storage, installation, and disposal areas. Where it is permissible to fill and drain adsorbers in place, it is imperative to provide space and routing (from the storage location to the air cleaning unit) for the charging cart and the adsorbent drums. This apparatus is a large piece of movable equipment. In addition, space for drums of adsorbent must be provided because they are used in conjunction with operation of the charging cart. Failure to provide adequate space in and around housings and mechanical equipment (fans, dampers, etc.) results in high maintenance and testing costs, inhibits proper care and attention, creates hazards, and increases the chance for accidental spread of contamination during service or testing operations. Recommendations for arrangement and space requirements for air cleaning components should be in accordance with ASME AG-1[4] and ASME N509[29] (for those system components that have not been incorporated into ASME AG-1). Even greater space requirements are needed for remotely maintainable systems. For systems not designed to meet ASME AG-1 requirements, guidance can be found in ASME N510.[23]

Ease of Maintenance and Testing

Simplicity of maintenance and testing is a primary factor in minimizing the time personnel must remain inside a contaminated housing and restricted areas of a building during a filter or adsorber change or test. Therefore, it is an important factor in reducing both personnel exposures and costs. The following strategies will help ensure simplicity of maintenance and testing:

- Filter housings should be laid out and designed in accordance with ASME AG-1[4] and ASME N509[29] to ensure quantitative tests can be performed and to minimize reaching, stooping, and the use of ladders or temporary scaffolding for gaining access to filter or adsorber cells. Some reaching and stooping is unavoidable in man-entry housings, but it should not be necessary for personnel to perform physical contortions or climb ladders to remove and replace filters in single-filter installations. Similarly, in bank systems, it should not be necessary for workmen to climb ladders or temporary scaffolding to gain access to the upper tiers of filters or adsorbers. If this is unavoidable, then permanent ladders and platforms need to be built into the air cleaning housing. Personnel entries into housings should be minimized. These are, at best, confined spaces that require permits for access and have contaminated surfaces that require additional, potentially costly and difficult, precautions.

- Racks (frames) should be designed to the requirements of ASME AG-1, Section FG,[4] and ASME N509[29] to ensure proper spacing between components for maintainability and testability.

- Electrical, water, and compressed air connections should be available nearby, but in no case should they be located inside the filter house.

- Materials-handling equipment should be employed, including dollies for moving new and used filters and adsorbers, hoists or other means of handling the heavy adsorber cells in systems containing these components, and elevators or ramps for moving loaded dollies up and down within the building.

- Filter housings should be located inside the building. It is undesirable for personnel to: (1) conduct a filter change or test out of doors where wind or rain may cause a spread of contamination, (2) cross a roof to gain access to a filter housing, or (3) wait for good weather to carry out a scheduled filter or adsorber change or test. Weather damage and corrosion are always possible, especially with wood-framed filters.

- Decontamination and clothing-change facilities (including showers) should be located nearby.

- Maintenance and testing (per ASME AG-1, Section TA,[4] and plant maintenance procedures) should be well planned and rehearsed. This is particularly important to keep radiation exposure for workers at as low as reasonably achievable (ALARA) levels.

- Adequate finger space (1 inch minimum is desirable) should be available between filter elements, and handles should be provided on heavy components such as adsorber cells.

- Cradles or benches should be built into the component mounting frame for aligning and supporting filters (adsorbers) prior to clamping to face-sealed mounting framers (see Chapter 4, Section 4.4.4).

- For simple filter and adsorber clamping devices, a properly designed bolt-and-nut clamping system has proven most satisfactory in the past, although numerous methods of minimizing or eliminating loose parts are currently being investigated. Toggle clamps, over-center latches, and other devices are easily manipulated and require no tools; however, they often tend to jam, become difficult to operate, or lose their ability to properly clamp the filter or adsorber cell after extended exposure to the hostile environment of a contaminated air cleaning system. Such devices should be used only after due consideration of the difficulties that would be involved in replacing them in a contaminated system (see Chapter 4, Section 4.4.6).

- Ledges and sharp corners that a worker might stumble over or might snag or tear their protective clothing on should be eliminated.

- Adequate lighting should be provided in, and adjacent to, the filter house and to other items that require periodic service, inspection, or testing.

- Means of communication between personnel inside and outside the filter house should be provided.

- Floor drains in housing and adjacent workspaces should be provided to facilitate easy removal of water spilled or applied during decontamination of the area after a filter or adsorber change. Drains must be designed so that no air can bypass filters or adsorbers.

- Rigid, double-pin-hinged doors should be available on personnel entry housings and should be large enough for personnel to pass through without excessive stooping or twisting. It should not be necessary to remove several dozen nuts from a hatch to gain entry to a personnel entry or single-filter housing. Not only is this too time consuming, but nuts tend to cross-thread or gall to the extent that it is often necessary to cut off the bolt to open a hatch; or the nuts get dropped and lost and are often not replaced, thus compromising the seal of the hatch. Sliding doors are not suitable because they will jam with any distortion of the housing wall (see Chapter 4, Section 4.4.17) and are difficult to seal.

- Maintenance and testing procedures specific to the system being tested should be well planned and rehearsed.

- There should be adequate space for materials and test equipment and access (through preplanned doors or panels) to both sides of filter and adsorber banks.

Construction

Designing for maintainability requires careful attention to the details of construction, including tolerances, surface finishes, and the location of adjacent equipment and service lines. Ducts and housings should have a minimum number of interior ledges, protrusions, and crevices that can collect dust or moisture, impede personnel, or create a hazard in the performance of their work. Prefilters at duct inlets will minimize the accumulation of dust and contamination in the ducts. If these are not provided and the hazard analysis permits, easily opened ports and hatches for inspection and cleaning must be provided at strategic and accessible locations in the duct. [Note: Easily opened ports and hatches are not appropriate for plutonium-bearing systems.] Duct runs should have enough mechanical joints to permit easy erection and dismantling. Otherwise, replacement of radioactively contaminated ducts can be an expensive and hazardous job.

Housings, ductwork, and component-mounting frames must be able to withstand anticipated system pressures and shock loadings without distortion, fatigue, or yielding that permits in-leakage or bypassing of the filters or adsorbers. These components must meet a pressure test in accordance with the requirements of ASME N509[29] and ASME AG-1.[4]

Interior surfaces and finishes warrant special attention. Regardless of the formulation when coatings are used, a primary factor in a long, dependable service life is proper preparation of the surface to be coated. Manufacturers' coating or paint instructions and plant procedures must be followed precisely. One alternative to the coating requirements is to build the housings and housing components from stainless steel or other harsh-environment-resistant materials. This reduces the need for frequent and costly repair to coatings that are damaged as a result of routine testing and maintenance.

2.4 Emergency Considerations

The ventilation and air cleaning systems of a building in which radioactive materials are handled or processed are integral parts of the building's confinement. In some cases, these systems may be shut down in the event of an operational upset, power outage, accident, fire, or other emergency. In other cases, they must remain operational to maintain the airflows and pressure differentials between building spaces and between the building and the atmosphere as required to maintain confinement. In some of these cases, airborne radioactive material may not be a problem until an emergency occurs. In all cases, however, a particular danger is damage to or failure of the final HEPA filters (and adsorbers in those facilities where radiolytic particulates could be released) that constitute the final barrier between the contained space (hot cell, glovebox, room, or building) and the atmosphere or adjacent building spaces. Even if the system can be shut down in the event of an emergency, protection of the final filters is essential to prevent the escape of contaminated air to the atmosphere or to allow personnel to occupy spaces of the building.

Consideration must be given to: (1) the possible effects of operational upsets, power outages, accidents, fires, and other emergencies on the ventilation and air cleaning systems, including damage to the filters and adsorbers from shock, overpressure, heat, fire, and high sensible-moisture loading; (2) the design and arrangement of ducts and air cleaning components to alleviate these conditions; (3) the means of switching to a redundant air cleaning unit, fan, or alternate power supply; and (4) the methods of controlling or isolating the exhaust system during failure conditions. To provide the necessary protection to the public and plant personnel, the air cleaning and ventilation system components on which confinement leakage control depends must remain essentially intact and serviceable under these upset conditions. These components must be capable of withstanding the differential pressures, heat, moisture, and stress of the most serious accident predicted for the facility, with minimum damage and loss of integrity, and they must remain operable long enough to satisfy system objectives.

2.4.1 Shock and Overpressure

Mechanical shock in an air cleaning system can be produced by an explosion in an operating area of the building, by an earthquake, or by rapid compression or decompression of the air inside a system caused by sudden opening or closing of a damper or housing doors. When pressure transients last for periods measurable in seconds, static pressure is primarily responsible for any destructive effect. For shocks that last only a few milliseconds with a nearly instantaneous pressure rise, as occurs in most chemical explosions, the extent of destruction is primarily a function of the momentum of the shock wave. Shocks produced by an earthquake or inadvertent opening or closing of a damper usually fall somewhere between these two extremes. Protection of the final filters and adsorbers against failure from shock can be accomplished by isolating them to prevent the transmission of destructive forces to them and by increasing the shock resistance of ducts, housings, mounting frames, and equipment supports.

The shock resistance of HEPA filters can be enhanced by faceguards and similar treatment may sometimes improve the shock resistance of prefilters. Most prefilters used today, however, probably have low shock and overpressure resistance, and a screen installed between them and the HEPA filters is recommended to prevent the condition shown in Figure 2.6. Adsorbers, both unit-tray and permanent single-unit types are generally of a robust construction that should be relatively unaffected by shock loadings if properly installed. Filter and adsorber mounting frames and housings designed in accordance with recommendations in Chapter 4 will probably have adequate shock resistance for most applications. The difference in the ability of the two fan installations, shown in **Figure 2.9**, to withstand a substantial degree of shock is readily apparent.

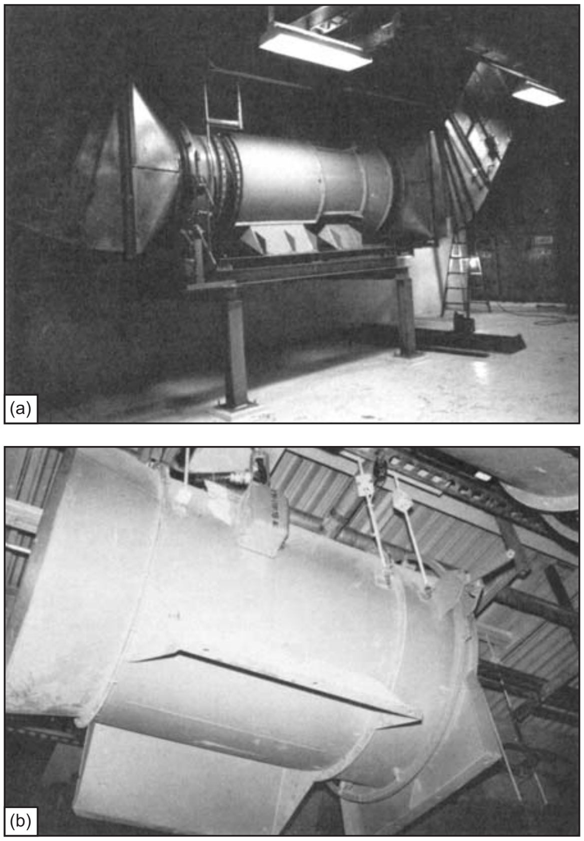


Figure 2.9 – Methods Employed for Installing Axial-Certrifugal Fans in Different Nuclear Reactor ESF Air Cleaning Systems—(a) Shock-Resistant Base-Mounted Fan; (b) Hanger-Rod Supported Fan. (Note anchor plates provided by Fan Manufacturer, but not used.)

Protection of the primary air cleaning components can be achieved by using fast-acting isolation. Although turning vanes, dampers, moisture separators, and prefilters may be damaged by a shock wave, they may also serve to attenuate its force to some degree and thereby provide a measure of protection to the HEPA filters downstream. Damage to dampers, however, can result in inability to control flows or isolate branch lines. Sand filters are employed in some DOE facilities for protection of the final filters and to prevent loss of confinement in the event of explosion, earthquake, tornado, fire, or shock. As discussed in Chapters 3 and 9, sand filters are large deep beds of graded sand and gravel, installed in underground concrete enclosures. In some cases they are employed as final filters. Because of their size, a true efficiency test cannot be performed on a sand filter installation. Field tests have shown leakages comparable to HEPA filters. Their large mass bed size will dampen most conceivable explosions and deflagrations. Airflow is upward through the bed, and leakage caused by the explosion should be only momentary because of the great mass of sand and gravel comprising the filter. The disturbed sand should fall back to heal the breach. This large mass of sand and gravel also provides a substantial heat sink in the event of fire in a ventilated space. The disadvantages of sand filters are very high initial cost and high pressure drop.

Explosion in an operating area of a building is probably the most likely type of shock-generating incident that one can expect in radiochemical, laboratory, and experimental facilities. A chemical explosion is no more than a rapidly burning fire and therefore, in a confined space, can be arrested if a suppressant can be introduced quickly enough.

2.4.2 Power and Equipment Outage

Emergency plans must account for the probable occurrence of power and equipment (particularly fan) failures. Such failures, if not property planned for, can result in a contamination hazard to the public or operating personnel, particularly in buildings with zone ventilation where airflow must be maintained to preserve pressure gradients between zones and to prevent backflow to contaminated air to occupied spaces. Possible emergency measures include redundant fans, redundant fan motors (perhaps served from independent power sources), and alternate power supplies (e.g., steam turbine or emergency diesel-electric generator). Where continuous airflow must be maintained, facilities for rapid automatic switching to an alternate fan, power supply, or emergency source, or to a standby air cleaning unit, are essential. However, if brief interruptions of flow can be tolerated, manual switching may be permissible at less expense. In any event, visible and audible alarms should be provided, both locally and at a central control station, to signal the operator when a malfunction has occurred. In addition, indicator lights to show the operational status of fans and controls in the system should be provided in the central control room.

2.4.3 Air Cleaning System Layout Considerations

The layout and location of air cleaning facilities can have a direct bearing on the system's capability of effecting control under upset conditions and of limiting the adverse consequences of such an upset.

Compartmentation and Segmentation

A higher degree of control is required in the event of a fire, explosion, equipment outage, or other system upset if the air cleaning system is segmented or if the individual air cleaning units are compartmented. Segmentation permits isolation of a damaged unit and minimizes the chance that the entire system will become inoperable at the same time. Series compartmentation is employed in some potentially high-risk applications to permit further isolation of the less critical air-pretreatment facilities (demister, prefilters) from the more critical final HEPA filters and adsorbers. Series parallel arrangement of a central exhaust filter system that handles high-specific-activity alpha-emitting materials is shown in **Figure 2.10**. In the event of fire or equipment damage in any one housing of this system, or in the filters, the housing can be isolated and the remainder of the system kept in service. Also, any one of the housings can be isolated for testing or filter change (under normal operating conditions) without interruption of work being conducted in the building. NRC Regulatory Guide 1.52[27] recommends that the installed capacity of any one air cleaning unit be no greater than 30,000 cubic feet per minute (cfm) to permit more effective control in the event of an emergency and to permit more reliable surveillance testing of the HEPA filter and adsorber stages of the unit.[29]

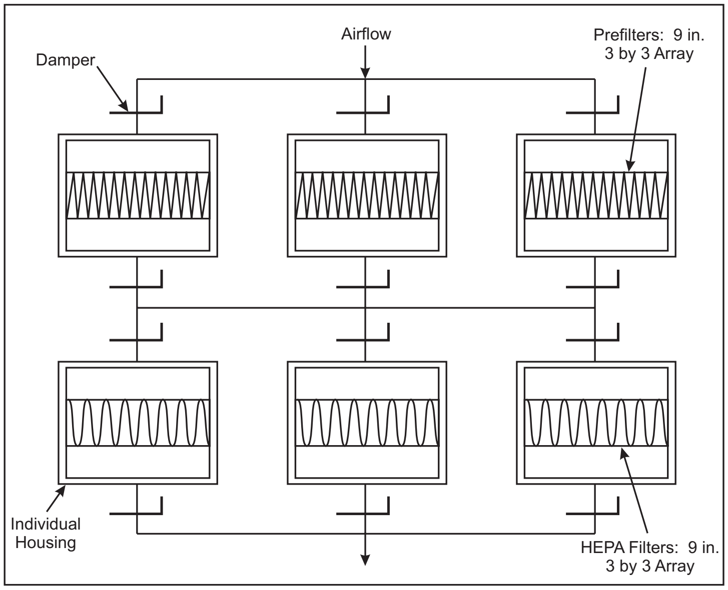


Figure 2.10 – Series-Parallel Arrangement of Central Exhaust Filter System of a High-Hazard Radiochemical Laboratory (Note: Dampers that Permit Isolation of Any Housing Without Stopping Exhaust Airflow)

Redundance

Redundant air cleaning facilities are often required in potentially high-risk operations, such as reactors and radiochemical plants, to ensure continuous ventilation in the event of failure of an online air cleaning unit. In the case of reactor post-accident cleanup systems, redundant air cleaning units are required even though the system is normally in a standby condition. **Figure 2.11** shows the segmented, redundant, normal offgas and building-exhaust air cleaning systems of an experimental water-cooled reactor with vented confinement. Of the two units of each system, which are normally online, one is capable of meeting exhaust requirements when the building supply fans are shut down in the event of an emergency. High-quality isolation dampers are essential in redundant systems, not only to protect the offline units when not in service, but to prevent bypassing of the air cleaning system through a damaged offline air cleaning unit.

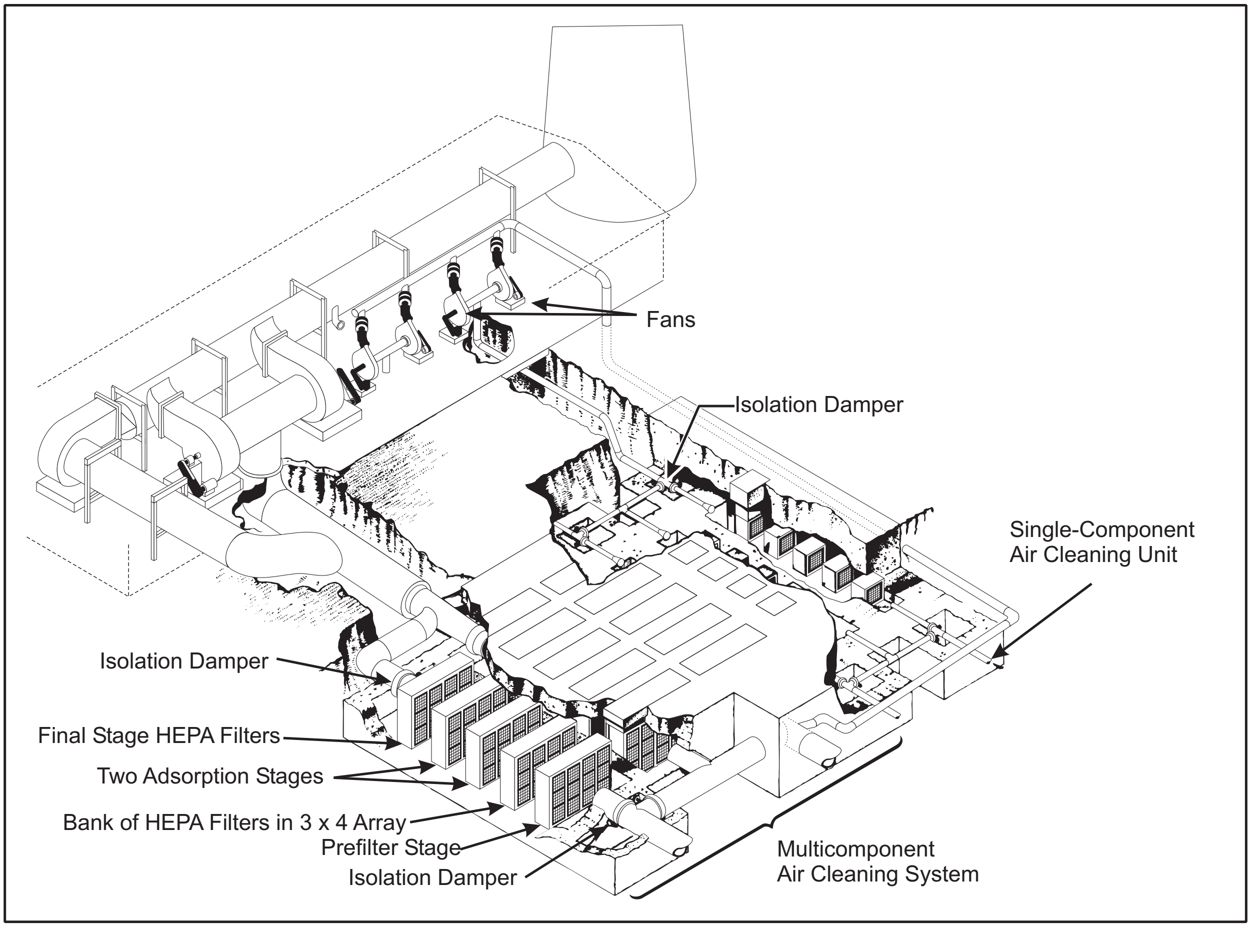


Figure 2.11 – Experimental Reactor

Location of Air Cleaning Facilities

The location of filters, fans, and other air cleaning components can play a major part in minimizing component damage and spread of contamination in the event of a fire, system upset, or other emergency. A common but undesirable practice has been to install such items in random locations in attics or unused building spaces. **Figure 2.12** illustrates a type of filter installation in which a wood-cased filter was simply clamped between two flanged duct transitions in an open attic space. There is no floor a catwalk adjacent to the filter, with the danger that service personnel risk falling through the ceiling to the room below. Access is limited by the adjacent hangers and ducts. Furthermore, because the location is in an open attic space, dropping a used filter during a filter change, or breach of the wood filter case in the event of a fire, would result in the spread of contamination throughout the entire attic, which would be difficult if not impossible, to cleanup. In-duct installations of this type, in which the wood filter case is part of the pressure boundary, do not conform with NFPA 90A.[29] For this reason, the design is not acceptable and a housing must be used.

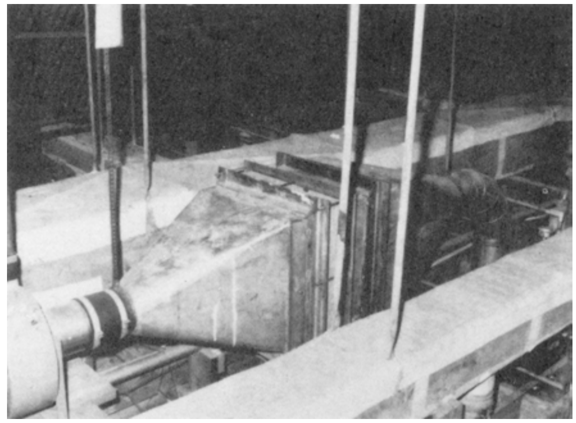


Figure 2.12 – An Illustration of Poor Filter Installation Practice

Figure 2.13 illustrates another example of poor filter installation and location. The location of the light troffer indicates that the air cleaning unit (which is provided for control room ventilation in a nuclear reactor) is located about 20 feet off the floor, and access is seriously impeded by hangers, cable trays, piping, and other equipment. This unit is a wood-cased chemical, biological, radiological (CBR) filter, which, like the filter installation shown in Figure 2.12 does not comply with NFPA 90A.[29] Again, this unit is located in an open and normally occupied building space where a serious spread of contamination could result if the filter were dropped during service or breached in an accident or fire. Furthermore, fire external to the filter could also breach the filter case and permit contamination to spread from the room to other portions of the building. **Figure 2.14** illustrates a better practice by showing an air cleaning facility installed in a large room that can be isolated as a radiation zone in the event of an emergency or spill without risking contamination of adjacent facilities.

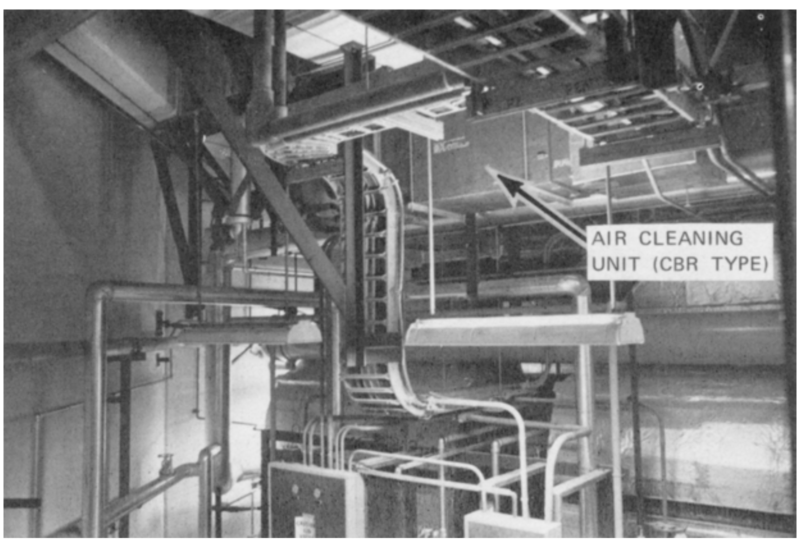


Figure 2.13 – An Illustration of Poor Filter Installation Practice

Another common practice has been to install ducts and filter housings on the roof of a building, which are accessible only over the roof. In the event a used filter is dropped during maintenance, there is a potential for contamination spread not only to a surface (the roof), which would be difficult to decontaminate, but to the atmosphere as well. For all systems, but especially for potentially high-hazard systems, it is recommended that all air cleaning components, including ductwork, be located inside a building space to provide a secondary

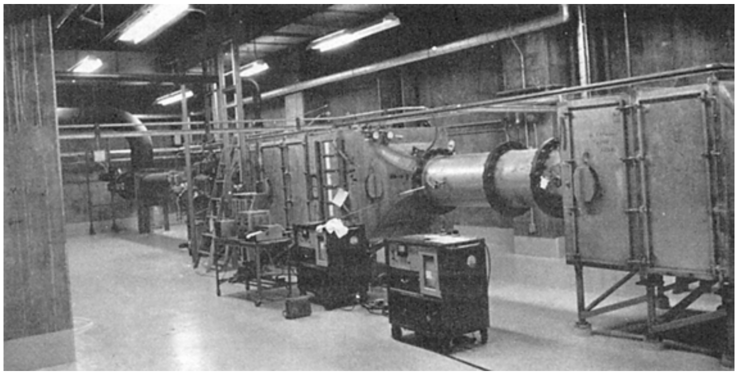


Figure 2.14 – Series-Compartmented Air Cleaning System

confinement against breach of the pressure boundary. Preferably, such building spaces should be heated to minimize condensation in the ducts during the winter months, and they should be easily accessible for inspection and service. Housings should be located in rooms that can be isolated during service or an emergency and that have walls and floors that can be easily decontaminated in the event of a spill. As a minimum precaution, the general areas surrounding the housing should be one that can be cordoned off as a contamination zone. Off-the-shelf bag-out housings of the type, shown in **Figure 2.15**, are being used increasingly for single-filter installations. Although the bag-in bag-out provisions of those housings offer a measure of protection against spills during service operations, the plastic bags employed can be torn by the sharp corners of steel-cased filter elements and adsorber cells. It is recommended, therefore, that these caissons be installed in isolable rooms or controlled building spaces, at least in those cases where intermediate to high-level radioactive material is, or could be, present in the duct. Additional information on caissons and bag-in bag-out filter installations is given in Chapter 6.

2.5 Multistage Filtration

Although a single stage of HEPA filters is sufficient to meet most decontamination requirements, two, three, or even more stages may be required to meet the stringent requirements of facilities in which plutonium and other transuranic materials are handled. Multistage HEPA filtration is also employed to increase system reliability through series redundancy.

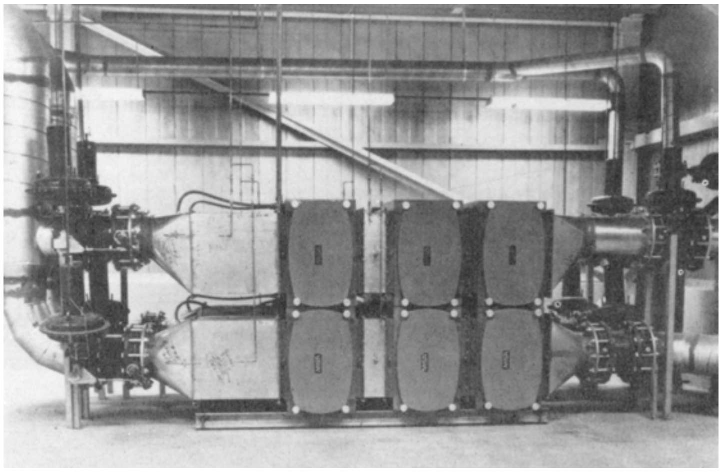


Figure 2.15 Exhaust Air Cleaning System of Radiopharmaceutical Company

2.5.1 Series Redundancy

Installations such as the DOE national laboratories and production facilities which have lived with radiation on a day-to-day basis for many years have found it necessary to employ series redundancy of HEPA filters in exhaust and air cleanup facilities for Zone I, and often Zone II, confinements. The purpose is to increase the reliability of the system by providing backup filters in the event of damage, deterioration, or failure of the first-stage filters. Each stage of filters must be individually testable if credit for redundancy is to be clamed. That is, if the stages are not individually testable, the combination of two or more stages must be considered as only a single stage from the standpoint of reliability. On the other hand, each untestable stage contributes to the overall filtration efficiency of the combination, although not to an extent equivalent to the nominal stage efficiency of 99.97 percent [decontamination factor (DF)=3333]; a maximum efficiency of 99.8 percent (DF=500) has been allowed in the past for untestable second- and third-stage filters, with full credit for the stage. For new systems, no credit should be assumed for non-tested filters.

Redundant stages should be well spaced, the first often being a duct-entrance filter in a room, glovebox, or hot cell, and the second being the final filters of a central exhaust system. In some systems, for example the ESF air cleaning units of nuclear power plants, the series-redundant filter banks are installed within the same housing. In any event, redundant stages should be spaced sufficiently far apart to allow for effective in-place testing and inspection of both faces of the filters; they should not be installed back-to-back or to other components of the system such as prefilters or adsorber cells.

2.5.2 Increased Decontamination Factor (DF)

The particle sizes of plutonium aerosols generated in chemical operations employed in nuclear fuel fabrication and reprocessing fall within the range of the size of maximum penetration (SMP) for HEPA filters, 0.07 to 0.3 μm light scattering mean diameter (LMD). Although 0.3 μm LMD is considered the SMP for dust and other unit-density particles, the SMP for high-density particles, such as plutonium, is substantially higher. The aerodynamic mean diameter of plutonium particles formed by condensation is thought to lie between 0.4 and 0.7 μm.[28] A HEPA filter, by definition, has a minimum filtration efficiency of 99.97 percent (DF=3333) for 0.3-μm particles (although most of the HEPA filters currently being validated by the DOE Quality Assurance Stations exhibit DFs on the order of 10^4). Current NRC Regulatory Guides recommend a total plant DF of at least 10^{11} for plutonium in gaseous effluents. Although some decontamination is effected by plant operations, the greatest portion must come from the HEPA filters, which means that two, three, or even more stages of filters may be necessary.

Theory predicts that the primary mechanisms in the arrestance of particles by a HEPA filter are diffusion and inertia; the effectiveness of these mechanisms varies with particle size, airflow velocity through the medium and, to a lesser extent, particle density as shown in **Figure 2.16**. Direct interception, or impaction, is a secondary mechanism that is independent of these parameters. As evident from Figure 2.16, these mechanisms combine to produce a statistical average DF, not an absolute value for a given particle size. For this reason, the effect of adding stages of HEPA filters is multiplicative and does not produce a screening effect that theoretically results in an absolute minimum DF for any given particle size. (In practice, however, some screening of particles substantially larger than the SMP can be expected.) In theory, therefore, the DF of a multistage HEPA filter installation would be $DF^n f$, where $DF f$ is the definition DF of the HEPA filter (DF=3333) and n is the number of stages. Work at the Los Alamos National Laboratory suggests that this theory is essentially true[30]; DFs of 10^4 for stages one and two and of somewhat less than 5×10^3 for the third stage of a three-stage system, with an average DF of 5×10^3 for each of the three stages, were determined. These results were obtained in a small-scale test system (about 25 cfm) in which conditions were idealized by eliminating gasket leakage and employing filter units that exhibited a test efficiency (according to DOE Quality Assurance Station testing) of greater than 99.99 percent.

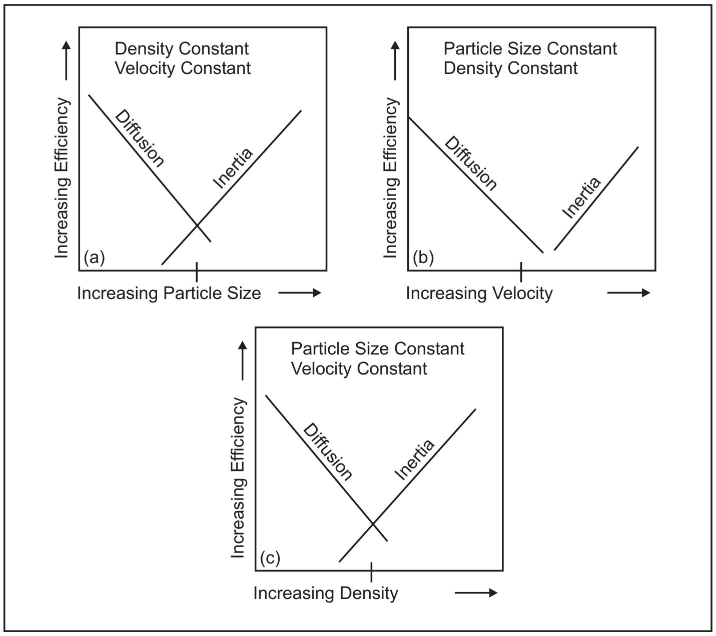


Figure 2.16 – General Effect of Principal Mechanisms that Affect the Arresting Efficiency of the HEPA Filter

Earlier less definitive tests and experience had indicated substantially lower values of DF in the second and third stages, and conservatism suggests that values lower than those obtained in the Los Alamos tests should be used in practice. Conservatism also suggests that a value no higher than DF 3333 be used for the first stage, and probably somewhat less to allow for filter degradation under service conditions. Although DF improves with dust lading of the filter, aging and exposure to moisture and corrodents may decrease the ability of the filter to maintain the higher DF under system upset conditions. For purposes of estimating the capability of a multistage HEPA filter installation under normal operating conditions, a DF of $(3 \times 10^3)^n$ can be safely used with systems that adhere to the design, construction, testability, and maintainability principles of this handbook or ASME N509.[33]

Accident analyses typically assume a first stage credit of 99.9 percent efficiency (DF of 10^3) for removal of plutonium aerosols. Second and subsequent stages typically assume an efficiency of 99.8 percent (DF of 5×10^2). These assumed efficiencies are based on the premises that: (1) the HEPA filters have successfully been through the DOE Filter Test Facility (FTF) at Oak Ridge; (2) they are installed and in-place leak tested to at least 99.95 percent[31]; (3) they are installed in a system built to the specifications of AG-1; and (4) are tested in accordance with national standards.

2.6 Passive Safe Shutdown of Systems

"Passive Safe Shutdown" (PSS) is an expression that describes a confinement concept in use at a hazardous nuclear facility, whereby potential air exhaust pathways are aligned through filtration components, but without a motive force pulling the air through. The concept is basically the same as a judicial arrangement of filtration assets during a facility blackout condition. The potential imminent failure of the exhaust filtration system may also warrant such an arrangement. The PSS concept can be applied as either a penultimate or a first response to an accident situation.

As a penultimate response, every hazardous facility manager should have such a prepared plan for what to do when the lights go out. This should include the arrangement of the facility in such a way that it poses the least threat possible to the facility workers, the environment, and the public. It may also be useful to enter this intentional "operational" mode under extenuating circumstances, such as the exhaust filtration system is in jeopardy of failure (e.g., from internal or external fire threats). However, the plan should also consider expeditious departure from the PSS mode after entry.

When PSS becomes the first, and sometimes only, response to an accident situation, additional attention must be given to potential leakage pathways and accident sampling. The reasons for this are simple. The accident itself could produce some unintended consequences when the PSS mode is entered and the facility is operating at, or greater than, atmospheric pressure. To understand these two potential challenges (i.e., potential leakage pathways and accident sampling) each will be examined in the context of a confinement, versus a containment concept.

Hazardous operations at DOE facilities are typically located inside a confinement. The confinement usually consists of the entire building structure and associated confinement ventilation system(s) (CVS). The building is maintained at a negative pressure relative to atmosphere by the CVS. The CVS is an assortment of several subsystems that cascades the building air from areas of lesser contamination to areas of greater contamination, with some intermediate contaminate removal via filtration. Prior to being exhausted from the building, the air undergoes filtration, sometimes through multiple stages of filters.

Air is supplied to the confinement building by various air supply systems. Typically, air is supplied at a rate slightly less than it is exhausted, such that a vacuum can be maintained throughout the facility. Air may also "leak" into the building through door seals or penetrations and account for the mismatch between supply and exhaust. Various dampers and valves are usually employed to direct the air to specific locations.

Theoretically, with the building maintained at a negative relative to atmosphere, all air that enters the building should exit only after it is filtered.

By contrast, in a containment concept, such as those employed at commercial nuclear power plants, air is bottled up inside an unfired code pressure vessel (the actual confinement) which is surrounded by a reinforced concrete structure, which provides the seismic resistance for the facility. Here there is no unintentional supply or exhaust of air expected during the course of the accident. Also, there is no cascading of air or vacuums relative to atmosphere. Actually, confinement pressures up to several atmospheres are expected. This is not to say that confinements are not found in commercial nuclear power applications, for they are. It's just that the containment is the primary retention device, and not a confinement.

For actual confinements, several factors may cause the building to either "breath" or "exhale." "Breathing" can be caused by the diurnal sun cycle which leads to the heating and cooling of the building and consequent expansion and contraction of the building air. Since the building seeks to remain at atmospheric pressure, it will breath, hopefully through a pre-established filtered pathway, to accommodate the expansion and contractions within the building. This pre-established filtered pathway is the very essence of the PSS concept. Changes in barometric pressure act in somewhat the same way.

The building can "exhale" by several mechanisms. Fires can cause the air to exhale from the building, as can the release of compressed gases, which hopefully are not flammable, inside the facility. Strong winds can create a vacuum on the leeward side of the building and pull air through various penetrations.

The purpose of the last two paragraphs is to demonstrate that there are mechanisms beyond our immediate control (i.e., diurnal cycling, barometric pressure swings, fires, compressed gas releases and strong winds) that can lead to undesirable releases from a structure that is in a passive state. Hopefully the releases will be through filtration devices, but this is dependent upon the integrity of both the structure and the exhaust pathway established.

The greatest threat to confinement, structural integrity, is an earthquake. At nuclear facilities, buildings and equipment, designated Safety Class or Safety Significant are specifically designed to withstand the effects of a design basis earthquake (DBE). This means the building should be structurally usable and the equipment able to perform its intended function after suffering the imparted motions of a DBE or one of lesser magnitude. Cracks and damaged penetrations may be significant in that they could provide potential unfiltered leakage pathways.

To gain some insight into the size of cracks that may be of interest, consider the following for diurnal cycling. A 2 million cubic foot building (200 feet long × 200 feet wide × 50 feet high) and a 25 degree Fahrenheit temperature increase, will lead to a 5 percent volume change over 10-hour period, leading to a leak rate of approximately 170 standard cubic feet per minute (scfm). Bypass leak rates of only a few volume percent have been shown in Documented Safety Analysis (DSA) reports to result in calculations that approach the exposure guidelines for the general public. The surface area represented by this building is approximately 80,000 square feet. Assuming a 10 square foot leakage pathway (i.e., an average size inlet duct), this represents a 17-foot-per-minute velocity from the pathway [or roughly 11.5-mile-per-hour (mph) velocity which is humanly perceptible]. At 100 square feet assumed surface area of cracks, that's down to 1.15 mph (not easily perceptible). A 10 square foot leakage pathway represents only 0.0125 percent of the surface area and could also be represented by a crack 960 feet in length and 1/8 of an inch wide. It is evident that even small holes and cracks are potentially extremely important to any confinement concept.

When it comes to building penetrations, doors are the most obvious. Under normal conditions, door seals will leak. Tell-tale air in-leakage marks have been observed at damaged facilities. Since air will follow the path of least resistance, if there is no impediment to in-flow during normal operations, there will be no impediment to out-flow during PSS conditions. Also, and most importantly, this may not be a filtered pathway. One facility, in response to establishing Technical Safety Requirements (driven by the importance of the bypass leakage assumptions to their DSA calculations), has actually measured the air in-leakage during normal facility operations and set an upper limit of acceptability and periodic surveillance requirements for operation. Doors, therefore, should be thoroughly analyzed for susceptibility to permanent distortion resulting from seismic events. This could occur at the door frame to building mounting as well as the door to the door frame mounting. The amount of expected distortion and resultant leakage pathway, should be taken into consideration in the safety basis for the facility.

The next obvious potential bypass leakage pathways are the inlet and exhaust duct penetrations. As with doorways, the attachment of the ductwork to the structure represents a potential failure point that should be analyzed. In addition to the penetration itself, the extension of the ductwork into the facility also offers a potential bypass leakage pathway, as the skin of the ductwork is actually an inward (or outward) extension of the confinement boundary. This boundary should end with a testable isolation valve or a seismically designed filtration system. A few facilities have actually fitted their inlets with HEPA filters, such that the facility can be alligned to breathe through both the inlet and exhaust HEPAs. Dampers should never be used for isolation purposes, as they are not designed for this purpose. Obviously, all penetrations through the ductwork up to the point of isolation represent potential bypass leakage pathways and should be limited and testable. Potential problem areas include fan shaft seals, boots on fans, valve and damper shafts, instrument penetrations, electrical penetrations, etc. All these should be considered in estimating potential bypass leakage. The seismically-designed ductwork supports should not be overlooked. Without them, the ductwork, that is expected to remain in tact, might not stand during a seismic event.

A not so obvious threat to a PSS confinement (or any confinement for that matter) is the storage of unsecured waste in large 100-cubic foot boxes or 55-gallon drums throughout the facility. During a seismic event, such unsecured items could move and possibly endanger the confinement boundary. The same is true for items stored inside filtration systems (i.e., ladders and tools used for filter testing and change outs). All these things must be considered.

Besides trash and testing tools, there is also concern for installed equipment that is not seismically designed or restrained. The potential interaction of nonseismically-designed equipment upon seismically-designed equipment is referred to commercially as "two over one" considerations. [Note: This is derived from the seismic level II (nonseismically-designed) and seismic level I (seismically-designed) designations used commercially.] This has led to cumbersome shield walls and restraints added to commercial designs. The bottom line is the potential motion of material and nonseismically-designed equipment and its resultant potentially detrimental impact on the confinement boundary should be taken into consideration.

Internal integrity may also be important if transport assumptions for zone-to-zone communications during potential accident scenarios effectively reduce the material at risk. All the concerns expressed for confinement boundary integrity (i.e., cracking, penetration, moving equipment, unsecured trash, etc.) now should apply to the zones themselves. This could become a calculational quagmire.

Besides bypass leakage considerations, the other significant challenge to the PSS concept involves post-accident sampling. Such sampling is necessary to adequately inform the facility management so appropriate and timely actions might be recommended for the protection of the public, workers, and the environment in the event of an accident. Without sample flow [because there is no power], installed instrumentation will not work because the electronics will divide the raw counts collected over a period of time (this is directly proportional to the amount of an assumed isotope released via the fixed pathway) by the average sample flow rate during the same period of time, which will lead (with division by zero) to meaningless numbers. It is also assumed that all the leakage is being directed past the monitor, which, as has already been discussed above, may not be the case.

The use of field sampling results for post-accident decisionmaking suffers from two serious deficiencies: accuracy and timeliness. With bypass leakage, it is impossible to determine, a priority just where the material will come from and at what flow rate. So, even though something may be measured, there is no assurance that it represents the total threat. Also, the time to gather and analyze a sample is too long compared to the time required for recommending protective actions. There is simply no substitute for directing a known flow quantity through a known pathway and past a monitor to assess the conditions emanating from inside an accident stricken confinement.

In conclusion, every hazardous facility should have a plan on how and when to best align for a blackout condition (i.e., a PSS plan) and on how and when to expeditiously exit a PSS state. That being said, a PSS concept for a post-accident condition requires both a detailed level of knowledge of the integrity of the confinement structure itself, all its penetrations, and potential equipment and material movements in the facility; and, development of reliable and timely sampling techniques. While such knowledge and development might be useful to pursue, it soon becomes obvious that it is overly burdensome to control all the potential threats to confinement integrity or to obtain reliable and timely estimates necessary for protection of the public, workers, and the environment. It is easier, more reliable, and practical to direct flow by force through a known pathway.

2.7 Air Cleaning System Design Considerations for Commercial Nuclear Power Plants

The purpose of this section is to introduce the reader to the lexicon and requirements for air cleaning systems at nuclear power plants. Except for those systems found in confinement, there are many similarities between the air cleaning systems used at nuclear power plants and those used at DOE facilities. The first difference is nomenclature (i.e., the names of components). At DOE facilities, the nomenclature used includes "safety class," "safety-significant," and "defense in depth," or simply production support. Nuclear power plant systems and equipment are classified as either nuclear-safety-related, ESF, or nonnuclear-safety-related. In some cases, nonnuclear-safety-related systems and equipment are designated as "Balance Of Plant." Some systems and equipment are referred to as "Important to Safety." This term is not recognized by regulatory agencies and organizations, but certain situations exist where an air cleaning system must perform a function that has fewer requirements than those for a system that is fully nuclear-safety-related. One example is the Technical Support Facility Ventilation Air Cleaning System for commercial nuclear power plants. This area is used by plant management and technical support staff to support the operating staff in the control room during unusual events or accidents. The Emergency Operations Centers (EOCs) at DOE facilities are similar in both function and design to commercial nuclear power plants Technical Support Centers. These systems are required to: (1) be constructed, operated, and tested in accordance with the requirements of U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.140,[32] (2) be able to provide a positive pressure within the Technical Support Center when it is operational, and (3) be supplied with Class 1E emergency power. These systems are nuclear-safety-related, but are not an engineered safety feature.

2.7.1 Engineered Safety Feature and Nonnuclear-Safety-Related Systems

Air cleaning systems designed for ESF applications at commercial nuclear power plants must meet the requirements of Regulatory Guides 1.52,[28] and 1.78,[33] as well as applicable portions of the facility's Standard Review Plan. These documents have been cited routinely by DOE, but generally are not mentioned in current DOE Orders. In addition, DOE cites numerous of its Orders that have special application to nonpower-related reactor activities. Many of these documents are site specific, and DOE is currently reviewing some of them for possible deletion and replacement (by reference) with consensus codes and standards.

Regulatory Guide 1.52[27] addresses ESF air cleaning system requirements. Regulatory Guide 1.140[32] addresses nonnuclear-safety-related air cleaning ("normal atmosphere cleanup") system requirements. Regulatory Guide 1.78[34] addresses climatic affects and requirements for outside air intakes.

For ESF applications, applicable regulations, codes, and standards must be combined with good engineering practice. Ease of maintenance, operability, testability, cleanability, and decontamination also must be carefully considered. In addition, air cleaning systems must be integrated into the overall plant or process design, including monitoring and control requirements. ESF systems are supplied with assured power from the plant Class IE emergency electrical power system.

Applicable Regulations and Standards for ESF Air Cleaning Systems

Air cleaning systems designed for ESF applications at commercial nuclear power plants must meet the requirements of ASME Standard N509, *Nuclear Power Plant Air Cleaning Units and Components*;[29] ASME Standard N510, *Testing of Nuclear Air Treatment Systems*;[23] ASME Standard N511, *In-service Testing of Nuclear Air Treatment Systems* (to be published)[35]; and ASME AG-1, *Code on Nuclear Air and Gas Treatment*.[4] It is good practice to implement the codes and standards referenced above for all nuclear-related air cleaning systems and components. All Safety Class and Safety Significant systems must be built to ASME AG-1 requirements.

Specific regulations, regulatory guides, Standard Review Plans (SRPs), and industry guidance and consensus standards govern the design criteria and operating characteristics for ESF air cleaning systems. Although these criteria are generated specifically for commercial nuclear generating stations, the principles can be adapted to other nuclear facilities.

Regulatory guides and SRPs provide more specific guidance and are considered acceptable ways of satisfying regulatory requirements. Regulatory Guide 1.52, *Design, Testing, and Maintenance Criteria for Post Accident Engineered-Safety-Feature Atmosphere Cleanup System Air Filtration and Adsorption Units of Light-Water Cooled Nuclear Power Plants*,[27] details criteria for operating Control Room air cleaning systems in a post-accident environment. Environmental and system design criteria, component design criteria, qualification testing, maintenance, and in-place testing are discussed in detail.

The ESF systems designed to contain and mitigate DBAs must be redundant and physically separated so that damage to one does not cause damage to the other.

Redundancy requires two complete trains of equipment and components. There are cases where ductwork has not been completely redundant. A common space served by the redundant trains, such as control rooms, may not require 100 percent redundancy of the ductwork, as long as it can be demonstrated that no common mode failures would render both trains of equipment inoperable.

Separation is required, so that postulated accidents such as internal missiles, fire, and flood cannot render both trains of the redundant system inoperable from the same event. Separation can be achieved by physically locating the trains far enough apart that postulated accidents cannot render both trains inoperable, or by erecting a physical barrier, such as a concrete wall, for protection.

The SRPs are documents prepared by NRC staff to document application review procedures for construction and operation of nuclear power plants (NUREG-0800).[36]

The following criteria are applicable to ESF systems for all applications:

- A single active failure cannot result in loss of the system functional performance capability.
- Failure of nonseismic Category I equipment or components will not affect system operation.

- A suitable ambient temperature can be maintained for personnel and equipment.

- The system can detect and filter airborne contaminants before personnel enter the area.

- The system can detect and isolate portions of the system in the event of a fire.

- The ESF ventilation system will continue to function during all DBAs that require the building or area of the plant to be habitable and that require the essential equipment served by the ESF ventilation system to remain in operation.

Most nuclear power plants restrict the amount of zinc and aluminum that can be used inside the confinement structures. Zinc and aluminum both interact with the spray chemistry of the emergency core cooling systems to produce hydrogen, which can accumulate in the confinement and become an explosion hazard in the event of an LOCA. These materials must be tightly controlled, and an accurate inventory must be kept when they are used inside confinement structures.

Since most HVAC and air cleaning systems use galvanized steel for ductwork and equipment housings, alternate materials need to be considered for use inside confinement structures. One option is to use stainless steel for ductwork and equipment housings. Stainless steel is expensive, but its advantage is that it does not require any coating to prevent the corrosion or scratching that can occur during repair, maintenance, or testing/surveillance activities. In addition, it is easier to decontaminate than some other materials. Another, less costly option is to use steel coated with a material that is compatible with the confinement environment. The disadvantage of using coated steel is that it does not hold up well in environments involving high rates of ductwork or equipment repair, maintenance, or testing/surveillance activities. The coating also must be inspected and repaired when damaged, which can cause critical time delays during refueling or other time-sensitive activities.

Galvanized steel ductwork can be used successfully outside confinement, and at a lower cost than stainless steel. Galvanized steel has many of the same advantages as stainless steel, such as ease of decontamination, and it holds up well in areas that are subject to frequent repair, maintenance, testing, and surveillance activities. One caution should be noted, however: if the galvanized coating is severely damaged or removed, as in cases when welded duct construction is used and when supports are attached by welding, then the damaged areas must be recoated with a zinc-rich paint to prevent corrosion.

Radiation considerations can also present some material challenges, especially for those units that are normally in standby but function during and after a DBA and collect large quantities of radioactive materials. Radiation exposures of ten to hundreds of millions of rads are possible and need to be considered. At these exposure levels, the decomposition of some organic materials (e.g., gules, gaskets, binders) becomes possible. [Note: One common sealant, Teflon®, is particularly susceptible to radiolytic decomposition starting at approximately 1,000 rads of exposure. One decomposition product of note is hydrofluoric acid.]

2.7.2 Design Considerations

A clear definition of the design parameters is probably the most important, but often the least appreciated, requirement leading to the development of a satisfactory air cleaning system. The design parameters must consider basic performance requirements; physical limitations; regulatory, code, and standard compliance; and accident confinement and recovery. All of these parameters must be identified as an initial system design step because they form the basis for design. This is the responsibility of the facility owner, who is often assisted by an architectural engineering firm with experience in this type of plant design. See Table 2.1 for system environmental parameters.

Outdoor design conditions can be obtained from the ASHRAE Guide and Data Books,[37] from local weather stations, or from site meteorological data. It is important when selecting outside design conditions to use the *most extreme* data, particularly for nuclear-safety-related systems, as they must be capable of operating in these extremes.

The following examples of design basis accidents should be considered when designing an air cleaning system:

- Reactor coolant system LOCA (large and small breaks).

- Seismic Loading. [Note: the loads that must be considered when designing the air cleaning system will be different if the system has to remain operational during and after the event, or if the system only has to maintain its structural integrity; i.e., the system does not have to function during and after an event.]

- Fire, smoke, and hot air (see Chapter 10).

- Tornado/high winds. [Tornadoes can cause damage due to a significant pressure drop [approximately 3 pounds per square inch in gauge (psig), negative] as the tornado passes over the facility. Openings and items (e.g., air cleaning equipment, ductwork, etc.) that are exposed to this pressure transient can collapse if they are not protected by tornado dampers. In addition, tornadoes and high winds can convey missiles that can enter intakes and other unprotected openings and damage safety-related systems and equipment.]

- Internal and external missiles. (Internal missiles are usually generated by rotating equipment failure. External missiles are usually generated by a tornado or high wind.)

- Active equipment failure. [This refers to failure of any equipment that provides an "active" function (e.g., pumps, fans, valves, dampers, switches, etc.) and must be relied on to safely shut down the facility and/or maintain it in a safe configuration.]

- Loss of onsite and offsite power. (The facility must be designed to be safely shut down and/or be maintained in a safe configuration in the event of a loss of onsite and offsite power.)

2.7.2.1 System Design

Individual ESF air cleaning systems are limited by Regulatory Guide 1.52[27] to approximately 30,000 cfm. When the system airflow exceeds this limit, multiple systems must be used in parallel. ESF systems contain the following sequential components: (1) a moisture separator to remove entrained water droplets, (2) a heater to control relative humidity (RH) when the RH of the air entering the carbon adsorber exceeds 70 percent, (3) prefilters, (4) HEPA filters, (5) a charcoal adsorber, (6) HEPA filters downstream of the adsorbers, and (7) a fan. Ducts, valves, and dampers are also included for system isolation and flow control, as well as related instrumentation. When the moisture and dust loads are low for all credible operating modes, the prefilter and moisture separator may not be required.

As stated previously, ESF systems designed to contain and mitigate accidents must be redundant, and the redundant systems must be physically separated so that damage to one does not cause damage to the other. Instruments must make flow rates and pressures available to the Control Room as well as locally, and must provide visual and auditory alarms as indicated in ASME AG-1, Appendix IA-C, Table IA-C.[4] All instruments, including heater, damper, and fan controls should meet the requirements of IEEE 323, *Standard for Qualifying Class 1E Electrical Equipment for Nuclear Power Generating Stations*[5] and IEEE 344, *Recommended Practice for Seismic Qualification of Class 1E Equipment in Nuclear Generating Stations*.[6] Regulatory Guide 1.100, *Seismic Qualification of Electrical Equipment for Nuclear Power Plants*,[38] and Regulatory Guide 1.105, *Instrument Set Points*,[39] are also applicable. Instrument controls and control panels should meet the design, construction, installation, and testability criteria in Section IA of ASME Code AG-1.[4]

The design, construction, and test requirements of *ASME Code AG-1*[4] apply to the following ESF air cleaning components and are titled accordingly.

- Section AA, "Common Articles"
- Section BA, "Fans and Blowers" (Motors for fans and blowers must also meet the qualification requirements of IEEE 334,[40] IEEE 323,[5] and IEEE 344.[6])
- Section DA, "Dampers and Louvers"
- Section SA, "Ductwork"
- Section HA, "Housings"
- Section RA, "Refrigeration Equipment"
- Section CA, "Conditioning Equipment"
- Section FA, "Moisture Separators"
- Section FB, "Medium Efficiency Filters"
- Section FC, "HEPA Filters"
- Section FD, "Type II Adsorber Cells"
- Section FE, "Type III Adsorber Cells"
- Section FF, "Adsorbent Media"
- Section FG, "Frames"
- Section FH, "Other Adsorbers"
- Section FI, "Metal Media Filters"
- Section FJ, "Low-Efficiency Filters"
- Section FK, "Special Round and Duct Connected HEPA Filters"
- Section IA, "Instrumentation and Controls"
- Section TA, "Field Testing of Air Treatment Systems"

2.7.2.2 Structural And Seismic Design

The structural design of ESF air cleaning systems must consider the service conditions that components and their housing may experience during normal, abnormal, and the accident conditions contained in Section AA of ASME AG-1.[4] The ESF air cleaning system must remain functional following dynamic loading events such as an earthquake. The ESF air cleaning systems, including all components, must have their structural design verified by analysis, testing, or a combination of both. Qualification criteria are contained in Section AA of ASME AG-1.[4] The design requirements for determining housing plate thickness and stiffener spacing and size are contained in ASME AG-1, Section AA, "Structural Design," Sections SA, "Ductwork," and HA, "Housings." [4]

The maximum allowable deflections for panels, flanges, and stiffeners for the load combinations are contained in ASME AG-1, Section SA, "Deflection Criteria."[4]

2.7.2.3 Equipment Qualification

The fundamental reason for qualifying equipment is to provide adequate levels of safety for the life of the facility. Equipment qualification assures the ESF system will satisfy two characteristics:

- The equipment will resist common mode failures due to aging degradation.
- Nonmetallic materials will survive anticipated environmental stresses.

Generic or Application-Specific Qualification

Qualification may be generic or application specific. Generic qualification is probably best applied by the original equipment manufacturer. This type of qualification program requires test parameters that may exceed the needs of the specified requirements to be able to use the qualified equipment in a variety of applications and environments. An application-specific qualification limits the use of the component or system to those with the same or lesser environmental parameters.

Mild or Harsh Environment Qualification

A mild environment qualification can usually be accomplished without determination of a qualified lifetime (per Section 4 of IEEE 323),[5] whereas a harsh environment program usually requires testing to verify performance under extreme accident conditions. Simulated aging is necessary to arrive at "end of life conditions" prior to accident condition testing.

Determining Mild or Harsh Environment

When the answer to all of the questions below is "Yes," the equipment should be assumed to be subjected to a mild environment and treated accordingly.[27] Otherwise, it should be treated under the assumption that it is subjected to a harsh environment.

- Will the environment where the equipment is located be unaffected during and after a DBA (i.e., will there be no significant changes in temperature, radiation)?
- Will the equipment perform its safety-related function *before* the environment becomes harsh?
- Will failure of the equipment in a harsh environment after it has performed its function:

- Result in misleading information?
- Affect the functioning of other safety-related equipment?
- Cause a breach of pressure boundary integrity?

Safety or Non-Safety-Related Function

It is necessary to determine whether the components are designated as safety-related or nonsafety-related. Nonsafety-related items can often be excluded from the qualification process when it can be shown that failure of that component would have no adverse effect on the safety function of the overall equipment.

Equipment Qualification Plan

The Qualification Plan must be developed in accordance with IEEE 323[5] and must include a determination of the qualification method, listing of the environmental service conditions, description of any required aging programs, protocol of the test sequence, and definition of the accident test profiles.

An aging program consists of all stress factors, including thermal aging, mechanical/cyclic aging, radiation exposure, and mechanical vibration. All are designed to simulate conditions that would be encountered during the expected life of the test specimen prior to an accident condition or test such as seismic pressure or LOCA.

Equipment Qualification Methods

Three equipment qualification methods are described below.

- Type Testing:
  - Accounts for significant aging mechanisms;
  - Subjects the equipment to specified service conditions; and
  - Demonstrates subsequent ability to perform safety function.
- Operating Experience:
  - Must be compared to equipment with the same generic design; and
  - Depends on documentation of past service conditions, equipment performance, maintenance, and similarity for its validity.
- Analysis:
  - Requires logical assessment or mathematical model of the equipment;
  - Requires the support of test data, operating experience, or the physical laws of nature; and
  - Must be documented to permit verification by a competent third party.

A combination of any of the above qualification methods is recommended.

2.7.2.4 Air Cleaning System Integration with the Entire Facility

A critical design consideration that is often overlooked is the question of how the air cleaning system interrelates with other air handling systems and the entire facility. Often areas of a facility are directly connected to more than one air handling system. There are an unlimited number of possible combinations, but some of the most common are:

- An ESF air cleaning unit exhausting an area supplied by a non-safety HVAC system;
- An ESF air cleaning unit in an area normally exhausted by a large fan that may or may not shut down when the safety system is activated;
- A Control Room ESF air cleaning unit designed to provide a positive pressure in an area served by other ESF and/or non-ESF systems;
- The maintenance of graduated levels of negative pressure in concentric rings in fuel plants or plutonium facilities; and
- Gloveboxes, hot cells, and laboratory hoods with independent filtration systems in rooms served by ESF or non-ESF systems.

These examples illustrate the need to consider the entire facility when designing an ESF system. Two questions must be addressed: (1) how can the system under design affect other systems and areas, and (2) how can the remainder of the facility affect this system?

2.7.2.5 Design Areas Requiring Special Attention

There are system characteristics that apply to all air cleaning systems regardless of their specific function or the nature of the facility. One is that they must be capable of continuing to meet quantifiable test criteria to provide evidence of maintaining acceptance limits over the life of the installation. Therefore, the ability to maintain and test systems is as important as the ability of the systems to meet the initial performance criteria. The following are samples of some of the factors that apply to all systems and must be addressed:

- Airflow distribution in the ducts and housings;
- Airflow balance through the inlet and/or outlet ducts;
- Fan balance, leaktightness, and a capacity to provide adequate pressures at all design flows;
- Access for inspection, maintenance, and replacement; and
- Instrumentation that integrates the overall control and monitoring requirements of the facility.

2.7.2.6 Location and Layout

The ducts of ESF air cleaning systems that pass through clean areas should be designed at a higher negative pressure, and the length of any air cleaning unit positive pressure discharge ducts that must pass through a clean space should be kept as short as possible. When an ESF air cleaning system is a habitability system, ducts carrying outside air that are routed through clean space should be designed at a negative pressure. Housings handling recirculated habitability air should be at a positive pressure when located in a contaminated space. Negative pressure ducts located in a contaminated space should be avoided. When this is not possible, all-welded duct construction should be used. The length of positive pressure ducts outside the habitability zone should be kept as short as possible.

Generally, the direction of airflow should be from less contaminated spaces toward areas with a higher level of contamination. All ducts and housings containing a contamination level higher than surrounding areas should be maintained at a negative pressure. Ducts and housings with lower concentration levels than surrounding areas should be at a positive pressure. Allowable leakage depends on the difference between duct/housing concentrations and surrounding area concentrations. For example, a once-through contaminated exhaust filter housing serving a radioactive waste handling area in a nuclear power plant may have the exhaust fan located downstream of the filter housing when the housing is 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 is under a negative pressure up to the fan. Therefore, leakage will be into the housing, and the potential impact of contaminated leakage on plant personnel during system operation will be minimized.

Such a system configuration does not mean that leakage can be ignored. Where it is crucial to personnel habitability, acceptable limits should be established and periodically verified by testing and surveillance. Rather, it means the potential for exposure has been reduced to ALARA levels by system design. When the space in which 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 to eliminate in-leakage of more contaminated air.

When the housings of habitability systems are located within a protected space, the fan should be located downstream of the filter unit to ensure that only cleaner air can leak into the housing. When the housing of a habitability system is located in an area outside a protected space, the fan should be located upstream of the filter unit to ensure that contaminated air cannot leak in downstream of the filter unit.

Location of fans and housings should be accomplished by assigning a positive designation to the atmosphere in the cleaner area or duct, and a negative designation to the more contaminated area or duct. When the pressure difference within an air cleaning housing or duct is positive (+), the fan should be on the contaminated air-entry side; when the pressure difference is negative (-), the fan should be on the "clean air" exit side.

Serviceability and maintainability are major considerations when designing an ESF air cleaning system. Access for servicing the inside and outside of the housing for filter replacement, maintenance, and testing must be provided. Housings should not be situated among machinery, equipment, and ductwork with any means for ready access. There must also be sufficient space in the access corridors and adjacent to the housing to allow handling of filters during change-outs, including space for stacking filters adjacent to the work area. Dollies are often needed to transport filters through the access corridors. When Type III carbon adsorbers are used, access to the area must be provided for the mobile carbon transfer equipment. Note that the fill method must be qualified to ensure adequate packing density. Hand filling is not acceptable. Recommended service clearances are given in ASME N509.[29]

2.7.2.7 Air Cleaning System Design Considerations for Commercial Nuclear Power Plant Control Rooms

The operation of a nuclear power plant is complex and must be performed with great care. Although there are a number of locations where control over operations is exercised at a nuclear power plant, the center of activity is the Control Room. Broadly described, the Control Room is a dedicated area at any type of nuclear facility where the plant operations controls are located.

Nuclear power plant operators are highly trained licensed individuals. Their primary function is to control the nuclear reaction to ensure the reactor is operated safely under both normal and abnormal conditions. Therefore, the Control Room design must ensure that environmental conditions allow achievement of this goal. Both Control Room operators and equipment (electrical equipment, cables, gauges, instruments, controls, and computers) must be protected from the radiation and radioactive material present during normal operation and during abnormal or accident situations, as well as toxic gases, fires, explosions, missiles, earthquakes, tornadoes, and floods. An environment must be provided where both temperature and RH are maintained to ensure the continuing performance of Control Room equipment and to provide reasonable standards of human comfort for the operators. The primary means of achieving these conditions are air cleaning, ventilation, and air-conditioning systems that are appropriately designed, tested, maintained, and operated in conformance with the facility design criteria and best engineering practices. In addition, to enhance operator performance, the Control Room environment must be free from excessive noise, equipped with adequate lighting, and be designed with easy accessibility to equipment controls.

Control Room System Design Criteria

The basic regulation applicable to nuclear station Control Room systems is 10 CFR Part 50, Appendix A, "General Design Criterion 19."[41] The regulation states, "A Control Room shall be provided from which actions can be taken to operate the nuclear power unit safely under normal conditions and to maintain it in a safe condition under accident conditions, including loss-of-coolant accidents. Adequate radiation protection shall be provided to permit access and occupancy of the Control Room under accident conditions without personnel receiving radiation exposures in excess of 5 rem whole body, or its equivalent to any part of the body, for the duration of the accident." Control Room habitability during a postulated hazardous chemical release also is the subject of two regulatory guides. Regulatory Guide 1.78, *Assumptions for Evaluating the Habitability of a Nuclear Power Plant Control Room During a Postulated Hazardous Chemical Release*,[34] identifies chemicals which, when present in sufficient quantities, could result in the Control Room becoming uninhabitable. Design considerations to assess the capability of the Control Room to withstand hazardous chemical releases either onsite or within the surrounding area are covered. SRP 6.4, *Control Room Habitability*,[36] contains guidance for reviewing Control Room ventilation systems and control building layouts, and is intended to assure that plant operators are protected against the effects of accidental releases of toxic and radioactive gases. The area served by the Control Room emergency ventilation system must be reviewed to verify that all critical areas requiring access in the event of an accident are included within the area (Control Room, kitchen, sanitary facilities, and computer facilities). The ventilation system layout and functional design must be reviewed to determine whether flow rates and filter efficiencies will be adequate to prevent buildup of toxic gases or radioactive materials inside the Control Room after an accident. Outside air intake locations for the Control Room must be reviewed to determine the potential release points of hazardous airborne materials to assure that such airborne materials cannot enter the Control Room.

The details of the ESF atmosphere cleanup system, including the credit to be assigned to the filtration system for iodine and particulate removal for use in dose calculations, are covered in SRP 6.5.1.[36] This information is identical to the information specified in Regulatory Guide 1.52.[27] The remainder of the Control Room area ventilation system is reviewed under SRP 8.4.1.3[36] A functional review of this system must be performed, including components such as air intakes, ducts, air-conditioning units, filters, blowers, isolation dampers or valves, and exhaust fans.

Control Room fire protection (for fires occurring either inside or outside the Control Room) is described in SRP 9.5.1.[36] Section 6.4 presents specific details concerning the applicability of fire protection features to assure Control Room habitability under all required operating conditions.

SRPs 12.3 and 12.4[36] provide guidance for radiation protection design features. Occupational radiation exposures are to be kept within ALARA limits by using appropriate shielding and air cleaning. Additional details on this subject are provided in Chapter 11.

The criteria for the design, installation, operation, testing, and maintenance of Control Room air cleaning systems have a single objective: to provide a safe environment in which the operator can keep the nuclear reactor and auxiliary systems under control during normal operation and can safely shut down these systems during abnormal situations to protect the health and safety of the public and plant workers.

Basic Control Room Layout

The entire Control Room envelope is serviced by the Control Room emergency ventilation system. All areas that require access in the event of a nuclear accident are included within this envelope. The Control Room emergency zone includes all of the instruments and controls needed for safe shutdown, the critical reference files, the computer room (when used as an integral part of the emergency response plan), the shift supervisor's office, a washroom, and a kitchen. Battery rooms, cable spreading rooms, switchgear rooms, motor control center rooms, and other spaces that do not require continuous or frequent occupancy after an accident are generally excluded from the Control Room emergency zone. However, these areas need to be provided with nuclear-safety-related cooling for essential equipment during and following DBAs. While these areas usually do not require the same level of protection from radiation and contaminants as the Control Room, their cooling systems (air handling and water cooling) should meet all of the other requirements.

Control Room General Ventilation Criteria

Control Room ventilation criteria are based on the premise that contaminants must be kept outside the Control Room. Therefore, Control Rooms are maintained at a positive pressure with respect to their immediate environs to assure that all air leakage flows out of the Control Room. The ventilation system should be capable of providing fresh outside air at a rate sufficient to dissipate any internally generated carbon dioxide or other noxious fumes.[42] The system also should be capable of providing sufficient cfm per occupant to maintain human comfort. There should be no noticeable drafts to disturb operators or documents. In addition, the ventilation system must take care of the Control Room cooling and heating loads.

Control Room Temperature and Relative Humidity

The Control Room HVAC system must be capable of maintaining a comfortable temperature and RH range, generally considered to be 73 degrees Fahrenheit (23 degrees Celsius) to 78 degrees Fahrenheit (26 degrees Celsius), and 20 to 60 percent RH (ASHRAE Comfort Standard 55-74).[42] A secondary criteria is that the air temperature at floor and head levels should not differ by more than 10 degrees Fahrenheit (5.6 degrees Celsius).

Effective temperature, which takes into account dry-bulb temperature, RH, and air velocity, is commonly used as a measure of maximum limit for reliable human performance. The maximum effective temperature for reliable human performance is believed to be 85 degrees Fahrenheit (29 degrees Celsius). As extremes, this effective temperature can be achieved with 100 percent humid air at 85 degrees Fahrenheit (29 degrees Celsius), or with 20 percent humid air at 104 degrees Fahrenheit (40 degrees Celsius). Air velocity under 100 fpm (30.5 m/min.) has a negligible effect on effective temperature. Effective temperature is not intended to be used as a design criterion, only as a guideline for limiting operating conditions. Because RH is not normally measured in a Control Room, a worst-case condition should be assumed, implying that a dry-bulb temperature of 85 degrees Fahrenheit (29 degrees Celsius) should be the maximum temperature for a Control Room. This temperature should not be exceeded for longer than 1 hour, after which steps should be taken to reduce the temperature. Previous regulatory requirements in this area were based on equipment qualification only, and required temperatures were to be kept under 120 degrees Fahrenheit (49 degrees Celsius). This is too extreme for an operator to function efficiently and has been revised.

Control Room Air Composition

Clean air breathed by operators can be compromised by radioactive and chemically toxic gases. Chlorine is used extensively at nuclear power plants, and is the principal toxic gas of concern. With respect to radioactive materials, the air composition is specified in 10 CFR 20, Appendix B, Table 2.[43] The limits specified for every radionuclide are given as the maximum allowable airborne radioactive material concentrations to occupational workers during normal operations. During an accident, the HVAC system must be designed to limit the dose to the Control Room operator to 30 rem thyroid exposure.

Control Room Noise Levels

Verbal communication is necessary for efficient Control Room operation. Background noise, particularly from HVAC systems, should not impair this communication. Background noise levels should not exceed 65 Decibels A-weighted (dBA), and sound absorption should be sufficient to limit reverberation time.

Control Room Fire Protection Criteria

Fire Events Inside the Control Room. For fire events inside the Control Room, the design must ensure that plant shutdown capability, independent of the Control Room, is provided. With respect to ventilation, means should be provided to remove combustion products from the Control Room. Smoke detectors are necessary to alert Control Room operators of a fire and should be located in Control Room cabinets, consoles, and air intakes. The location of air supply intakes must be remote from all exhaust air and smoke vent outlets. The outside Control Room air intakes and all recirculation portions of Control Room ventilation systems require manual-isolation fire and smoke dampers. Peripheral rooms within the Control Room emergency ventilation zone should have fire dampers that close when the fire detection or fire suppression system begins operation.

Fire Events Outside the Control Room. The Control Room complex should be separated from the remainder of the plant by fire dampers. Important HVAC fire protection features, in addition to detection, include:

- Fire suppression,
- Qualified penetration seals for all penetrations,
- Portable blowers for smoke removal, and
- Location of all ventilation intakes and exhausts in relation to fire hazard.

2.7.2.8 Control Room Ventilation System Arrangements

The influx to a Control Room of radioactive and other contaminants can be eliminated by a ventilation system designed to filter the inlet air and by pressurizing the room to ensure that any leakage will be out-flowing. Design alternatives include one-pass purified outside air, recirculation purified air, stored bottled air, and a choice of dispersed air inlets.[44] Each system has a different application, with advantages and disadvantages. This section will discuss the four types, present models for calculating doses to the Control Room operators, and associated air cleaning requirements.

Control Room Infiltration

Infiltration is defined as unintentional leakage of air into the Control Room caused by pressure differences across the boundary of the Control Room air space. Typical leak paths are cracks around doorframes; duct, pipe, and cable penetrations; structural joints; and damper seals. Good Control Room design minimizes leakage paths by using gaskets, weather stripping, and sealing techniques. However, continuous distributions of microscopic capillaries and pores in concrete are possible, making complete elimination of infiltration difficult.

Pressure differentials may be due to natural phenomena such as wind and temperature or barometric differences. Pressure differences can also occur when there are flow imbalances between the Control Room and adjoining spaces.

Precise evaluation of Control Room infiltration is difficult to predict in the design phase because of the many variables (e.g., wind direction and speed, building geometry, Control Room leaktightness, and internal building pressure distribution) that can combine in different ways. In addition, the degree of Control Room isolation after an accident associated with ingress/egress traffic further compounds the situation. One approach is to measure infiltration at a number of Control Rooms and analyze the data. An isolated Control Room can be pressurized to determine the pressurization flow rate required to maintain a constant pressure. Tracer gases may also be used in a series of concentration decay measurements under various atmospheric conditions to establish empirical correlation between Control Room configuration, construction quality, ventilation characteristics, and infiltration characteristics. A study performed at the Zion Generating Station in Zion, Illinois using sulfur hexafluoride, provided extremely useful results. Sulfur hexafluoride was used because it is nontoxic, nonreactive, inert, and easily detectable by electron capture gas chromatography. With a measured makeup flow of 1,700 cfm, total infiltration leakage was experimentally determined to be 150 cfm. This was reduced by 50 percent when simple corrective measures were taken (new gaskets).

Air Cleaning Criteria

The most important feature of a Control Room air cleaning system is its ability to deliver sufficient quantities of clean air to the Control Room so that operators can perform their assigned duties in comfort and safety.

During normal operations, the Control Room ventilation system keeps out dust and noxious contaminants and maintains effective temperature at acceptable levels. It also keeps the Control Room pressurized to 1/4 in.wg to prevent in-leakage. During an accident situation, the Control Room air cleaning system must continue to function and provide a habitable environment for the operators. The system must be designed to seismic Category I and must be redundant to satisfy the single failure criterion. Automatic activation is necessary. Design features and the qualification requirements of an ESF Control Room air cleaning system are contained in Regulatory Guide 1.52[27] and ASME Code AG-1.[4] The components included in each of the redundant filter trains are: (1) demisters to remove entrained moisture, (2) prefilters to remove the bulk of the particulate matter, (3) HEPA filters, (4) iodine adsorbers (generally, activated carbon), (5) HEPA filters after the adsorbers for redundancy and collection of carbon fines, (6) ducts and valves, (7) fans, and (8) related instrumentation. Heaters may be used to reduce the RH entering the carbon beds to maximize performance and remove radioiodine species. **Figure 2.17** is a schematic of a typical ESF air cleaning system.

Subsystems

Cable Spreading Rooms. These rooms contain the cables that are routed to the Control Room. They are normally cooled by a 100 percent recirculation air conditioning unit that is nuclear-safety-related and has an assured (nuclear-safety-related) source of cooling to maintain the space temperature for all applicable design basis events. This unit may be a part of the control complex HVAC system.

Emergency Electrical Switchgear Rooms. These rooms contain the essential switchgear for the plant. They are normally cooled by a 100 percent recirculation air conditioning unit that is nuclear-safety-related and has an assured (nuclear-safety-related) source of cooling to maintain the space temperature for all applicable design basis events. This unit may be a part of the control complex HVAC system.

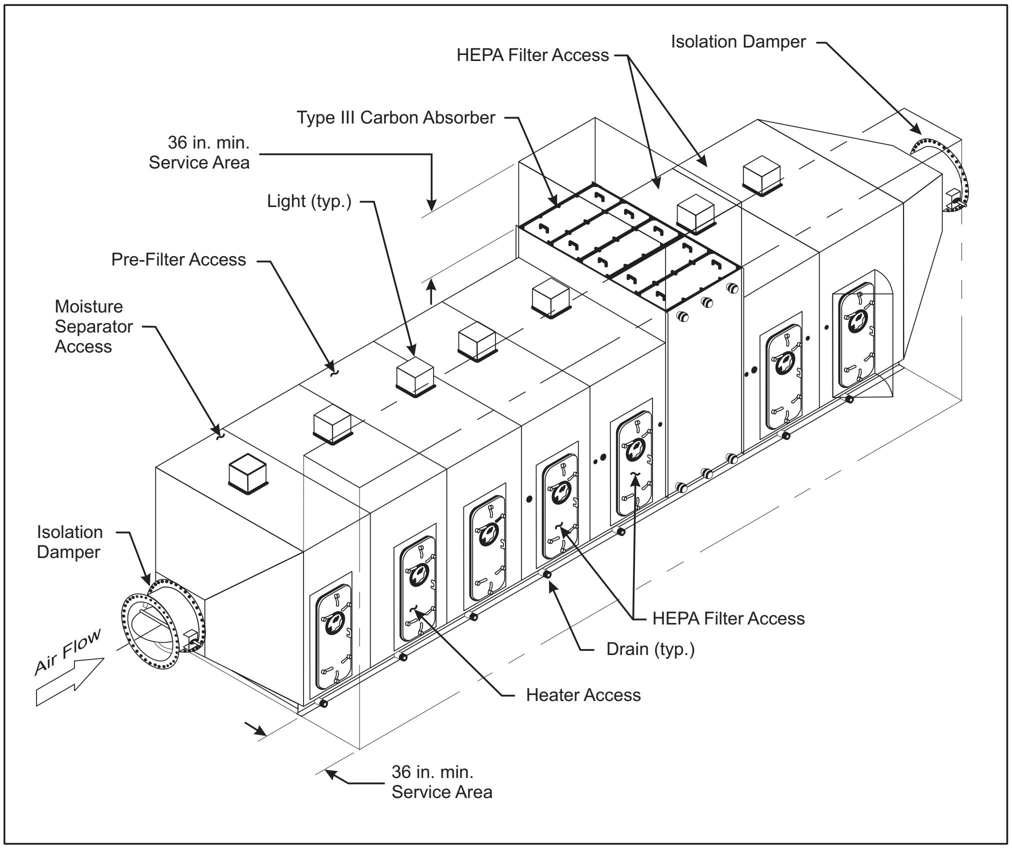


Figure 2.17 – Typical Air Cleaning System for Nuclear Power Plant Applications

Battery Rooms. The essential battery rooms contain the batteries that provide backup power for certain design basis events. They should be designed for a maximum room temperature of 77 degrees Fahrenheit (25 degrees Celsius) per IEEE Standard 484[43] and should be provided with an assured (nuclear-safety-related) source of cooling. These batteries also produce hydrogen when they are being charged. Therefore, a nuclear safety-related exhaust system is required that provides a minimum of five room air changes per hour. Also, the exhaust pickup points must be located at the ceiling of these rooms because hydrogen is lighter than air and will pocket at the highest point in the room.

Testability

Qualification testing and quality assurance of individual components by manufacturers in accordance with ASME N509,[29] ASME Code AG-1,[4] and ASME NQA-1[44] are required. After installation, pre-operational tests on individual components and the complete system are necessary. Deficiencies need to be repaired prior to accepting the system for operation and subjecting the system to radioactive contamination. An operating system must undergo periodic surveillance testing to verify that it can continue to perform its intended function. Technical Specifications, a part of the license for each nuclear power station, define the limiting conditions for operation (LCO) and the surveillance requirements for satisfying the LCOs. The LCOs specify which actions must be taken if the system becomes inoperable. The surveillance requirements are contained in Regulatory Guide 1.52,[29] ASME N510,[23] and ASME Code AG-1.[4]

Inspections of Control Room ventilation and radiation protection provisions for Control Room personnel are performed during the construction, pre-operational, and operational stages. In the United States, regional staffs perform this function at nuclear power plants. Inspection guidance is contained in manuals in the form of inspection modules. Inspections are performed to ensure that all systems will perform their intended functions, that operating procedures are in place, and that training has been provided.

Licensee Event Reports (LERs) submitted to the NRC by operators of commercial nuclear power plants are a useful source of information on the performance of habitability systems in Control Rooms, as well as other air cleaning systems. It is important to evaluate them and factor the lessons-learned into future activities. Owners of commercial nuclear power plants evaluate LERs through their Operating Experience Program.

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